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Outstation display systems
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Meteorological Office Outstation Display System: from concept to reality

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Summary

The development of the concept of an Outstation Display System (ODS) is described. ODS is intended to support forecasters by the reception, storage, processing and display of data as well as providing facilities for the generation of products. The present configuration of an ODS is described in terms of its hardware and software. Plans for the remainder of the development and installation programme for ODS are outlined.

1. Introduction

The Systems Development Branch of the Meteorological Office (Met O 22) has, for the last 10 years, been working to spread the benefits of automation to the outstations of the Meteorological Office. In the late 1970s, much attention was given to how best to provide an automated facility for the plotting of charts at the major forecasting outstations, at which this was a manually intensive function. The Outstation Automation System (OASYS) was developed and deployed at London (Heathrow) Airport, Headquarters RAF Strike Command (HQSTC) and London Weather Centre, in 1980, 1981 and 1983 respectively. OASYS was a relatively expensive system, originally costing about £300 000 each. It consists of two minicomputers supporting a variety of peripheral equipment which includes two pen plotters capable of plotting charts up to A0 size.

When the feasibility of OASYS was being considered, major issues that arose were where the observational data base should be located and where the computations to generate the graphical plots should be performed. In the end, it was decided to transmit the raw observations from Bracknell to each site, store the data in a local data base, and generate graphical output locally from the information held in the local data base. One important consequence of this approach was that it gave the users at each outstation the ability to decide when a particular product should be generated. After one false start on the method of data acquisition, it was arranged for data to be broadcast to each OASYS from the Meteorological Telecommunications Centre at Bracknell according to a fixed routeing list. This ensures that all the required data are broadcast to the outstation as soon as they are available. On receipt, all data are stored automatically without operator intervention.

During the planning of OASYS for HQSTC, a requirement was stated for automated support for the front line RAF stations. Much emphasis was placed on the requirement for rapid retrieval of data on demand, e.g. airfield observations and forecasts (METARs and TAFs). To meet this requirement, Met O 22 considered the possibility of supporting terminals at each RAF station connected to OASYS at HQSTC to provide access to the OASYS data base. It was clear that a major expansion in computing power would be required to support such a large terminal network.

The next step in the development of these ideas was the instigation of a pilot project which would not necessitate the enhancement of OASYS. The objective was twofold: firstly, it was to demonstrate that the claimed benefits of automated support were real, and secondly, to determine the best technical design for an operational system. Equipment was purchased and installed at two stations, RAF Lyneham and RAF Honington, and came to be known as ROAST (Remote Outstation Automation System Terminal). It consisted of simple components — a monochrome Visual Display Unit (VDU) (including storage for seven screens-full of data but with no internal processing power) and a dot matrix printer. Each ROAST was connected (using special communications protocol converters) by a 4800 bits-per-second circuit to OASYS at HQSTC. Fig. 1 shows the arrangement. The pilot project ran for the period from October 1983 to March 1984.

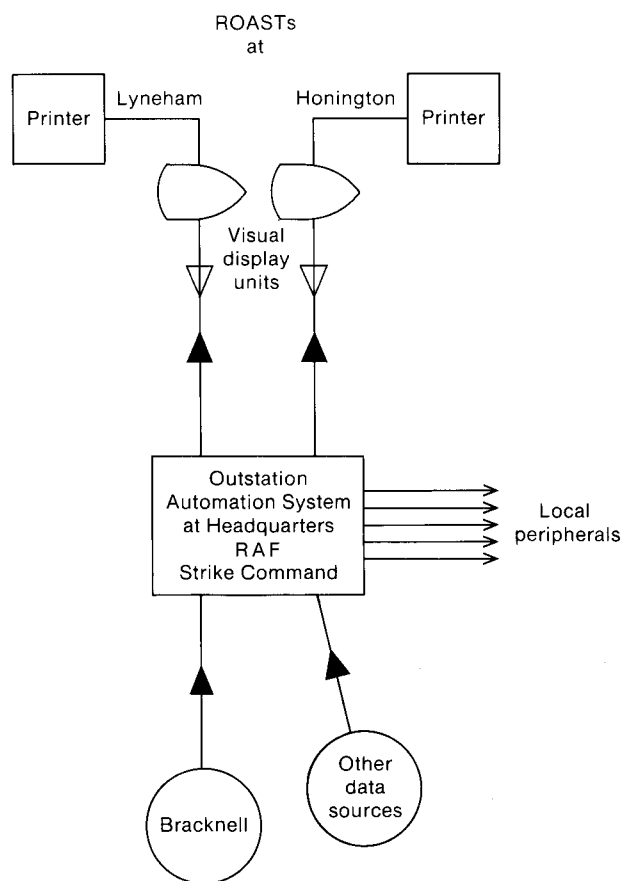


Figure 1. The ROAST (Remote Outstation Automation System Terminal) pilot project.

The ROAST pilot project enabled a number of valuable conclusions to be drawn. Firstly, it was clearly demonstrated that the provision, on demand, of observational data was a major advance over the current method of receiving such data according to a strict, inflexible schedule via slow telegraph circuits. Secondly, the displays of data, both soft and hard copy, were useful not only for direct use by the forecaster but also as an aid in briefing aircrew and other RAF personnel. Thirdly, it was felt that further advantages would accrue if it were possible for the data to be displayed in graphical formats, as these can be assimilated more quickly (note that the limited experimental graphics which were provided on the printer took too long to draw to be of much benefit). Finally, shortcomings were recognized in the responsiveness of the system — at peak times, when OASYS at HQSTC was heavily loaded, response times were often several minutes and, in addition, the ROASTs were affected by even partial outages of OASYS itself.

2. Development of the concept of the Outstation Display System

In order to design an operational version of ROAST, it was necessary to take into account a number of factors:

- (a) The conclusions drawn from the pilot project.
- (b) The need, eventually, to support at least 40 ROASTs.
- (c) The requirement that ROASTs should be compatible with, or indeed become part of, a general modernization of the means of distributing data to the outstations and the methods of display and use of these data by outstation staff.

During 1983/84, staff of the Telecommunications and Systems Development Branches worked together to produce an outline strategy for a new Weather Information System (WIS). WIS was designed to replace the existing telecommunications support for outstations, both military and civil, with a new, integrated digital network. The existing teleprinter, facsimile and radar rainfall and satellite data networks would be phased out and all data would be carried reliably over the new network which would have a much greater capacity. The data would be delivered to each outstation in a digital format and permit the use of digital storage and processing techniques in a general-purpose display system. This display equipment, known as the Outstation Display System (ODS), would carry out a large range of functions, including data storage, processing and display. The necessary telecommunications infrastructure, which would provide the facilities described above, became known as the Weather Information Network (WIN), and it included the provision of a dedicated communications node at each outstation, the Outstation Communications Processor (OCP), thereby separating communications functions from the data-processing functions of ODS. The WIS concept was accepted by the Directorate of the Meteorological Office in 1984.

Within the design for WIS, ROAST became part of the modular, microcomputer-based ODS capable of being enhanced to provide all of the required functions under the plan for WIS. All data required by ODS would be broadcast from central sources, mainly Bracknell and HQSTC via the WIN, and then stored locally on magnetic disc storage which would be supported by the ODS microcomputer. This would ensure that the requirement for guaranteed response times would be met because the possibility of contention between requests for similar data by staff at different stations would not arise. To restate this, each ODS would have a local data-base, entirely analogous to that on OASYS. Other advantages of adopting this distributed-processing and data-base approach were that it provided much more resilience against hardware failure and it avoided the problems and expense of supporting a large terminal network, from which many requests for similar data would be received simultaneously at a central computer.

Fig. 2 illustrates the conceptual model of ODS which evolved. It was conceptual as the links shown between the various items of equipment were meant to represent logical connections and would not necessarily have a direct equivalent in practice. ODS would be based on one or more general-purpose microcomputers with peripheral devices, the range and type of which would differ from station to station, depending on requirements. All transfers of data, both into and out of the ODS, would be via the OCP. This was an important feature, as it off-loaded the overheads of dealing with multiple communication protocols from ODS and would facilitate the upgrading of communications facilities independently of ODS. Magnetic disc storage would hold the data base of incoming data, and support the processing of data and the generation of products. At least two VDUs were provided to enable forecasters and supporting staff to access ODS. At least one of these VDUs needed to be able to display graphical and image data in addition to accepting graphical input so that forecast products (e.g. significant weather charts) could be prepared. Printer(s) were provided to enable hard copy to be produced. It was not intended to provide the facility to print out imagery, either satellite or radar rainfall, unless the expense of so doing could be separately justified.

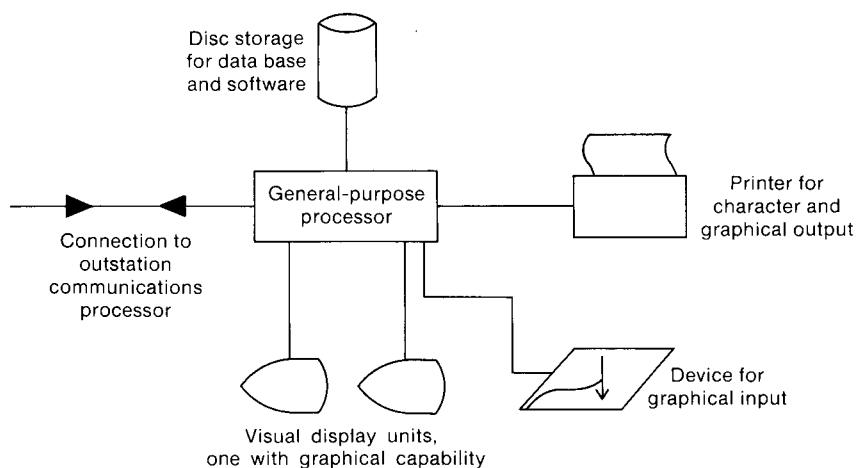


Figure 2. A conceptual model of ODS (Outstation Display System).

3. Prototype ODS and the development of the User Requirement

During the latter half of 1984, work was undertaken to build a functional prototype of ODS. There were several objectives in acquiring such a prototype:

- To enable experience to be gained with the relevant microcomputer technology and to demonstrate that this technology could support the required ODS functions.
- To allow more precise specifications to be made in the Operational Requirement which would be the basis for the competitive procurement of the operational hardware.
- To enable experimental work to be carried out, particularly on the user interface.

It should be stressed that the system was not intended as an engineering prototype but as a functional prototype, the aim being to demonstrate the various ODS functions rather than to implement these functions in a form close to the future operational configuration.

The prototype ODS was constructed from components which would allow the objectives to be met and which would entail the minimum of new software being written. Equipment which was software compatible with OASYS was therefore selected and the system is shown schematically in Fig. 3. As soon

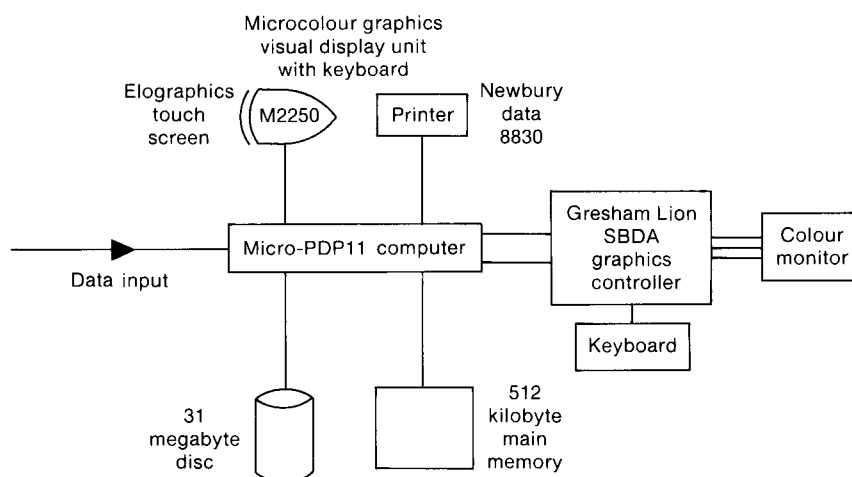


Figure 3. The prototype ODS (Outstation Display System).

as the hardware was available, software was transferred from OASYS, modified as necessary, and by January 1985 a demonstrable prototype was available. During 1985 and the first half of 1986, the prototype system was extensively used for experimental work, developing ideas regarding the user interface and other important parts of the ODS software. The acquisition of the functional prototype proved to be a very valuable investment:

- (a) It helped to demonstrate and develop the ODS concept.
- (b) It allowed forecasters to be more closely involved with the development of the user interface.
- (c) It enabled the design of major components of the operational software to be developed before a contract for the operational equipment had been awarded.

(As an aside, it is becoming increasingly accepted in the software industry that prototyping is a powerful technique for refining user requirements and designing the user interface.)

A detailed User Requirement for ODS was developed in 1985 and considered the three major functions, namely:

- (a) The acquisition, storage and display of various types of data — coded observations and text, coded numerical forecast data, pictorial data, radar rainfall imagery and satellite imagery.
- (b) The processing of data — local forecasting algorithms, climatological processing and data archiving.
- (c) The generation of textual and graphical products (including coded surface observations).

The User Requirement attempted, where possible, to quantify these various requirements and to assign priorities to them. Ergonomic factors, configuration and availability of the required facilities were also considered.

4. Initial procurement and installation of ODS hardware

During 1985 proposals were prepared for the purchase of an initial batch of ODS, consisting of 15 systems, for installation at eight RAF stations (Lyneham, Honington, Coningsby, Leuchars, Marham, Wattisham, Lossiemouth and Brize Norton). Six of the stations were to be provided with two systems, and one system would be deployed at Bracknell to support development of the software. It was decided that the initial systems should provide ROAST-type facilities but with the additional benefit of graphical displays. As WIN would not be available in time to support the initial systems, it was decided

to provide an interim scheme for the communications. This would provide a data broadcast from Bracknell and would operate asynchronously at a speed of 4800 bits per second. As a consequence of the complexity of transmitting binary data asynchronously, character data only are sent. The limitation to character data and the relatively low speed of the circuits would restrict the classes and quantities of data which could be carried. It would therefore not be possible to transmit imagery or pictorial data, i.e. charts, until the full network, WIN, was installed. Consequently there was little point in providing ODS with the capacity to handle and display data which could not be received for at least 2 years, and the initial configuration of ODS was conceived as being limited to meeting only a subset of the total requirement. However, it was important to ensure that any equipment purchased could be expanded and enhanced, at the appropriate time, to meet the full requirement.

After a full, competitive procurement, the contract was awarded to Digital Equipment Corporation Ltd (DEC). The hardware configuration of each system is illustrated in Fig. 4.

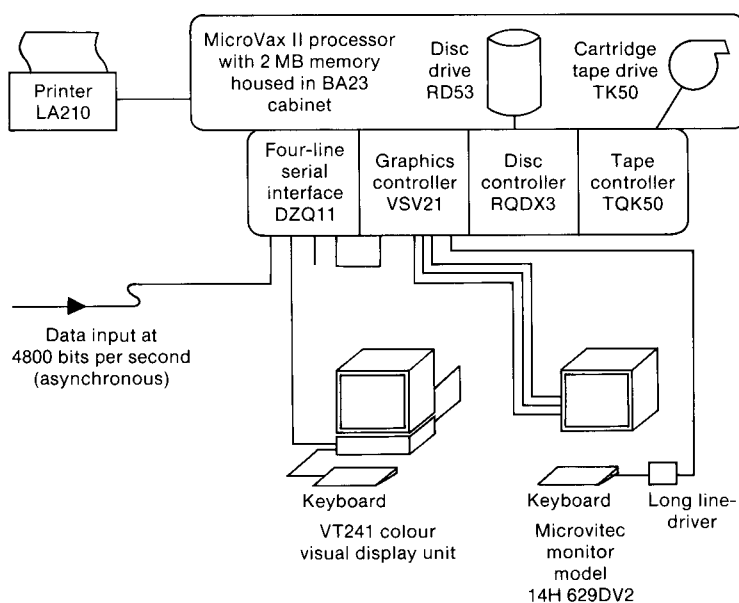


Figure 4. The initial configuration of ODS (Outstation Display System).

Each system is based on a MicroVax II processor. This is a very powerful microcomputer which is software compatible with DEC's range of larger VAX processors and is capable of being enhanced in a variety of ways. The systems were installed with two megabytes of main memory, and with 71-megabyte discs which hold the software and the data base. A cartridge tape drive enables the reloading of software, software updating, and the backing up of user-created files. Two VDUs are provided. One is a medium-resolution graphics device which is capable of producing graphical displays with a resolution on the screen of either 512×512 pixels or 640×480 pixels (picture elements) in up to 16 colours (these colours being selected from a palette of 4096 colours). This display, which is used in support of the forecaster, provides high-performance drawing of pictorial information and has the capability to display images. The second VDU is mainly for use by a supporting member of staff and at present provides an alphanumeric function. However, it does have a limited, if relatively slow, graphics capability which may be exploited later in the development programme. This VDU also has a colour

capability, enabling the simultaneous display of up to 4 colours, selectable from a palette of 64. The printer uses high-speed matrix technology, allowing printing at 240 characters per second, and can also provide limited graphical capability with a resolution of about 70 dots per inch.

The first two systems were delivered to Bracknell in July 1986 and the installations at the eight outstations were phased over the period October 1986 to January 1987. By February 1987, all of these systems were successfully installed and accepted. Each installation was planned individually, within the overall guidance that the processor should be installed in the communications room; the noise generated by the cooling fans in this equipment making it unsuitable for installation in a small forecast office. The remainder of the equipment was installed in the forecast office, the printer being supplied with an acoustic cover to reduce the noise level. Fig. 5 shows the equipment installed in the Meteorological Office at RAF Lyneham.

5. Software design

5.1 General considerations

Although the experience gained with the design and implementation of OASYS and ROAST was heavily drawn upon and many of the ideas used in the design of these systems were reused or modified, the software development team started the ODS design afresh. This was for a number of reasons. Firstly, ODS was conceived as an interactive system to support outstation forecasters, whereas OASYS had been designed principally to provide an automatic plotting function, even though graphics VDUs for forecasters' use had been added later. Interactive working demands response times which are short, preferably sub-second. In addition, the system must be easy to operate without becoming tedious for the experienced user.

Secondly, OASYS has dedicated operators whereas ODS is not intended to have operators as such, just users of the system. This implies that, wherever possible, all routine functions should be carried out automatically, without user intervention, or in some cases without the presence of any staff at all. It has therefore been necessary to build resilience into the software and care has been taken so that error conditions are handled without recourse to operator intervention.

Thirdly, with the advance of computer technology, the performance constraints lie in different aspects of the machines. OASYS is based on DEC PDP11/60 processors which are limited, by their architecture, to a maximum memory of 256 kilobytes. The MicroVax processors used in ODS have much larger main memory (2 megabytes is presently installed, but this is expandable to 16 megabytes). The computing speed is comparable, if not slightly faster than the PDP11/60, but the average disc access time is similar to that on OASYS. It therefore becomes feasible and worthwhile to try to use the increased memory available to reduce the number of disc accesses and hence increase the speed of certain operations. In the most active parts of the system, input and output operations are often minimized in the ODS design at the expense of increased use of memory.

The final general consideration in the design was the ease of maintenance of the software and its robustness and flexibility. Although these factors were also important with OASYS, they became more so with the ODS project because of the following factors:

- (a) The long-term nature of the project.
- (b) The large number of ODS which it is intended to install eventually (in excess of 60).
- (c) The remoteness of most of the sites from Bracknell where the staff tasked with supporting the software are based.

The software design is modular so that one area can be changed without impacting on others. The bulk of the software is written in FORTRAN 77 as it is suitable for this application; the FORTRAN

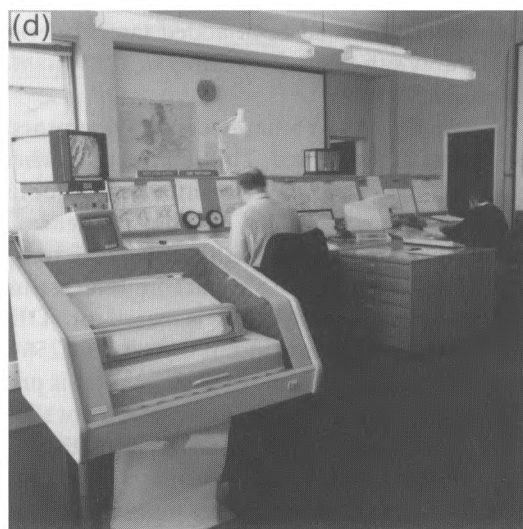
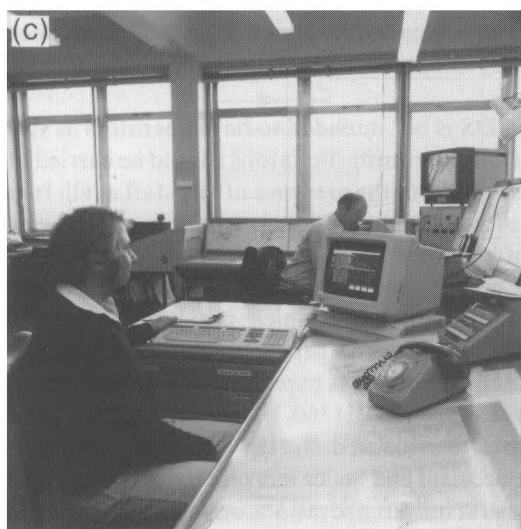
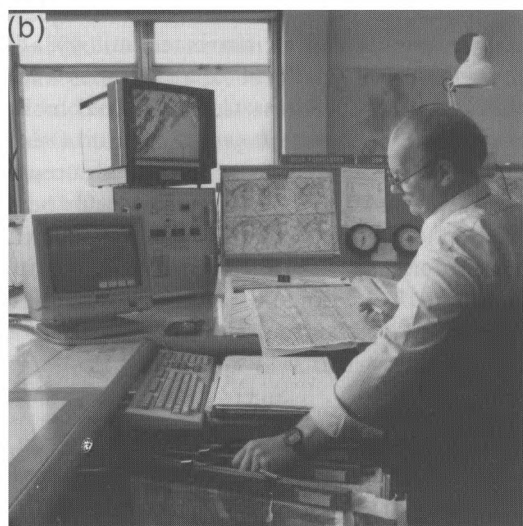
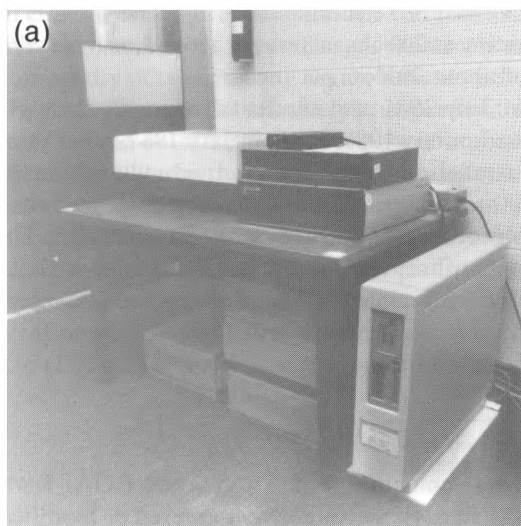


Figure 5. Photographs of the initial ODS (Outstation Display System) hardware installed in the Meteorological Office at RAF Lyneham: (a) the processor installed in the communications room (to the right of the table), (b) the graphics VDU (Visual Display Unit) installed for use by the forecaster, (c) the second VDU installed for use by support staff and (d) the printer with its acoustic cover.

compiler produces very fast code on the MicroVax, and FORTRAN is the standard language used within the Headquarters building at Bracknell.

The software divides up naturally into a number of functional areas, but for brevity this article will only describe the design of three fundamental aspects: communications, data base and user interface.

5.2 Communications and data bases (see Fig. 6)

The reception and storage of data are controlled by three processes running continuously and independently of any user interaction. These are data acquisition, pre-storage and storage, and are described in turn.

(i) *Data acquisition.* The first process takes data from the input port at 4800 bits per second and writes it to a 'raw-data' memory buffer. This buffer is arranged as a circular list of 8 kilobytes (see Knuth (1973)* section 2.2.2). This process is the most time-critical task in ODS and is consequently given the highest level of processing priority. If no data are received for 15 minutes at a stretch, a warning message is printed out to alert the user to a possible communications failure.

(ii) *Pre-storage.* This process takes data from the 'raw-data' buffer and determines the start, end and type of each bulletin and copies each report within the bulletin to a second circular buffer (the 'report' buffer) prefixed by a header containing an indication of the data type and length of the report.

(iii) *Storage.* The third process takes each report from this second buffer and deals with it according to its type. SYNOPs and METARs are decoded into binary representations for each weather element and this decoded form and the original report are stored in a common specialized data base. This enables the very rapid retrieval of, say, all observations of temperature for the United Kingdom. The original report is stored as received, as a matter of policy, so that it is available for scrutiny. This can be particularly valuable in the event of data being received in a corrupted form. Ship reports, TAFs, and upper-air reports are each stored in their individual data bases, and all other reports are placed in a 'catch-all' data base.

5.3 Data-base organization

All the data bases have two components:

- (a) A disc file to hold the data.
- (b) An index of pointers into the data file to allow the retrieval software to find quickly the data which the user has requested.

For performance reasons the index to the SYNOP/METAR data base is held permanently in memory, and is shared by all the storage and display programs needing it. In contrast, the other data bases have disc-based indexes in the form of indexed-sequential files.

The data themselves are all held in direct-access files but the file for SYNOPs and METARs is arranged differently from the others. Each possible SYNOP or METAR from each station at each hour of the day is allocated its own dedicated record in the file. The other data files are simply written to in a sequential fashion until the end is reached whereupon writing recommences at the beginning. The size of each of these files is chosen so that this 'wrapping around' never occurs at intervals of less than 24 hours.

* Knuth, D. E.; *The art of computer programming (second edition) Vol. 1: Fundamental algorithms*. Reading, Massachusetts, Addison-Wesley, 1973.

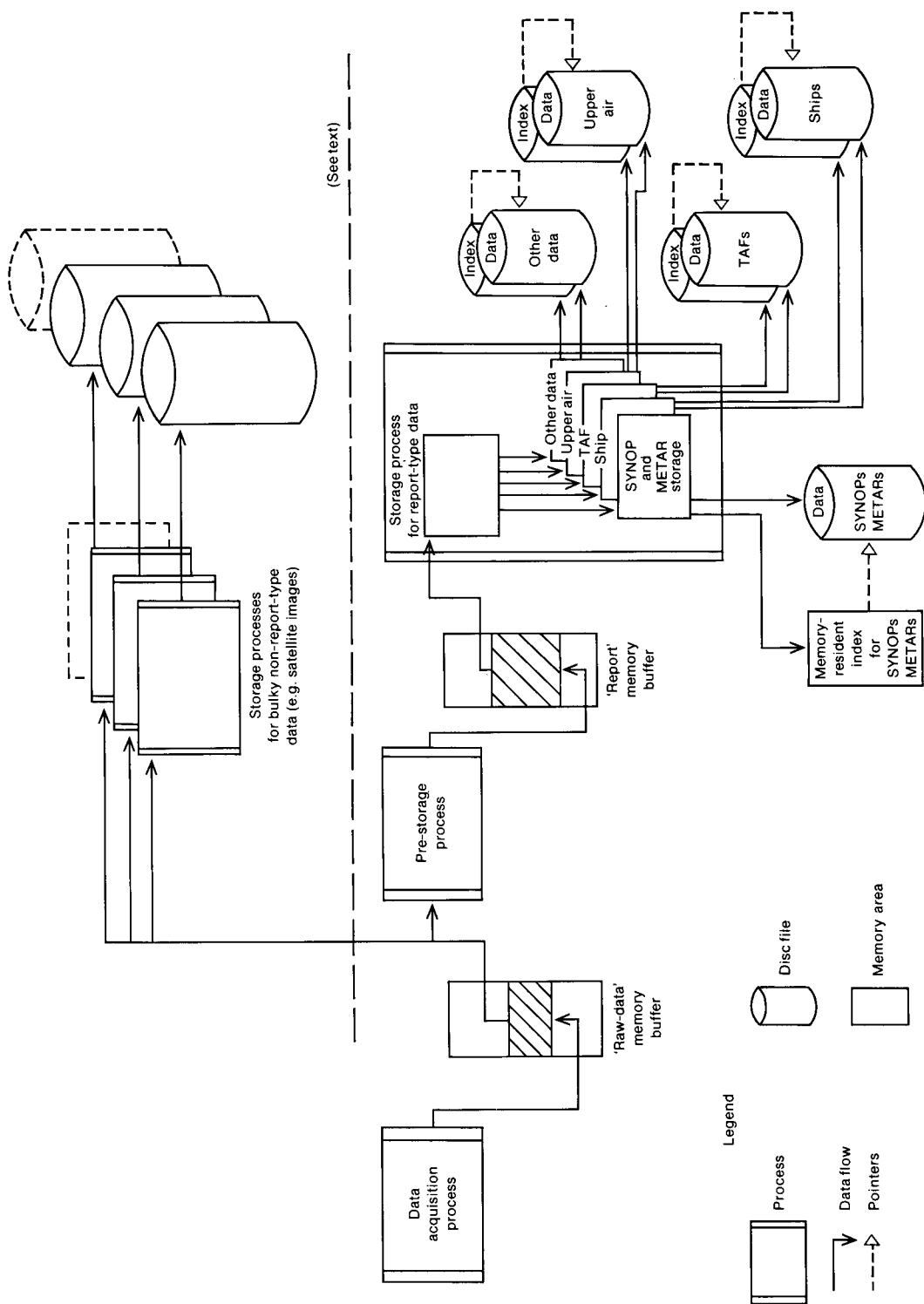


Figure 6. Data acquisition and storage processes used by ODS (Outstation Display System).

5.4 *User interface*

The method which the user employs to obtain information from ODS is designed to be as self-explanatory as possible for the beginner and yet allow short-cuts for the expert. It consists of a menu system with full screen 'pages' of options displayed and, when a selection is made, this leads to further pages until at some point the user is asked to enter information such as a station number or a geographical location for which data are required. At all times, relevant helpful hints are available at the touch of a key. The top level, or master, menu is illustrated in Fig. 7.



Figure 7. The master menu displayed on ODS (Outstation Display System).

5.5 *Software implementation*

Excellent progress has been made with the production of the necessary software. An early version of the software was installed at Lyneham at the end of October 1986, with the first full release of software being provided to all other stations as their equipment was installed. Additions to the software have been made subsequently. These software updates are provided to outstations on magnetic tape cartridges and the updates are installed by the outstations' own staff.

At the time of writing, ODS is able to receive and to store all character data which are transmitted to it. The menu system allows users to retrieve data on demand in a variety of formats. Hard copy facilities are provided. One graphical display has been provided so far (the plotting of a sequence of hourly observations for a selected station) and others, such as plotted tephigrams, are in the pipeline.

6. Future programme for ODS

Approval was given for the continuation of the ODS programme during 1987 with installations at the following sites: Coltishall, Cottesmore, Cranwell, Finningley, Kinloss, Leeming, St Mawgan, Wyton, Manchester, Meteorological Office College and HQSTC. Equipment similar to that provided for the first batch of stations will be installed. The interim scheme for communications to the first eight stations will be extended to supply data to these stations as well.

The installation of equipment at additional stations cannot be continued much beyond that planned for 1987 until WIN has been installed. It is therefore planned in 1988 to concentrate the available resources on upgrading the first two batches of systems with additional equipment, in readiness for the additional quantities and types of data that will become available across WIN. Several parts of ODS will need to be upgraded. Main memory will be added to increase the overall system throughput. Extra disc storage will be added to provide adequate space for the additional products, in particular satellite imagery which is very bulky. Furthermore, there will be advantages of resilience in having more than one disc drive. An additional communications interface will be added which will provide the high-speed connection to the OCP. A graphics printer will be provided to enable high-resolution copies of charts and other graphics output to be produced. Finally, it is intended to provide a new generation of higher performance graphics displays. These will have a higher resolution than the existing ones and will also enable more colours to be displayed at one time. A means of providing input to the screen, to enable a forecaster to generate charts, will also be provided. It is expected that a full configuration ODS to support a single forecaster will cost about £45 000.

The installation programme is expected to continue until 1992, by which time all forecasting offices will have been equipped with ODS, providing an interactive graphical display unit for each forecasting work position. Temporary installations of ODS, to run alongside OASYS, will be provided for the London Weather Centre and HQSTC pending the eventual replacement of OASYS by the next generation of systems at these larger forecasting units.

Much software has still to be written, including the provision of an expanding range of graphical displays. However, the biggest change anticipated in the way ODS will work in the future will be to allow the reception and storage of large volumes of data, such as satellite images and charts, encoded in binary formats. The quantity of data involved is such that it will be important for these data to be stored on disc with the minimum of processing. Consequently, it is planned that such data will be taken directly from the 'raw-data' buffer and written to disc, by-passing the pre-storage step. This is illustrated in Fig. 6 above the dashed line. Another major enhancement in the facilities will be the provision of the means for forecasters to generate products, both textual and pictorial. A major software development effort will continue to be required to provide these functions and the other facilities which are specified in the User Requirement.

The direct measurement of geopotential height from orbiting platforms

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Summary

The horizontal gradient of geopotential height is an important element in determining the field of atmospheric motion by numerical means. Orbiting platforms can provide consistent measurements over otherwise data-sparse areas, thereby complementing the conventional network of observations. To date, geopotential height has been determined from orbiting platforms via retrieved profiles of temperature and an additional external measurement of surface pressure. We describe here a method of determining geopotential height directly by combining satellite measurements of pressure, temperature and geometric altitude.

1. Introduction

Routine observations from both geostationary and polar orbiting satellites contribute substantially to the global observing system for operational meteorology. In addition to information about weather systems which can be derived from visible and infra-red images of clouds and the earth's surface, a range of variables, including temperature, humidity and wind (from tracking clouds) is available for direct incorporation into numerical global forecasting models (see, for instance, Houghton *et al.* (1984)). The main advantages of observations from polar orbiting satellites are that global coverage is available twice per day and that, because a single instrument is involved for all the measurements, a high degree of consistency in the measurements is achieved. A further characteristic of satellite observations is that, although the vertical resolution for some measurements (e.g. temperature and humidity) is poor, the horizontal resolution of these measurements is high — considerably higher than is available from conventional observations, even in data-rich areas. It is, therefore, valuable to investigate whether it is possible to increase the range of observations which can be made from satellite vehicles.

2. Requirements of numerical models

Numerical models for weather prediction require an analysed field of the distribution of mass (i.e. the density field) throughout the atmosphere as a starting point for the integration of the equations of motion (see, for example, Gadd (1985)). In the operational model currently employed in the Meteorological Office, the density field is described in terms of the distribution of geopotential height on surfaces of constant pressure. The geopotential height, h , is defined by the relation

$$h = \Phi / g^* \quad \dots \dots \dots (1)$$

where $g^* = 9.8 \text{ m s}^{-2}$ is an average value of the acceleration due to gravity and the geopotential, Φ , of a body at a particular place above the earth's surface is its potential energy per unit mass, that is

$$\Phi = \int_0^z g'(z, \phi) dz \quad \dots \dots \dots (2)$$

where $g'(z, \phi)$ is the apparent acceleration due to gravity which is a function of the altitude, z , and the latitude, ϕ .

Applying the hydrostatic relation to equation (2) yields the difference in geopotential between two different levels denoted by the subscripts 1 and 2.

$$\Phi_2 - \Phi_1 = -R \int_1^2 (T/p) dp \quad \dots \dots \dots (3)$$

where R is the gas constant for air and T is the temperature at a level where the pressure is p .

From equation (3) it will be clear that to obtain a complete field of geopotential, knowledge is required of the distribution of temperature throughout the atmosphere together with the distribution of geopotential on one surface of constant pressure. This latter information is provided at the moment from measurements of surface pressure which can easily be turned into values of geopotential on the 1000 mb surface.

This paper describes a method of measuring, directly from an orbiting platform, the geopotential height well away from the surface.

3. The principle of the measurement

The principle of the proposed measurement is to determine simultaneously the pressure at a suitable altitude above the earth's surface by a direct observation of the radiance emitted from the atmosphere, and the geometric height of the region at which the pressure is measured (see Fig. 1). The radiance is measured when viewing along a path that does not intercept the surface of the earth, a so-called 'limb' path. This permits a much finer vertical resolution than can otherwise be achieved, and prevents

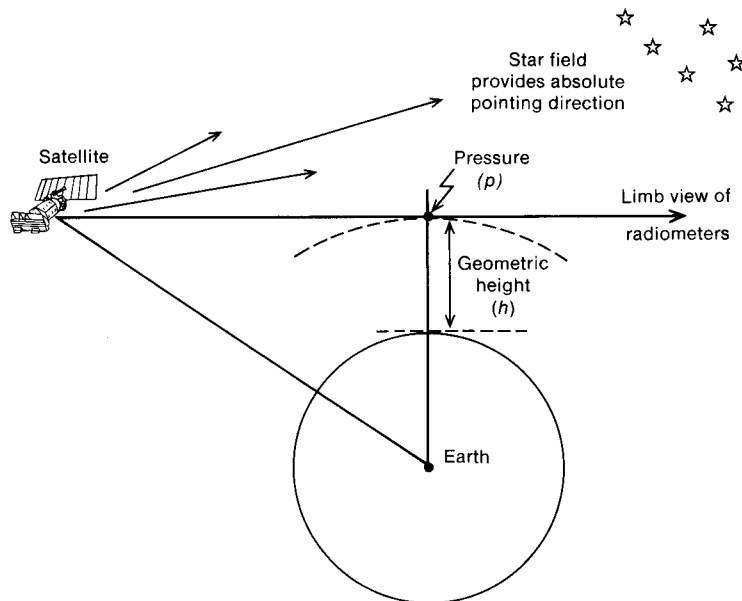


Figure 1. The geometry of the proposed measurement. The satellite measures simultaneously the pressure at the tangent to the earth, p , and the geometric height of the tangent, h .

contamination of the measurement by radiance from the earth itself. The geopotential height corresponding to the geometric height can be calculated from an explicit form of equation (2), given that the latitude of the point on the surface below this region is known.

To determine the pressure accurately from a radiance measurement, the emission observed must be from a gas which is substantially uniformly mixed at an altitude high enough to avoid contamination by clouds. Emission from carbon dioxide (CO_2) in its $4.3 \mu\text{m}$ or $15 \mu\text{m}$ bands from a region well above the tropopause is suitable. The altitude of measurement should not be too high; it should be sufficiently low to be easily useful in operational meteorology. The compromise altitude adopted for this study was about 25 km, corresponding to a pressure of 25 mb.

4. Required accuracy

It is convenient to consider the 500 mb level which, being in the middle of the atmosphere, is one of the most relevant from the forecasting point of view. The accuracy of measurement of the geopotential height of the 500 mb surface will depend upon the accuracy of measurement of both the 25 mb geopotential height and the intervening temperature field.

A computer simulation was performed in which random errors with specified statistical characteristics were applied to the temperature profile and to the height of the 25 mb surface. Repeated application of the technique produced the curves in Fig. 2. As would be expected, only with perfectly known temperatures can the errors at 500 mb be kept down to those at 25 mb. Existing methods of determining the 500 mb height, using remotely sensed temperature profiles coupled with surface-pressure measurements, show errors of about 30 m in the northern hemisphere and 45 m in the southern hemisphere where observations are much more sparse (see, for example, Allam (1987)). To be of value, a new system must be capable of significant improvement on these figures; a baseline value for the purposes of this investigation was taken to be 25 m. Fig. 2 indicates that with a root-mean-square (r.m.s.) error in the temperature of 0.7 K specified at each level, the requirement for the maximum r.m.s. error in the height of the 25 mb surface is about 15 m. For the number of levels used in the simulation, an r.m.s. temperature error of 0.7 K at each level is equivalent to the r.m.s. error of 0.2 K in the mean temperature of the whole layer.

With the temperature sounding instruments which will be carried on board polar orbiting satellites in the late 1980s, namely the High-resolution Infra-Red Sounder (HIRS) and the Advanced Microwave Sounding Unit (AMSU), it is not unreasonable to assume that the mean temperature between 500 mb and 25 mb will be determined to 0.2 K. The rest of this article therefore addresses the problem of the possibility of the measurement of geopotential height at 25 mb to within 15 m.

5. Determination of geometric height

The proposed measurement is of the geometric altitude of the 25 mb surface. It is not feasible to determine this quantity from a single observation: instead, observations will be made at a number of appropriate pressures and the value at 25 mb determined by interpolation. These observations will be made by using a vertical array of detectors to receive radiation from the atmosphere's limb (Fig. 1), positioned such that their fields of view scan across the 25 mb surface. For each detector, the pressure at the tangent point of the path from which the radiation originates will be measured; details of this measurement will be given in the next section. The geometric height of the tangent points for each of the fields of view will also be calculated.

The determination of the geometric altitude (Fig. 3) relies upon simultaneous measurements of the satellite ground-track, satellite altitude and the direction of the line of sight of the radiometer. To

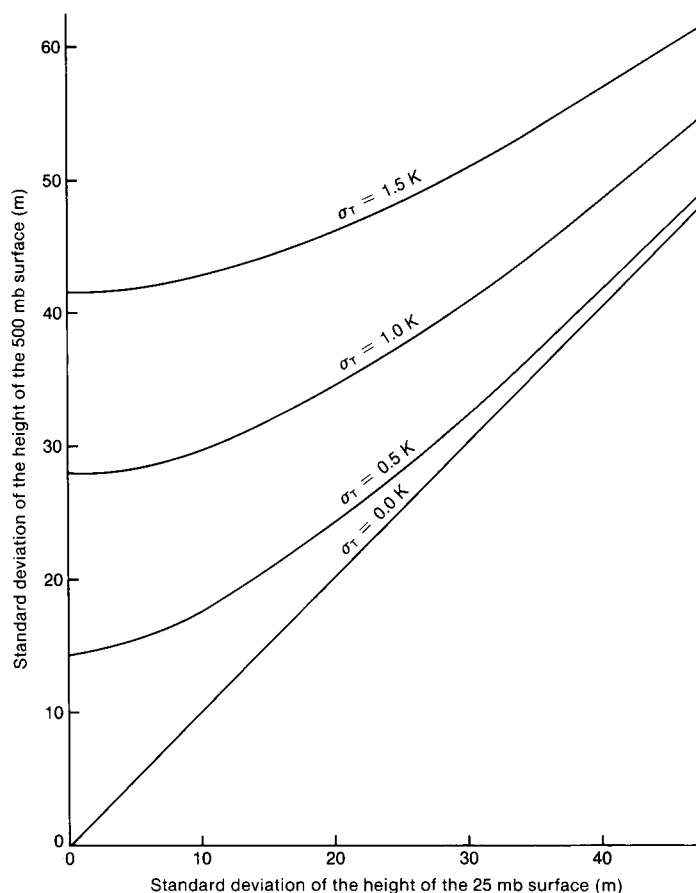


Figure 2. Standard deviation of the height of the 500 mb surface as a function of that of the 25 mb surface for different values of the standard deviation of temperature, σ_T , specified at standard levels within a profile. The nominal height of the 25 mb surface was 25 000 m and that of the 500 mb surface was 5537.5 m. The results were determined by Monte Carlo simulation.

determine the direction of the radiometer's line of sight, a star mapper will be required. This instrument observes the apparent positions of suitable stars to derive its pointing direction relative to some universal set of coordinates. Coupling this knowledge with the angle between the lines of sight of the star mapper and the radiometer enables the pointing direction of the radiometer to be determined. The angle between the two lines of sight can be measured accurately before launch, but the stresses of launch and the changes in the gravitational environment could cause significant relative shifts. A calibration of the angle in flight would be required.

Errors in the determination of these quantities would all have an impact on the final measurement of the tangent height. These errors are dealt with more fully in an expanded version of this paper (Allam 1987) to which the reader is referred.

Summarized below are the precisions in the various parameters needed to measure the height of the 25 mb pressure surface to better than 15 m.

- (a) The altitude of the satellite has to be known to better than 17 m.
- (b) The direction of the line of sight of the radiometer must be known to about 1 arc second in the vertical, but less accurately horizontally. The angle between the line of sight of the star mapper and

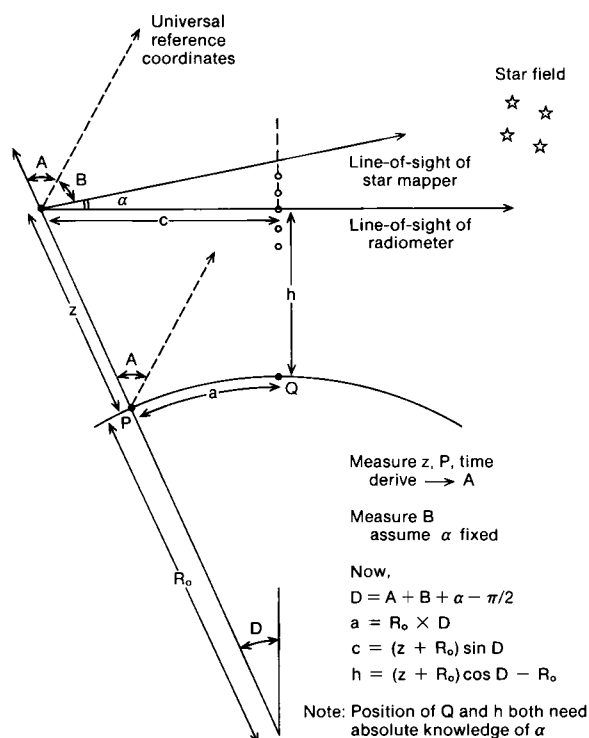


Figure 3. Method showing how the tangent height can be determined from observed quantities. The dots near the tangent point indicate schematically the altitudes of the measurements of pressure from the vertical array of detectors referred to in section 5.

that of the radiometer should also be known to about 1 arc second. The short-term variability of the pointing direction should be less than about 0.1 arc seconds in 2 seconds.

(c) Differential heating of opposite sides of the instrument mounting leading to a temperature differential of 1 K could cause significant distortion. This should either be prevented or measured independently, thereby allowing a correction to be made.

(d) A determination of the apparent ground-track of the satellite would be required to about 30 m, which is equivalent to knowing its equator-crossing time to within about 4 ms. An orbital model capable of predicting the satellite's position relative to the earth to this accuracy would also be required.

The values for the errors given above are those which would apply if each error only applied in isolation. Because in practice several sources of error will be compounded, the aim should be to achieve precisions of measurement no greater than, say, two-thirds of those quoted above.

Of the above parameters, the position parameters (a) and (d) do not present too much difficulty. Techniques are available (for instance, radar altimetry) with which the altitude and position of satellites can be determined to considerably better than what is required. Limiting structural distortion as mentioned in (c) or allowing for it should also be achievable with careful design. The more difficult measurement is that of the angle of the line of sight (b).

Because of the availability of Charge-Coupled Device (CCD) arrays with large numbers of elements (for example, several thousand squared) and high sensitivity, substantial developments in the technology of star mappers have recently become possible. For instance, one being built for the

Roentgen Satellite (ROSAT) mission for X-ray astronomy can detect stars down to 6.5 magnitude over a field of view of $2^\circ \times 10^\circ$ or can make an attitude measurement to between 3 and 5 arc seconds in a 1 second integration time. It is a relatively small instrument (about 50 mm in each linear dimension) and very substantially less complicated than that being built for the Space Infra-Red Telescope Facility (SIRTF), which will have a precision of 0.1 arc seconds. For our purposes, a star mapper will be required with rather higher performance than the ROSAT model, but less sophisticated than those designed for the larger space telescopes.

6. The determination of pressure

The radiation received by a detector on the spacecraft which is observing the atmospheric limb is dependent on the amount of emitting gas, its pressure p and its temperature T within the field of view of the radiometer. An advantage of the limb view at the levels that are being considered is that cold space from which no radiation originates is behind the atmosphere, and no clouds are present to interfere with the radiation stream.

The intensity of radiation, I , (or the radiance) measured by the satellite radiometer is

$$I = \int B(x, T) d\tau(x) \quad \dots \dots \dots (4)$$

where $B(x, T)$ is the Planck black-body function at the temperature T which exists at a point x on the limb path. The transmissivity, τ , from the point x to the satellite for radiation over the range of wavelengths observed by the radiometer and the integration is over the whole path viewed by the radiometer. It is useful to employ $-\ln p$ as a variable instead of x , in which case

$$I = \int B(-\ln p, T) \left\{ \frac{d\tau}{d(-\ln p)} \right\} d(-\ln p). \quad \dots \dots \dots (5)$$

The second term under the integral is known as the 'weighting function' since it determines the relative contribution from different pressure levels to the total received radiation. Eyre and Jerrett (1982) give a complementary and more physical explanation of these principles of radiative transfer.

Fig. 4 shows a set of weighting functions for a radiometer viewing a limb path with a tangent pressure of 25 mb at various spectral intervals within the $15 \mu\text{m}$ CO_2 band. The reasons for selecting this tangent pressure were outlined in section 3. For curves 1 to 4 of Fig. 4, a large proportion of the radiance would be characteristic of a layer within a few kilometres of the tangent pressure. Curve 5 is for a highly absorbing part of the spectrum for which most of the radiance comes from points much closer to the satellite, and therefore higher in the atmosphere, than the tangent point. Such regions of the spectrum would need to be avoided.

With the simplifying assumption of an isothermal atmosphere, the intensity that would be measured at the satellite can be related to the tangent height of the path being observed using equation (5). Fig. 5 shows this relationship and indicates that a wave-number interval can be selected such that the intensity varies strongly with the logarithm of the tangent pressure between about 10 mb and 50 mb. At low levels (below about 100 mb) the atmospheric limb becomes completely opaque for both upper and lower limits of the intervals. Above about 10 mb, the intensities vary more slowly with the logarithm of the tangent pressure and are in any case rather small. Curves similar in shape to those in Fig. 5, but displaced in the vertical, would apply to other spectral intervals in the $15 \mu\text{m}$ CO_2 band. Thus, a measurement of intensity made using a suitable wave-number interval could provide a sensitive determination of the tangent pressure.

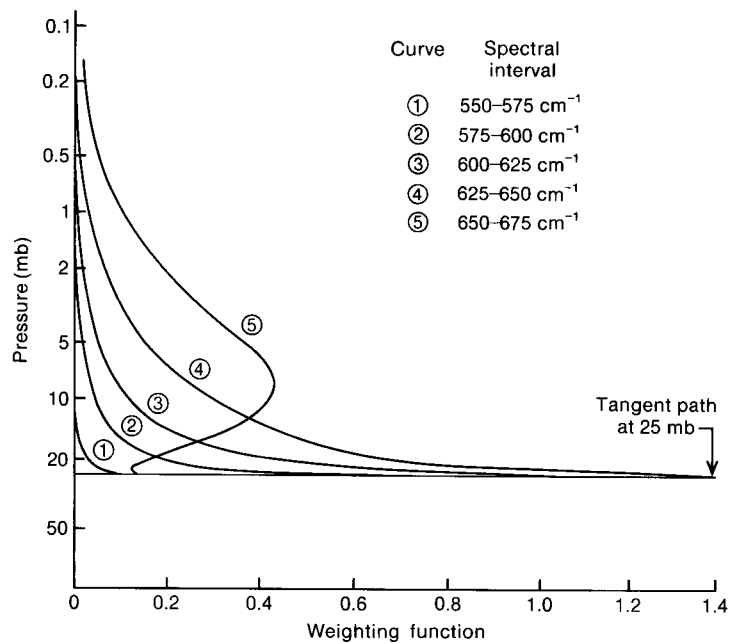


Figure 4. Total weighting functions for tangent path at 25 mb for different spectral intervals in the $15\ \mu\text{m}$ carbon dioxide band.

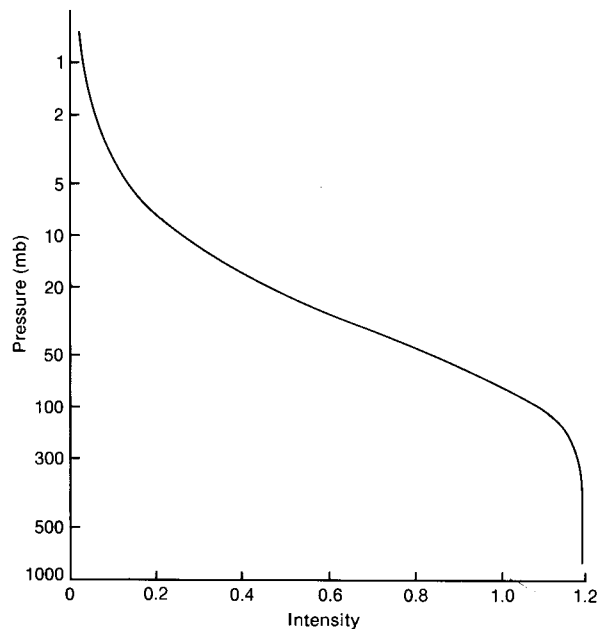


Figure 5. The relationship between the atmospheric pressure at the tangent point and the intensity that would be measured within a wave-number interval of $600\text{--}625\ \text{cm}^{-1}$, computed using equation (5).

Given that good information is available about the properties of the transmissivity for the CO₂ absorption bands being used, two quantities in equation (5) need to be determined, namely T and p . Drummond *et al.* (1980) pointed out that both can be retrieved for a limb path from measurements at two spectral intervals. A practical instrument would employ radiometers observing in two or more spectral intervals so that both temperature and pressure could be retrieved simultaneously. This retrieval process would also use information which would be available from other sources regarding the atmospheric temperature field (see, for example, Eyre (1987)).

The purposes of this study require an estimate of the accuracy with which the radiances would need to be measured in order to achieve an error in pressure equivalent to an error of 15 m in geopotential height. To simplify the calculation, the assumption has been made that the temperature field is known together with appropriate estimates of the errors in that field.

A computer simulation of the effect of random errors in the measurement of intensity from five detectors, with fields of view separated by 2500 m, upon the error in the determination of the height of the 25 mb surface was performed using a curve similar to that shown in Fig. 4; the details are given in Allam (1987). The results showed that in order to determine the height of the pressure surface to 15 m, the random errors in intensity should be less than 0.1% of the black-body intensity. With care, this is achievable.

7. Synthesis of the two measurements

The fields of view of the five radiometers would be directed to span the 25 mb level. Values of the pressure viewed by each radiometer would be obtained. The geometric heights of their fields of view could be computed from observations of the star field and from knowledge of the position of the platform as indicated in a previous section. Interpolation could then be used to give the geometric height of the 25 mb pressure surface. The geopotential height corresponding to this geometric height can be computed through the use of an explicit form of equation (1).

Since measurements of geopotential height in the atmosphere are available by conventional means (for example, from surface pressure and radiosonde temperatures) over much of the land surface of the globe, it is not necessary for the satellite measurements of geopotential height to be absolute. What is needed is the ability to interpolate between places where there are good conventional measurements.

8. Conclusions

A system has been proposed which uses five measurements of the intensity of infra-red radiation emitted from the limb of the atmosphere together with simultaneous observations of the position of the star field to derive the geopotential height of the 25 mb surface. It was shown that, to be useful to operational meteorologists, this surface should be known to about 15 m.

The precisions of various parameters to achieve this goal have been calculated and are summarized below.

- (a) Altitude of satellite — 17 m.
- (b) Ground track of satellite — 20 m or 3 ms.
- (c) Pointing direction of radiometers.
 - Accuracy — 0.7 arc seconds
 - Stability — 0.1 arc seconds/3 seconds
- (d) Random noise in detectors — 0.1% of black-body intensity.

Realizing that what are required are relative measurements to provide adequate interpolation between places where the geopotential height can be determined by conventional means, the precision required of all the measurements seems to be within the state of the art.

Acknowledgements

Dr J. Barnett of Oxford University and Dr R. Holdaway of the Rutherford-Appleton Laboratory have provided useful information and helpful advice.

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Improving precipitation forecasts from the Meteorological Office fine-mesh model by using a modified evaporation scheme

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Summary

A new treatment of the evaporation of precipitation in the fine-mesh model is described. The improved forecasts of precipitation, especially of showers, are illustrated by the results of one case study.

1. Introduction

During the last 3 years a significant number of fine-mesh model forecasts have underestimated the extent of showers over the United Kingdom, especially in northerly and north-westerly airstreams. It was felt that this behaviour may have been due to excessive evaporation of convectively produced rain. Therefore, a series of experiments was carried out to see if the precipitation forecasts could be improved by modifying the evaporation scheme which was being used in the operational model.

2. The parametrization schemes

2.1 The operational evaporation scheme (prior to 22 July 1987)

The operational precipitation scheme has been described in detail by Bell and Dickinson (1987). The model produces large-scale (dynamic) precipitation when air at a model grid point becomes supersaturated as a result of ascent or radiative cooling. The excess water vapour is then condensed and allowed to fall as precipitation (either rain or snow depending upon the temperature). As the precipitation falls the melting of snow is taken into account and both types of precipitation are assumed

to evaporate at a rate, E , which depends upon the difference between the saturation specific humidity, q_s , and the specific humidity, q , of the surrounding air:

$$E = \beta(q_s - q).$$

The value of β chosen for dynamic precipitation was $2 \times 10^{-5} \text{ s}^{-1}$ (where q and q_s are in units of kg kg^{-1}) irrespective of the intensity of precipitation. Kessler (1969) proposed that β should depend upon the density of rain (per volume of air), which in turn is related to the rainfall rate. A precipitation rate of 0.1 mm h^{-1} would give an evaporation rate, for air near the ground, similar to that obtained from using $\beta = 2 \times 10^{-5} \text{ s}^{-1}$. However, at higher rainfall rates the use of this value slightly underestimates the evaporation compared to that given by Kessler's expression for β .

The deep convection parametrization scheme used in the model is based on parcel theory modified by entrainment. The scheme assumes that in each grid box there is an ensemble of buoyant convective plumes which entrain air from the surroundings and ascend until they are no longer buoyant. If the cloud depth is greater than a certain critical value and the cloud-water mixing ratio exceeds a specified threshold value (whichever is the smaller of the local saturation specific humidity and 1 g kg^{-1}), the cloud water in excess of the threshold is assumed to fall as precipitation. As the precipitation falls through the air beneath the cloud, which is assumed to cover 10% of the grid box, the effects of evaporation of rain and melting of snow are taken into account. The expression used to calculate the evaporation rate of convective rain is the same as that used for dynamic rain except that β has a value of 10^{-3} s^{-1} which corresponds to a rainfall rate of 50 mm h^{-1} near the ground. Clearly this value of β is only really applicable for intense thunderstorms.

2.2 The modified evaporation scheme

Rowntree (personal communication) has suggested that the representation of evaporating precipitation in the fine-mesh model would be improved if β depended upon the precipitation rate. Therefore, following Kessler (1969), β for dynamic precipitation was assumed to be given by

$$\beta = 1.34 \times 10^{-2} R^{0.6} \text{ s}^{-1}$$

where R is the precipitation rate in $\text{kg m}^{-2} \text{ s}^{-1}$ (mm s^{-1}). For example, a precipitation rate of 1 mm h^{-1} would give a value of $\beta = 9.8 \times 10^{-5} \text{ s}^{-1}$ whereas a rainfall rate ten times larger would give $\beta = 3.9 \times 10^{-4} \text{ s}^{-1}$. For simplicity this expression for β is used for both rain and snow.

For convective rain, the evaporation depends upon the fractional area of precipitating cloud, A , and the local rainfall rate over that area, R_1 , so

$$\beta \propto A R_1^{0.6}.$$

To use this expression A and R_1 must be expressed in terms of the grid-box average precipitation rate, R_1 , predicted by the model. By definition $R_1 = R/A$ and, from a study of ship and radar data collected during the GARP Atlantic Tropical Experiment (GATE), $A \propto R^{0.5}$. Substituting these into the expression for β gives

$$\beta = 4.37 \times 10^{-2} R^{0.8} \text{ s}^{-1}$$

where R is expressed in terms of $\text{kg m}^{-2} \text{ s}^{-1}$. A rate of 1 mm h^{-1} corresponds to $\beta = 6.2 \times 10^{-5} \text{ s}^{-1}$, whilst a

rate of 10 mm h^{-1} corresponds to $\beta = 3.9 \times 10^{-4} \text{ s}^{-1}$. As the grid-box rainfall rate grows, β increases more for convective rain than for dynamic precipitation because the fractional area of precipitation also increases.

At the same time that β was changed, the threshold liquid-water content in convective cloud for which precipitation forms was changed from 1 g kg^{-1} to 0.1 g kg^{-1} . This reduces the moistening and cooling when final detrainment occurs and the remaining cloud liquid water is re-evaporated.

3. The trial

In order to assess the impact of the modified scheme upon the fine-mesh precipitation forecasts, 11 pairs of trial and control forecasts were compared using:

- (a) The June 1987 version of the fine-mesh model to provide an up-to-date control forecast.
- (b) The trial version containing the modified evaporation scheme.

The 11 cases were selected from the previous 12 months in order to cover a wide range of synoptic situations over the United Kingdom; the data times of the cases and the reason they were chosen are as follows.

00 GMT 19/5/86	development of a mesoscale convective system
00 GMT 10/6/86	cool, wet, cyclonic weather
12 GMT 16/6/86	hot, humid weather with the risk of thunderstorms developing
12 GMT 22/7/86	original operational model gave a poor forecast of showers over south-east England for the Royal Wedding day on 23 July
00 GMT 23/7/86	original operational model gave a poor forecast of showers over south-east England for the Royal Wedding day on 23 July
12 GMT 27/8/86	depression in the North Sea moved slowly north-east and showers developed in the cool strong northerly airstream over much of the United Kingdom
00 GMT 29/9/86	large anticyclone controlling the weather over most of Europe
00 GMT 11/1/87	coldest period of the winter when strong easterly winds brought extremely cold weather from Siberia across the United Kingdom
12 GMT 11/2/87	slack low pressure area persisted over the United Kingdom
00 GMT 28/3/87	deep depression moved slowly northwards over Norway and a strong northerly airstream covered the United Kingdom
00 GMT 13/6/87	operational model failed to predict the heavy showers which occurred

The results from all the cases studied are given in Hammon and Wilson (1987); only one case will be considered in detail here.

4. The case of 00 GMT on 19 May 1986

The synoptic situation and the original fine-mesh forecast for this time have been described in detail by Morris (1986). The control forecast described here differs slightly from the original forecast since a more up-to-date version of the model was used.

During 19 May, an upper trough in the Atlantic was moving slowly eastwards towards Biscay, maintaining a south-westerly upper flow over the United Kingdom. Thunderstorms developed in the warm, humid air mass over Spain and western France ahead of an approaching cold front and started to move northwards towards the United Kingdom. During daylight hours, southern England remained dry, warm and mainly sunny. However, during the late evening, cloud increased over south-west England, Wales and the west Midlands and sporadic outbreaks of rain and isolated thunderstorms were reported from the unstable medium cloud. During the night, thunderstorms and outbreaks of heavy rain

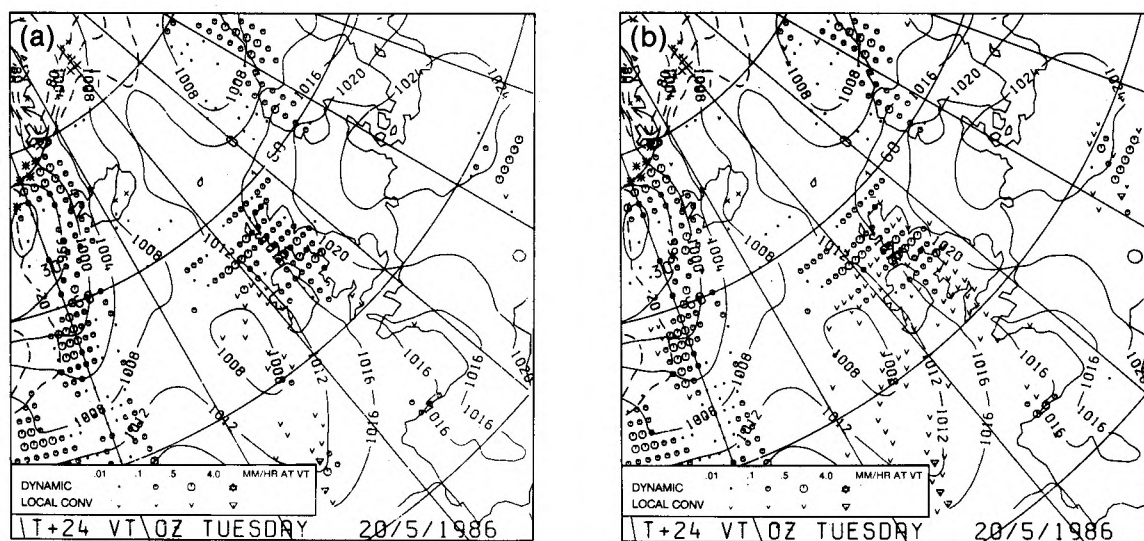


Figure 1. Fine-mesh numerical forecasts of mean-sea-level pressure (mb) and rainfall rates for T+24, verification time 00 GMT on 20 May 1986, from (a) the operational version and (b) the trial version of the model.

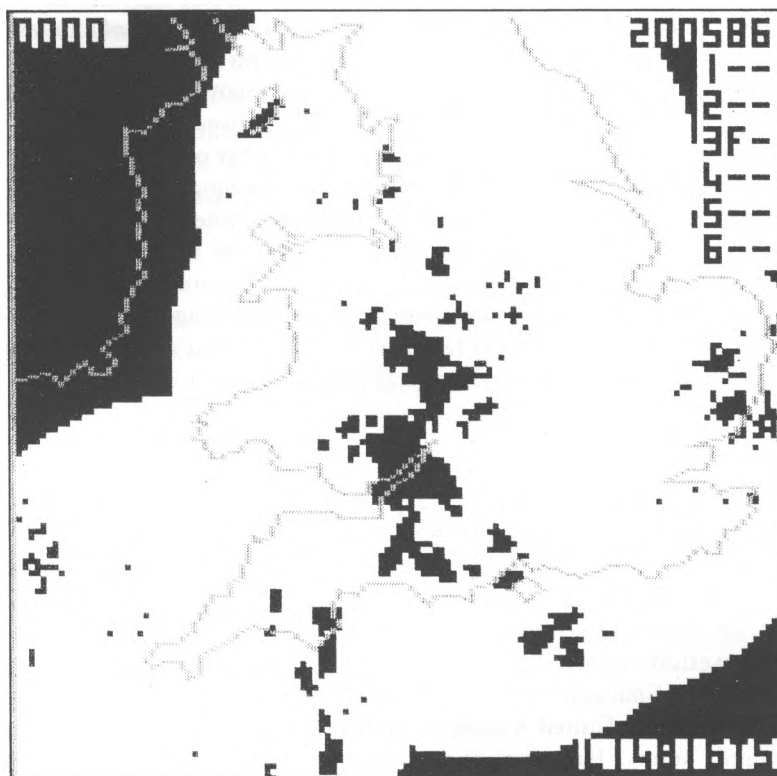


Figure 2. Radar picture showing the distribution of rain for rates above 0.1 mm h^{-1} at 00 GMT on 20 May 1986.

became more widespread, spreading northwards and eastwards over the rest of England, but Cornwall and west Wales stayed dry.

The main difference between the trial and control forecasts was noticed at T+24, verification time 00 GMT on 20 May (see Fig 1); in Fig. 2, the radar picture shows the rain area at 00 GMT. Both versions of the fine-mesh model produced very similar forecasts for the convective cloud tops and depths (i.e. tops 20 000–27 000 ft and depths 10 000–14 000 ft). However, whereas the control version forecast only had isolated showers at two grid points in south-west England from this cloud (see Fig. 1(a)), the trial version forecast widespread showers over Wales and south-west England (see Fig. 1(b)). These extra showers forecast by the trial version gave 6-hour rainfall accumulations of 0.1–1.0 mm. Although the trial forecast has predicted showers too far west, it gives a better indication of the northwards spread of the thundery rain. At T+36, verification time 12 GMT on 20 May, the forecasts were very similar.

5. Conclusions

The main conclusions from the complete set of cases are listed below:

- (a) Forecast mean-sea-level pressure is the same with both schemes.
- (b) The modified scheme produces a significant increase in the number of light showers forecast over the sea (between 0.1 mm and 1.0 mm added to the 6-hour accumulations of rain). However, there are indications that showers over the sea may be too widespread with the modified version.
- (c) There is a slight increase in the number of light showers forecast over land with the modified scheme — of the eight cases in which the forecast of showers over land is important, the forecast distribution of showers is improved in six cases by using the modified scheme.
- (d) There is a slight decrease in forecast amounts of low and medium cloud with the modified scheme. For low clouds the decrease was very small, but the decreases are more noticeable for medium clouds (mainly confined to unstable airstreams and the outer edges of depressions). Frontal clouds are mainly unaffected.
- (e) The indications are that there is a switch from dynamic to convective rain with the modified scheme.
- (f) When the model ascents from the two versions differ, those from the modified scheme are very slightly warmer and drier. In most cases the increase in temperature is only 0.1–0.2 °C.

Because the modified scheme tends to improve the forecasts of convective rain, it was incorporated into the operational model on 22 July 1987.

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Golden anniversary of the Naval Meteorological Branch

Commander G. Sullivan, Royal Navy

Naval Liaison Officer to the Meteorological Office

Extract from the December 1937 edition of the *Meteorological Magazine*:

The Admiralty have established a branch of the Hydrographic Department to take over the administrative duties connected with meteorology in the Fleet. The new Admiralty branch is to be known as the Naval Meteorological Branch of the Hydrographic Department and Captain L.G. Garbett, R.N. (rettd.), has been placed in charge with the title Chief Superintendent of Naval Meteorology. The change will involve a reorganisation in the Meteorological Office, the remaining duties of the old Naval Division, of which Captain Garbett has been in charge since 1921, being allocated to other Divisions.

Such were the terms in which this publication announced, 50 years ago, the termination of the Meteorological Office's responsibility for providing meteorological support for the Royal Navy. In fact that responsibility had lasted for only 16 years. With the advent of naval aviation an Admiralty Meteorological Section had been established in 1916. This was initially formed within the Naval Air Department and subsequently transferred to the Hydrographic Department. It was in 1921 that this section was taken over by the Naval Division of the Meteorological Office.

However, with the rapid expansion of the Fleet Air Arm in the 1930s, the training of naval officers as meteorologists, and the establishment of meteorological offices on board aircraft carriers, it became obvious that the navy needed a dedicated support organization of its own and thus on 1 August 1937 the responsibility for naval meteorology was transferred back to the Hydrographer of the Navy.

The split from the Meteorological Office proved to be more of an amicable separation than a divorce. The Royal Navy relied, as it continues to rely, on the Meteorological Office for raw and some processed data, and for the maintenance of shore-based meteorological communications and instruments.

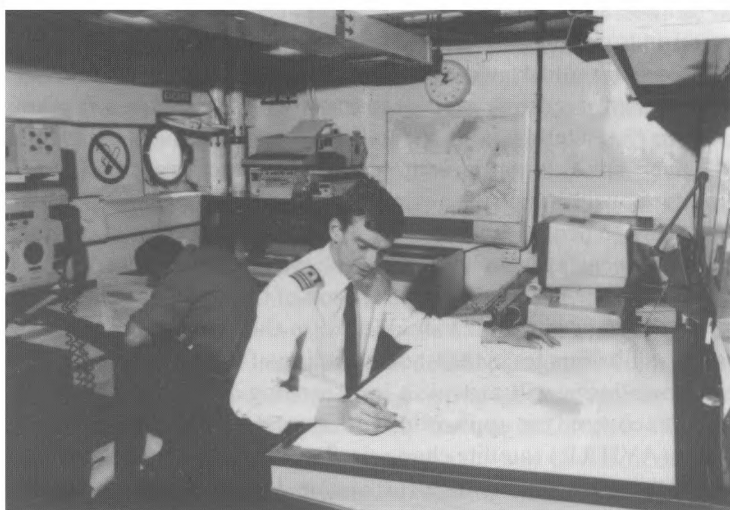
In its 50-year history the Naval Meteorological Branch has changed dramatically. In the 1940s and 1950s the Branch expanded. The tasks were heavily orientated towards support of fixed-wing carrier aviation and at one stage 70 ships and 30 Naval Air Stations were manned. In 1950 the Branch became the Naval Weather Service Department under its own Director (DNWS). In the 1960s the carrier fleet diminished rapidly but new responsibilities emerged as the importance of oceanography to submarine and anti-submarine warfare (ASW) became apparent. In 1966, to reflect these new responsibilities, DNWS became the Director of Meteorology and Oceanographic Services (Navy), with a second change in 1974 to the Director of Naval Oceanography and Meteorology, DNOM. To emphasize the shift of responsibilities the naval meteorologist acquired the new and unlovely title of the 'METOC' officer. Naval METOC training and responsibilities now cover the assessment and prediction of the oceanographic environment and its effect on a wide range of surface ship, submarine and aircraft acoustic sensors and weapons systems. The tasks of the navy's aircraft carriers are now predominantly ASW and in addition to this traditional 'big ship' requirement the services of the METOC officer are now in great demand in frigates equipped with low-frequency passive sonar.

Today a total of 85 officers are serving in dedicated METOC billets (26 of them at sea) supported by approximately 145 ratings of the Naval Airman (Met) and WRNS Met (Observer) Branch.

On 18 September 1987 more than 100 retired and serving officers of the Meteorological Branch attended a Reunion Dinner at HMS *Daedalus*, Lee-on-Solent. The opportunity to reminisce and to expound on the dramatic changes of the last 50 years was not missed! Neither was the opportunity to speculate as to what the next 50 years might hold.



HMS *Invincible*. Aircraft complement; normally 9 ASW Sea King Helicopters and 5 Sea Harriers, but can carry up to 22 aircraft in any combination. METOC complement; 1 Commander, 1 Lieutenant Commander, 1 Lieutenant, 1 Petty Officer Airman (Met), 2 Leading Airmen (Met) and 2 Naval Airmen (Met).



The Meteorological Office, HMS *Ark Royal*. Equipment includes Weather Satellite Image Receivers, Dedicated Radio Teletype and Facsimile Communications, Computer Systems for Evaluating Sonar Performance, and the ofly scuttle in the ship!

Conference Report

Workshop on Satellite and Radar Imagery Interpretation, Meteorological Office College, Shinfield Park, England, 20–24 July 1987

A Workshop on Satellite and Radar Imagery Interpretation was held at the Meteorological Office College, Shinfield Park from 20–24 July 1987. It was organized and hosted by the Meteorological Office and was also sponsored by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), who provided an excellent preprint volume of the papers presented at the workshop, and the World Meteorological Organization.

The proposal for a workshop came from a planning meeting of the Operational World Weather Watch Systems Evaluation for the North Atlantic (OWSE-NA) in 1984. It was intended that experts in the various aspects of imagery interpretation from around the world would gather together to exchange their knowledge and ideas, with a view to enhancing the value of the data from radars and satellites to weather forecasters. The workshop, which was a mixture of 30 lectures from invited speakers and periods of working group discussions, was attended by over 75 participants from 22 countries. The workshop focused on the application of image data from satellites and radar in the understanding and forecasting of weather systems affecting mid latitudes. The participants were a mix of research workers, practising forecasters and experts in systems development.

The lectures included a series describing the uses of imagery (principally satellite) in the identification, understanding and forecasting of synoptic-scale weather systems such as depressions and fronts and sub-synoptic-scale (mesoscale) features such as polar lows, convective clusters and sea fog. Various conceptual models of weather systems and their possible use by forecasters were described. The applications of the satellite images as diagnostic tools to aid in analysis and forecasting were shown. Of particular promise in this respect was the use of images from the satellite water-vapour channel in observing the location and evolution of upper-air circulations. The technique can be used in areas where no higher-level clouds are apparent on the infra-red images and at night when visible images cannot be used. Water vapour images are particularly valuable in explaining the structure of the moisture associated with mid-latitude depressions and fronts. However, as with other types of satellite images, very careful interpretation is required.

A second series of lectures illustrated the possibilities for using satellite and radar images in combination with mesoscale forecasting models to provide forecasts for a few hours ahead (so-called 'nowcasts'). Images from the satellites and radars could provide high-resolution input fields to the forecast model and, given suitable equipment to display these images and the forecasts from the mesoscale model simultaneously (we were shown the attractive French system), it would be possible to make detailed nowcasts and to provide interactive adjustment of the model products. It was shown too that reasonably accurate forecasts for an hour or two ahead (crucial for outdoor events or on occasions of severe weather) could be made by simple extrapolation of the cloud and rain shown on recent images. Animated sequences of the images were a valuable aid in this process. In other lectures, the value of animated sequences of satellite images in the understanding of the development of weather systems was clearly shown. These movie-loops will provide a key teaching aid in the future.

A third series of lectures covered the applications of the various images from the Advanced Very High Resolution Radiometer (AVHRR) satellite channels. Two topics were of particular interest: the use of Channel-3 data (with a wavelength between the visible and infra-red channels) in observing non-meteorological subjects (such as pollution and duststorms) and in identifying precipitating convective clouds, and the use of combined data from more than one channel for cloud classification or

nephanalysis and for observing fog or low cloud at night. The use of separate colours for each channel gave remarkable results.

Three working groups were given the difficult tasks of:

- (a) Assessing the present situation and making proposals for future work on the use of imagery together with routine synoptic data and numerical forecast model products in forecasting, especially nowcasting.
- (b) Assessing conceptual models of atmospheric systems and their use in interpreting imagery as a precursor to improved analyses and forecasts.
- (c) Identifying the requirements and priorities for training forecasters in the interpretation and use of imagery.

The discussions within the working groups were wide-ranging and of considerable interest and value to the participants who were able to appreciate the viewpoints of people from other disciplines. For example, many research workers in this area have not been practising forecasters and at times have appeared unaware of the detailed requirements and problems of forecasters, such as time constraints. Hopefully that problem will have been resolved, to some extent, by the workshop discussions.

The group discussing the possible way ahead in the use of imagery in forecasting and nowcasting concluded that priority should be given to developing local and regional climatologies and statistics of parameters that can be observed using imagery, such as the occurrence of showers or sea fog as a function of wind direction and speed. These climatologies and statistics, together with conceptual models, would provide the bases for the future development of knowledge-based ('expert') forecasting systems which were seen as of probable value in forecast offices, but rather far into the future. The mixing of numerical and pictorial data was thought to have considerable potential. Radar and/or satellite images could be superimposed on analysed or forecast fields provided by numerical models of parameters such as pressure, rainfall, wet-bulb potential temperature, vertical velocity and many others, or simply displayed with routine synoptic observations. These processes would have the joint benefits of improving the understanding of the imagery or the forecasts, and of widening the possibilities for quality control or cross-checking of the observations or model analyses or forecasts. To facilitate this application the group identified a pressing requirement for the development of new display systems which would be geared to the needs of the forecaster. The new displays should be user-friendly, acting as a flexible tool to assist the forecaster, rather than having fixed timetables or preselected routines. The systems would need to be very fast, reliable and easy to use, capable of allowing interaction between forecasters and model analyses or forecasts and, bearing in mind the developing nature of the work, capable of being expanded to accommodate new ideas.

The group assessing conceptual models of atmospheric systems considered in detail the requirements of forecasters for the models. It was essential for a weather system to have a unique and repeatable satellite and/or radar pattern which could be related to analyses or forecasts of parameters which are readily available from numerical forecast models, such as pressure, vertical motion and vorticity. The conceptual model should accurately describe the life cycle of the weather system which can be observed using the imagery. The complete model should provide detailed guidance to the forecaster on when and how it should be used. The group concluded that some existing models, such as those explaining cyclone comma clouds, had merit and could be adapted easily for use in forecast offices. Many others were incomplete or inadequate and required further development and assessment to test, amongst other things, the robustness of the models under routine forecasting conditions. The advent of new display systems, as described above, would facilitate the work on model development and increase the receptiveness of the forecasters to the new ideas. The group recommended the formation of an

international committee to oversee the development and implementation of the conceptual models around the world.

The third group, reviewing training needs, saw the chief requirement as that of increasing the forecasters skill in interpreting the satellite and radar imagery. The benefits of the increased skill would be, amongst other things, better and earlier detection of dangerous weather, better analyses and forecasts over data-sparse areas, and a greater understanding of numerical model analyses and forecasts so that errors may be recognized. The group identified a need to develop training resources and materials and suggested that this should involve some forms of standardization and exchange between countries. Workshops were seen as a valuable method for co-ordinating the rapid exchange of ideas, but there was also a pressing need for the development of more modest training aids such as movie-loops, slide sets and manuals. These manuals should lead the forecaster through an understanding of the 'physics' of the imagery, such as the characteristics of the various satellite wavelengths, and on to detailed interpretation and use of images, including the application of conceptual models.

The workshop was extremely well organized and very successful. The invited speakers and working group chairmen were well chosen and their contributions to the success of the workshop are acknowledged. For the participants, particularly the forecasters, the workshop will have increased their perception of what can (and cannot) be achieved using satellite and radar imagery and in what directions progress is likely to be made in the future. It will be interesting to witness the gradual process of forecasters introducing the new ideas and techniques into their routines and as a result, hopefully, leading to an improvement in the quality and utility of their forecasts. As a start, all forecasters should delve into the preprint volume.

C.A. Nicholass

Review

Climate and plant distribution, by F.I. Woodward. 150 mm × 228 mm, pp. xi + 174, *illus.* Cambridge University Press, 1987. Price £22.50 (hardback), £8.95 (paperback).

This book is part of the *Cambridge Studies in Ecology* series. The central thesis in plant ecology is that climate exerts the dominant control on the distribution of the major vegetation types of the world. Awareness of a link between climate and plants was expressed as early as 300 BC by Theophrastus. The ability to investigate the nature and cause of such links has improved tremendously with the introduction of new research techniques in recent years. Many of these have extended the temporal and spatial scale of inquiry.

Investigation of the relationship between climate and vegetation requires both theoretical and empirical input from a wide range of disciplines encompassing palaeoecology, climatology, ecology, physiology, biochemistry, genetics and many others. This difficult synthesis of topics has been achieved by the author at a level suitable for life-science undergraduates and generally interested scientists who do not wish to delve into the intricacies of the diverse disciplines.

The first three chapters form an important descriptive background of techniques used, basic ecological concepts applied and observations of the distributions of species in relation to climate at different spatial and temporal scales. This is built upon in chapters 4 and 5 in reviewing approaches to explanation and modelling of the observed correlations between climate and vegetation. In each chapter

interesting examples (particularly of field studies) are used to relate the theoretical discussions to tangible phenomena.

In chapter 1 the history of identification of links between climate and plant distribution is outlined. The clear correlation between temperature as derived by oxygen isotope studies and vegetation distribution, reconstructed via pollen analysis, is established. This leads to the question as to the nature and explanation of this correlation, which is tackled in the remainder of the book.

The fundamental concept of response time, which is used frequently in later chapters, is well explained and illustrated with specific examples in chapter 2. It is acknowledged that the simple relationship between response time and changes in geographical extent, as elicited by climatic fluctuations, may of course be interrupted by catastrophic events which take the conditions well beyond the species tolerance limits, but this aspect is in general omitted from further discussions.

Chapter 3 is the only chapter that deals directly with climate. The latitudinal variations in components of the surface energy balance are discussed. The energy available for botanic processes is dependent on this balance and thus susceptible to climatic change. A sample of some of the deterministic extrinsic factors and stochastic intrinsic influences on climate are reviewed, but only briefly.

The physiological response of plants to radiation and moisture is considered in chapter 4. A review of simple processes and reference to illustrative field studies are used to explain the increasing poleward impact of minimum temperature through mechanisms such as frost and drought. Higher temperatures are rarely a limiting factor at lower latitudes, where it is suggested that competitive exclusion due to factors such as soil or moisture availability dominate. It is proposed that minimum temperature can be used as a parameter to model plant physiography and a hydrological model based on the Penman–Monteith equation can be used to predict leaf-area index, vegetation structure and mass. The global climax vegetation distribution predicted by application of this model is compared to, and shows many common features with, observations. Further possible refinements to the global-scale model are suggested.

Having considered the impact, through temperature and moisture balance, of climate on global zonation of vegetation in chapter 4, the mechanisms by which climate may control variations in plant taxa, dispersal and migration, both within and between latitudinal zones, are considered in chapter 5. Many interesting examples from recent literature of dispersal and migration studies are cited. The main emphasis of the chapter being the importance of life stage and response time in determining the ability of plants to respond to climatic variations.

The book is concluded with a very short chapter which introduces briefly the topics of finer-scale climate–vegetation interactions such as genetic variation in life cycle between populations of one species under various climatic conditions. The reader may have benefited from a final chapter with greater emphasis on a résumé of the major ideas approached throughout preceding chapters.

This is a well written and captivating introduction to the central theme of ecology. Theories are explained critically and simply with extensive reference to recent literature. The bibliographies which conclude each chapter provide a large selection of texts in which the topics that have been reviewed may be investigated further. Throughout, interesting examples of field studies are used to relate theory to reality, which adds greatly to the enjoyment of the reader. The book is recommended as a challenging introduction to the complex response of plants to climate.

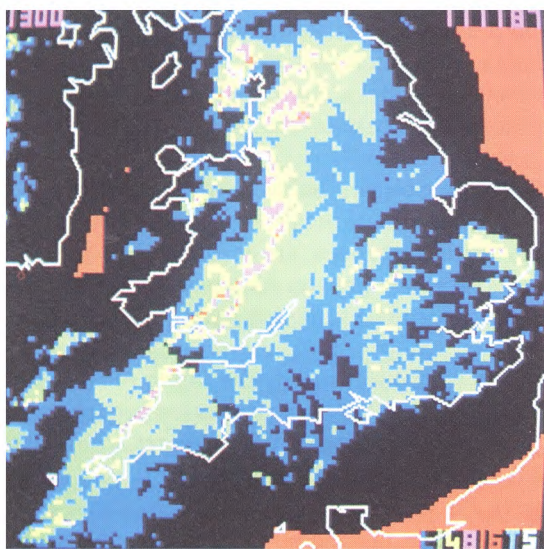
M. Wilson

Radar photograph — 11 November 1987 at 1300 GMT

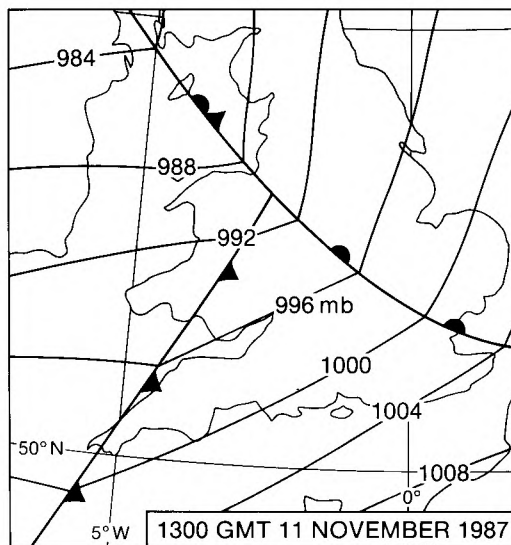
The colour picture (derived from the UK radar network) shows precipitation data from a composite of seven radars. It includes data from the radar at Castor Bay, Northern Ireland, which became operational in early November 1987. The corresponding surface analysis is also shown.

The precipitation is associated with a partly occluded frontal system. The occlusion is located close to the rear edge of the precipitation occurring over the Irish Sea and northern England. The surface warm front cannot be related to any precipitation feature; however, the cold front is marked by a line of heavy rain (line convection) which could be tracked for about eight hours as it crossed England and Wales until it moved out of radar coverage over south-east England.

The cold front, which turned out to be very active in terms of precipitation, but was weak in terms of thermal contrast, was intensely observed as it crossed the south-west approaches and Brittany as a part of the Mesoscale Frontal Dynamics Project*. As the surface cold front crossed Brittany during the evening it continued to be marked by line convection.



Key. Rainfall intensity (mm h^{-1}): cyan >32 , red >16 , magenta >8 , yellow >4 , green >1 , blue <1 .



* Clough, S.A.; The mesoscale frontal dynamics project, *Meteorol Mag*, 116, 1987, 32–42.

Meteorological Magazine

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Dynamics of rotating fluids



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Studies of geostrophic turbulence, chaos and other non-linear phenomena in rotating fluids: the role of combined laboratory and numerical experiments

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Geostrophic turbulence occurs in many natural systems, including the Earth's atmosphere and oceans. So the non-linear dynamical processes involved are not only of interest to fluid dynamicists, but their study also bears directly on the interpretation of a wide range of natural phenomena and on technical problems encountered in practical meteorology and climatology, where a satisfactory theoretical basis for predictability is still lacking. In terms of resources, by far the greatest effort expended on geostrophic turbulence is made by meteorologists throughout the world, who carry out extensive programmes of observations of the atmosphere and related simulations, using some of the most powerful computers available for scientific research. Oceanographers are now joining in as they develop ambitious observational and computer-simulation programmes.

A complementary approach to the study of geostrophic turbulence and related non-linear flow phenomena in rotating fluids underlies the papers by Dr P.L. Read and Dr A.A. White, which the Editor has asked me to introduce. More modest than field studies in its demands on resources, the approach has proved extremely successful over a number of years. The work involved comprises systematic studies of the hydrodynamics of rapidly rotating fluids over a wide range of conditions, including laboratory systems and planetary atmospheres (using observations obtained by others from space missions). The use of laboratory systems is unusual in the investigation of large-scale natural systems, for in general it is impossible to achieve dynamical similarity, but in the case of geostrophic turbulence and other less chaotic but still essentially non-linear phenomena in rapidly rotating fluids, the key parameters governing the behaviour of large-scale systems *are* attainable in the laboratory. This discovery was amongst the main findings of laboratory experiments carried out by the writer and others well over thirty years ago, when transitive and intransitive flows, vacillation, multiple equilibria, etc. were first produced and studied. Through the work of leading theoreticians, these laboratory results have influenced studies of large-scale atmospheric motions, and they were seminal in certain developments in the basic mathematical theory of non-linear systems.

To paraphrase remarks of Lorenz (1967)*, by indicating the flow patterns that can occur and the conditions favourable to each, the initial experiments made possible the separation of essential from minor and irrelevant considerations in the theory of the global atmospheric circulation. They show, for instance, that while condensation of water vapour may play an essential role in the tropics, it appears to be no more than a modifying influence in temperate latitudes, because hydrodynamical phenomena found in the atmosphere, such as cyclones, jet streams and fronts, also occur in the laboratory apparatus where there is no analogue of the condensation process. Similar remarks apply to topographic features, which were intentionally omitted in the (initial) experiments. The so-called 'beta-effect' — the tendency for the relative vorticity to decrease in northward flow and increase in southward flow because of the variation with latitude of the Coriolis parameter — now appears to play a lesser role than had once been assumed. Certainly a numerical weather forecast would fail if the beta-effect were disregarded, but the beta-effect does not seem to be required for the production of typical atmospheric systems. The experiments have emphasized the necessity for truly quantitative considerations of planetary atmospheres. These considerations must, at the very least, be sufficient to place the Earth's atmosphere in one of the free non-axisymmetric regimes of thermal convection discovered in the laboratory work.

When the early experiments were carried out, available laboratory techniques were comparatively rudimentary and the role of computers very limited, owing to their ability to deal with nothing more complicated than the simplest flows encountered in the laboratory. Numerical modelling of these laboratory flows has made great strides in recent years, and the most powerful computers can now cope with many of the flow phenomena we are now able to produce and study in some detail in the laboratory, using the most advanced measuring systems we have been able to develop. The findings of these combined laboratory and numerical studies and associated analytical work continue to influence leading theoretical meteorologists and oceanographers, and they are now being applied systematically in diagnostic studies of the atmosphere and the testing of numerical models. So it is entirely appropriate that research of this kind should be carried out in meteorological institutions and its findings reported and discussed in journals such as the *Meteorological Magazine*.

*Lorenz, E.N. *The nature and theory of the general circulation of the atmosphere*. Geneva, WMO No.218. TP.115, 1967.

The dynamics of rotating fluids: the ‘philosophy’ of laboratory experiments and studies of the atmospheric general circulation

P.L. Read

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Summary

It is instructive to consider the underlying basis for regarding certain laboratory experiments as contributing insight and information relevant to dynamical meteorology and oceanography. An intimately related question is ‘what is meant by the term “model” in meteorology and oceanography, and what purpose does it serve?’ The motivation and ‘philosophy’ behind such experiments are discussed by elucidating the general role of laboratory experiments and other models in fluid mechanics and in atmospheric dynamics. The thermally driven rotating annulus is examined as a particular example of relevance to general circulation studies in meteorology, and compared and contrasted with other experimental systems in fluid mechanics.

1. ‘Models’ in basic and applied science

In engineering and applied sciences, the term ‘model’ is commonly used to represent a device which imitates the behaviour of a physical system as closely as possible, but on a different (usually smaller) scale. The aim of such a model is normally to evaluate the behaviour of the physical system under practical conditions, for reasons connected with the exploitation of that system for economic, social, military or other purposes. Numerical weather prediction (NWP) models, for example, clearly fall into this category. By their very nature, such models are extremely complicated entities. Like the atmosphere itself, therefore, it is generally impossible to comprehend fully the complex interactions of physical processes and scales of motion that result in their synoptic behaviour. The success of these models can only really be judged by the accuracy of their predictions as directly verified against subsequent atmospheric observations. Climate models, on the other hand, are often comparable in complexity to those used for NWP, yet are frequently used in attempts to answer questions of economic, social or military importance for which little or no atmospheric data may be available to verify their conclusions (e.g. the CO₂ problem, the ‘nuclear winter’ debate, etc.).

In constructing such models and interpreting their results, it is necessary to make use of a different class of model — the ‘conceptual’ or ‘theoretical’ model — which may represent only a tiny subset of the processes active in the much larger, applications-oriented model, but whose behaviour may be completely understood (both qualitatively and quantitatively) from first principles. To arrive at such a complete level of understanding, however, it is usually necessary to make such models extremely simple in construction and highly idealized. An important prototype of such a model in fluid mechanics is that of dimensional or ‘scale’ analysis (a hybrid form of the technique was called ‘inspectional analysis’ by Birkhoff 1960), in which an entire problem is reduced to a determination of the essential balance of forces, and the consequent dependence of one or more observable (dimensionless) parameters on others in the form of power-law exponents. Following a systematic scale analysis, it is often possible to arrive at a scheme of approximations to the full mathematical description of a problem (e.g. the Navier–Stokes equations) which may then permit analytical solutions to be obtained. The quasi-geostrophic approximation is another important prototype (for example see Gill 1982) which enables a number of essential dynamical processes (e.g. barotropic and baroclinic instabilities, Rossby waves, ‘free modes’, etc.) to be studied in simplified (but nonetheless representative) forms.

For the basic researcher, such models are an essential device to aid and advance understanding. The latter is achievable because simple models enable theories and hypotheses to be formulated in a way

which may be tested (i.e. falsified, in the best traditions of the scientific method) against observations (e.g. of the atmosphere of the Earth and of other planets) and/or experiments. The ultimate aim of such studies in atmospheric science are an overall framework which sets in perspective all planetary atmospheres, of which the Earth's is but one example — see Fig. 1 (also see Lorenz 1967, Hide 1969, 1977, Hoskins 1983). Indeed this role is explicitly recognized in the World Climate Programme for example (see Lorenz 1967, World Meteorological Organization 1975).

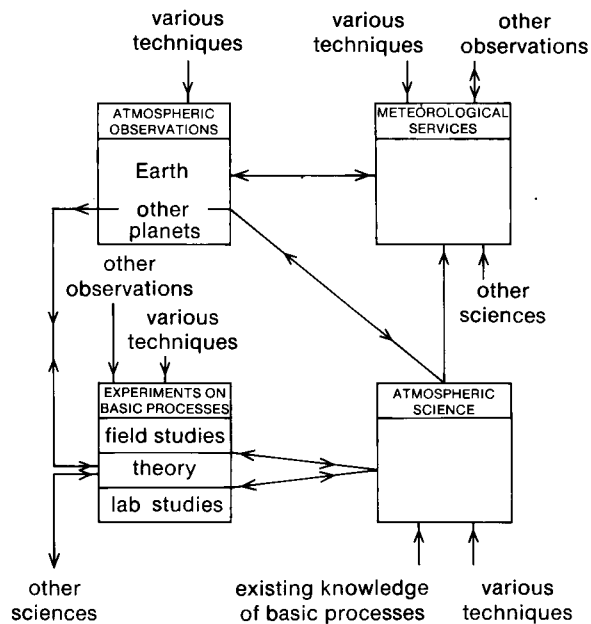


Figure 1. An attempt to illustrate the relationship between atmospheric science, applied meteorology and research on basic processes.

The role of laboratory fluid mechanics experiments in this scheme would seem to be as models firmly in the second category. Compared with the atmosphere, they are clearly much simpler in their geometry, boundary conditions and forcing processes (diabatic and mechanical). Their behaviour is therefore governed by a system of equations which can be stated exactly (i.e. no controversial parametrizations are necessary), although exact mathematical solutions may still be impossible to obtain. Unlike the atmosphere, however, it is possible to carry out controlled experiments in the laboratory to study dynamical processes in a real fluid without recourse to dubious approximations (necessary to analytical studies). For certain purposes, therefore, laboratory experiments can complement studies using complex numerical models, especially since (a) experiments have virtually infinite resolution compared with their numerical counterparts (subject only to the continuum hypothesis!) and (b) they are very cheap to run! In the context of simple analytical models of atmospheric processes, it is sometimes possible (though by no means automatically true) that a suitably designed laboratory experiment can be used to obtain a physical realization of that model in a real fluid, provided certain scaling assumptions (for 'dynamical similarity') can be satisfied (e.g. Birkhoff 1960). Such an experiment can be regarded as a 'test bed' for that model under highly controlled conditions.

In discussing the role of laboratory experiments, however, it is not entirely true to say that they have no direct role in the construction of more complex, applications-oriented models. Because the numerical

techniques used (finite-difference schemes etc.) in such models of the atmosphere can also be used to simulate flows in the laboratory under similar scaling assumptions, laboratory experiments can also be useful 'test beds' for directly verifying the accuracy of such techniques in a far more rigorous way than is possible using atmospheric data alone (see Hignett *et al.* 1985, White 1988).

2. General circulation studies and the rotating annulus

If the central problem concerning the global circulation of the Earth's atmosphere is that of 'predicting from the laws of classical physics that the atmosphere is necessarily organized as it is', then any approach towards obtaining such a prediction should include a minimal number of essential physical ingredients. At its most basic level, the general circulation is but one example of thermal convection due to impressed differential heating in the horizontal in a fluid of low viscosity and thermal conductivity. Laboratory experiments investigating such a problem should therefore include at least these factors, and be capable of satisfying scaling requirements for dynamical similarity to the relevant scales of motion in the atmosphere. Such experimental systems may then be regarded as representing the general circulation in the absence of various complexities associated, for example, with radiative transfer, atmospheric chemistry, boundary-layer turbulence, planetary curvature, topography, etc. (although some of the latter, such as planetary vorticity gradients and topography, can be included in a systematic way if required).

Experiments of this type are by no means a recent phenomenon, with examples published as long ago as the 19th century (e.g. Vettin 1884, Exner 1923, and see Fultz 1951 for a review of this early work). The modern development of experiments on the general topic of rotating fluids was begun by Taylor (1923), who also contributed greatly to the theoretical development of the subject. It was not until the late 1940s, however, that Fultz began a systematic series of experiments at the University of Chicago on rotating fluids subject to horizontal differential heating in an open cylinder (hence resulting in the obsolete term 'dishpan experiment'), and set the subject onto a firm footing (see Fultz *et al.* 1959). Independently and around the same time, Hide (1958) began his first series of experiments at the University of Cambridge on flows in a differentially heated rotating annulus, initially in the context of fluid motions in the Earth's liquid core. It is the latter system which is now considered in detail.

3. Flow regimes and transitions in the rotating annulus

The typical construction of the annulus is illustrated schematically in Fig. 2, and consists of a working fluid (usually a viscous liquid, such as water or silicone oil) contained in the annular gap between two coaxial, circular, thermally conducting cylinders, which can be rotated about their common (vertical) axis. The cylindrical sidewalls are maintained at constant but different temperatures (though see Read 1988) with a (usually horizontal) thermally insulating lower boundary and an upper boundary which is also thermally insulating and either rigid or free (i.e. without a lid).

Although a number of variations in these boundary conditions have been investigated experimentally, all such experiments are found to exhibit the same three main flow regimes, for example, as the rotation rate Ω varies. These consist of axisymmetric flow (in some respects analogous to Hadley flow in the Earth's tropics, and frequently referred to as the 'upper-symmetric regime'; see below) at very low Ω , regular waves at moderate Ω , and highly irregular, aperiodic flow at the highest values of Ω attainable (see Fig. 3). In addition, axisymmetric flows occur at all values of Ω at a sufficiently low temperature difference ΔT (a diffusively dominated regime termed 'lower symmetric' to distinguish it from the physically distinct 'upper-symmetric regime' mentioned above). The location of

these regimes are usually plotted on a 'regime diagram' with respect to the two most significant dimensionless parameters,

- a stability parameter or 'thermal Rossby number' $\Theta \equiv g\alpha\Delta Td/[\Omega(b-a)]^2$ providing a measure of the effect of buoyancy forces relative to Coriolis accelerations
- a Taylor number $\tau_a \equiv \Omega^2(b-a)^5/[v^2d]$ measuring the effect of viscosity relative to Coriolis accelerations

where g is the acceleration due to gravity, α the thermal expansion coefficient of the fluid, v the kinematic viscosity and a , b and d are the dimensions indicated in Fig. 2. Fig. 4 shows a typical regime diagram with the locations of the regimes illustrated in Fig. 3 indicated.

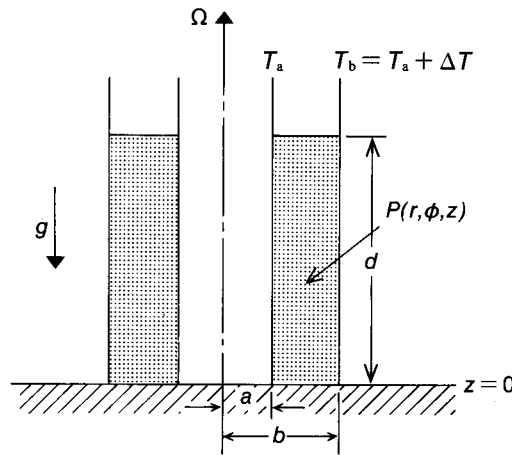


Figure 2. Schematic diagram of a rotating fluid annulus subject to a horizontal temperature gradient. P is a general point with polar coordinates (r, ϕ, z) in a frame of reference rotating with the apparatus, Ω is the angular velocity of basic rotation and g is acceleration due to gravity; region occupied by fluid is $a \leq r \leq b$, $0 \leq z \leq d$; T_a and T_b denote the respective temperatures of the cylindrical boundaries $r = a$ and $r = b$.

The regular waves may be either steady (apart from a slow drift) or 'vacillating' (i.e. with a periodic or nearly periodic time dependence). 'Amplitude vacillation' occurs in association with transitions towards a lower wave number (obtained by reducing Ω and/or increasing ΔT), and is characterized by periodic modulation of the wave amplitude and phase speed. 'Structural vacillation' (also known as 'shape' or 'tilted-trough vacillation') occurs as the irregular flow transition is approached, and is characterized by a nearly periodic tilting of the wave axis. This becomes more pronounced as Ω is increased, until the regular flow pattern breaks down into fully irregular flow. Another important property characteristic of the regular flow regime is that of intransitivity (i.e. multiple equilibrium states), in which two or more alternative flows with differing azimuthal wave number m can occur for a given set of parameters. The state obtained depends upon the initial conditions. In addition, transitions between different states in the regular regime, achieved by slowly changing the external parameters, often exhibit hysteresis, in that the location of a transition in parameter space depends upon the direction from which that transition is approached (e.g. $m = 3 \rightarrow 4$ does not occur at the same point as $m = 4 \rightarrow 3$). The latter properties are intimately connected with non-linear effects in the flow (for example see Pippard 1985) arising from the advection of heat and momentum in the fluid.

From a consideration of the conditions under which waves occur in the annulus (especially the location in parameter space of the 'upper-symmetric' transition, see Fig. 4) and a comparison with the

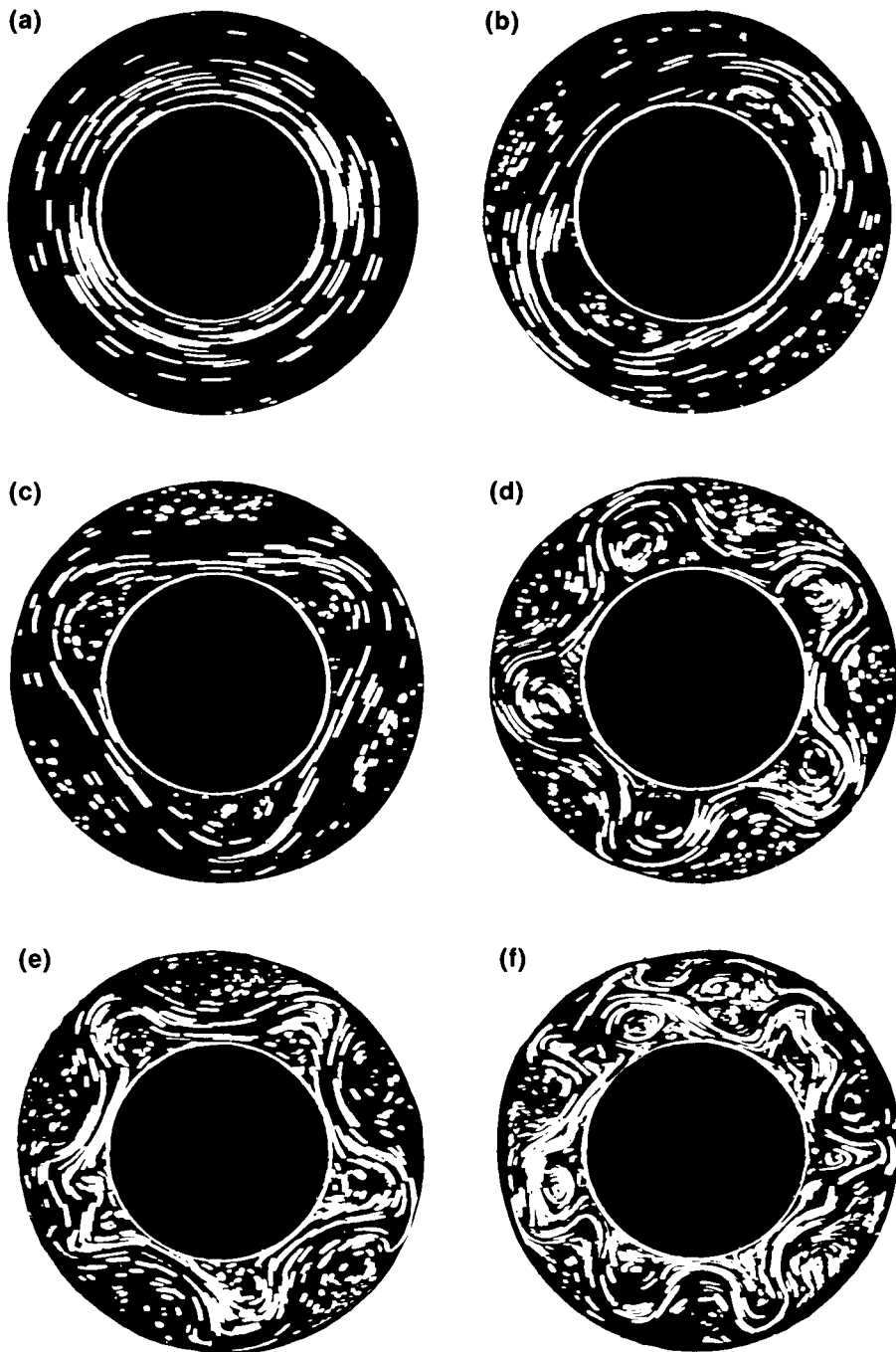


Figure 3. Streak photographs illustrating the dependence of flow type on rotation rate. Photographs were obtained in an annulus of $(b-a) = 4.64$ cm, $d = 13.5$ cm, $\Delta T = 9$ K, in a working fluid of water/glycerol solution with density $\rho = 1.037$ g cm $^{-3}$, and show the flow 0.5 cm below the free upper surface. Values of Ω and Θ are: (a) 0.41 rad s $^{-1}$ and 7.3 ; (b) 1.07 rad s $^{-1}$ and 1.07 ; (c) 1.21 rad s $^{-1}$ and 0.84 ; (d) 3.22 rad s $^{-1}$ and 0.118 ; (e) 3.91 rad s $^{-1}$ and 0.080 ; (f) 6.4 rad s $^{-1}$ and 0.030 .

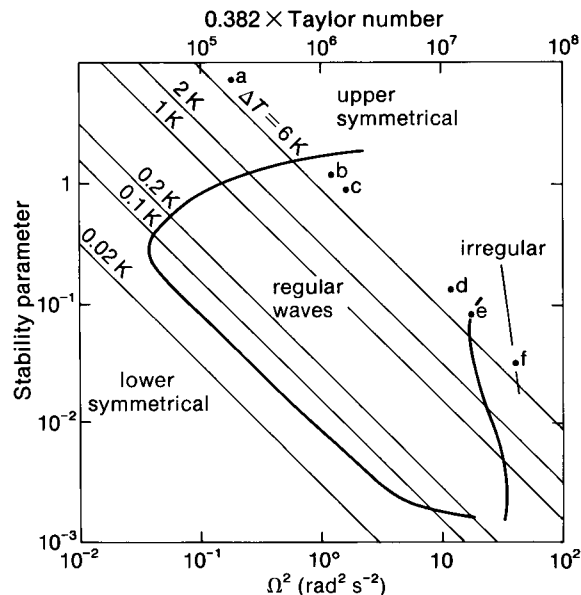


Figure 4. Typical regime diagram illustrating the dependence of the mode of convection on the two principal dimensionless parameters required to specify the system, namely a stability parameter and Taylor number (see text). The locations of the flows illustrated in Fig. 3 are shown as points a to f relative to the (approximate) regime boundaries.

results of linear instability theory, it is concluded that the waves in the annulus are fully developed manifestations of baroclinic instability (often referred to as 'sloping convection' from the geometry of typical fluid trajectories, for example see Hide and Mason 1975). Since these flows occur in the interior of the annulus (i.e. outside ageostrophic boundary layers) under conditions appropriate to quasi-geostrophic scaling, a dynamical similarity to the large-scale mid-latitude cyclones in the Earth's atmosphere is readily apparent, though with rather different boundary conditions. A more detailed discussion of the properties of these flows is given by Hide (1969, 1977) and Hide and Mason (1975). Associated with this conclusion is the implication that the waves develop in order to assist in the transfer of heat both upwards (enhancing the static stability) and horizontally down the impressed thermal gradient.

4. Other experimental systems

The regime structure for the thermal annulus is remarkable in exhibiting highly regular and predictable non-axisymmetric flows over a wide range of parameters. If such a regime structure were to apply generally to any fluid system, it could have important implications for theories of atmospheric predictability. Evidence for regular flow regimes in systems more closely akin to planetary atmospheres is currently sparse (for example see James and Gray 1983), although the atmospheres of Mars and Jupiter display some intriguing examples of highly persistent and regular features (for example see Leovy 1979). It is of interest, therefore, to compare the regime structure of the thermally-driven annulus with that of other fluid systems in the laboratory which investigate quite different dynamical processes.

4.1 The two-layer annulus or open cylinder

Another system which exhibits baroclinic instability in a different form to that of the thermal annulus is found in the rotating, two-layer experiment (for example see Hart 1979). Two immiscible liquids of

differing density are placed in an open circular cylinder or coaxial annulus (see Fig. 5(a)) which can, like the thermal annulus, be rotated about its vertical axis of symmetry. Motions are driven by rotating the rigid upper boundary of the fluid at a different rate to the rest of the apparatus, imparting a vertical shear which causes an axisymmetric deformation of the fluid interface (thereby storing potential energy in a way analogous to the sloping isotherms in the thermal annulus). Baroclinic instability occurs via non-axisymmetric deformations of that interface, thereby transferring angular momentum (rather than heat). A significant advantage of this system in the study of sloping convection is that it is more amenable to mathematical analysis than the thermally driven system (for example see Pedlosky 1979).

The regime diagram is schematically shown in Fig. 5(b), plotted in terms of the following dimensionless parameters:

- a Rossby number $Ro \equiv \Delta\Omega/2\Omega$ (usually plotted as the inverse of Ro) which measures the relative importance of inertial accelerations due to the imposed shear with respect to the Coriolis accelerations associated with the basic rotation
- a Froude number $Fr \equiv \rho_0(2\Omega b)^2/(g\Delta\rho d)$ (roughly equivalent to $1/\Theta$ — see section 3) measuring the effect of buoyancy forces relative to Coriolis accelerations

where Ω is the basic rotation, $\Delta\Omega$ the difference in rotation between the main apparatus and the lid and $\Delta\rho_0$ is the mean density. At low Fr and/or very small Ro , all flows are axisymmetric, while at $Fr > 5$ with moderate Ro , waves are found to occur. As in the thermally driven annulus, these waves are regular and steady at moderate values of Fr , and undergo periodic modulations at larger values. At the highest values of Fr attainable the flow becomes irregular and aperiodic, much as observed in the thermal annulus at low values of Θ .

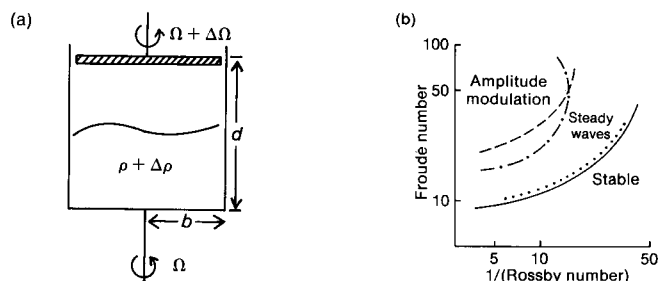


Figure 5. (a) Schematic diagram of the two-layer baroclinic system (shown for an open cylinder). (b) Regime diagram for co-rotating two-layer flow. Continuous line shows the observed neutral curve, dotted line shows a theoretically predicted neutral curve, dash-dotted line shows the transition to amplitude vacillation, while the dashed line shows a prediction from a spectral numerical model (see Hart 1979).

4.2 Rayleigh-Bénard convection

The properties of thermal convection without rotation in the presence of an unstable thermal gradient in the vertical have been studied for many years (for example see Swinney and Gollub 1985 for a review). The regime structure is found to depend significantly upon the aspect ratio D/L (where D and L are vertical and horizontal length scales respectively). Fig. 6 shows a typical regime diagram for low aspect-ratio systems (from Krishnamurti 1973), which depends mainly upon the following:

- a Rayleigh number $Ra \equiv g\alpha\Delta TD^3/kv$ measuring the importance of buoyancy forces with respect to diffusion associated with viscosity and thermal conduction
- a Prandtl number $Pr \equiv \nu/k$ which measures the relative importance of viscous to conductive diffusion

where k is the thermal diffusivity and ν the kinematic viscosity. No convection occurs at all when $Ra < Ra_c$, where Ra_c is a critical or transitional value of Ra , typically ~ 1500 . When $Ra > Ra_c$, convection begins in the form of steady, two-dimensional rolls; the precise form and orientation of these depend upon the lateral boundaries. As Ra continues to increase, the rolls give way first (at high Pr) to steady, three-dimensional cells, then to time-dependent flows, which can be regular and periodic (especially at low Pr), before finally becoming irregular and turbulent. For large aspect-ratio systems, there is little evidence for regular behaviour at the onset of convection, with the flow rapidly becoming irregular and turbulent (with the development of plumes etc.).

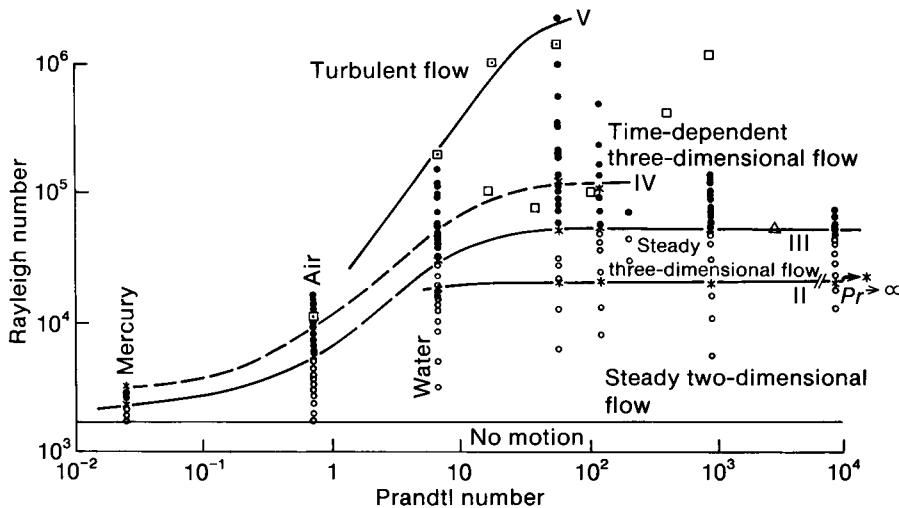


Figure 6. Regime diagram for low aspect-ratio Rayleigh-Bénard convection as a function of Rayleigh and Prandtl numbers (from Krishnamurti 1973).

4.3 Taylor-Couette flow

The instability of a homogeneous fluid subject to mechanical shear at its boundaries is another classical problem in fluid mechanics, and was extensively studied (both theoretically and experimentally) by Taylor (1923). To study the flow in the laboratory, the fluid is usually contained in an annulus of narrow gap width ($b - a$) and large depth, in which the inner and outer cylindrical sidewalls may be rotated independently (at Ω_a and Ω_b — see Fig. 7(a)). The flow obtained depends principally upon Reynolds or Taylor numbers measuring the relative importance of viscous and Coriolis forces near each side boundary, and defined by Ω_a , Ω_b , a and b (i.e. $Re_a \equiv \Omega_a a^2 / \nu$ and $Re_b \equiv \Omega_b b^2 / \nu$) and the main aspect ratios of the apparatus. Because the experimental arrangement is simple and easy to control (and has applications connected with the lubrication of bearings), it has received wide attention, especially in recent years in connection with the rich behaviour observed in its transitions to turbulent flow (for example see Swinney and Gollub 1985 for a review).

At low values of Re_a (keeping Re_b constant and positive) the flow is uniform throughout the apparatus, in response to the imposed shear. Above a critical value of Re_a (related to the Rayleigh criterion for inviscid centrifugal instability, e.g. Greenspan 1968), the flow develops a series of steady axisymmetric rolls which are periodic along the rotation axis (Taylor vortices). As Re_a is increased further, the rolls develop waves in the azimuthal direction ('wavy vortex flow'), and the flow becomes doubly-periodic (see Fig. 7(b) — adapted from Andereck *et al.* 1986). At much higher values of Re_a ,

further instabilities occur until fully turbulent flow is obtained, although the detailed sequence of events is highly complicated (the sequences are discussed in some detail by Andereck *et al.* 1986). Intransitivity in the number of Taylor vortices obtained at a given set of parameters in the regular flow regime is often exhibited much more strongly in the Taylor–Couette system than in the thermal annulus, in the sense that many more distinct states may be obtained for a given set of parameters.

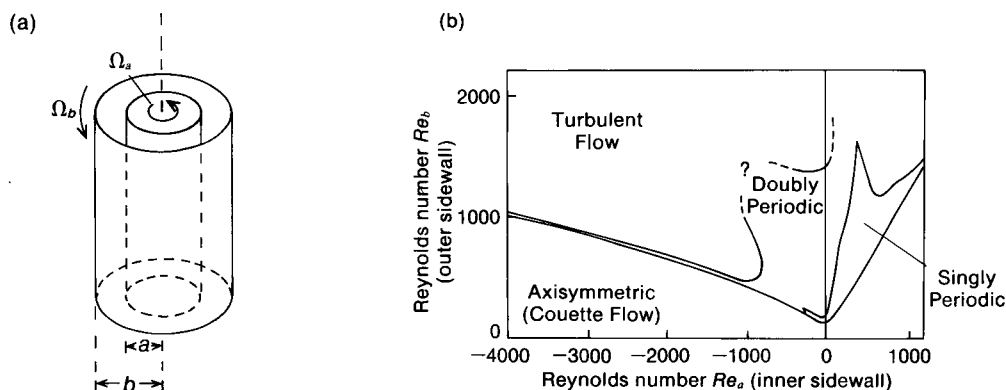


Figure 7. (a) Schematic diagram of the Taylor–Couette system, and (b) regime diagram as a function of Re_a and Re_b near the onset of Taylor vortices (adapted from Andereck *et al.* 1986).

5. 'Universal' behaviour and dynamical systems

The above examples serve to demonstrate (and the list is by no means exhaustive) that the presence of steady symmetric, regular periodic, and irregular flow regimes are the norm rather than the exception in fluid mechanics (at least for systems characterized by a degree of spatial symmetry in their boundary conditions). Some justification for this conclusion has recently emerged from studies of the general theory of non-linear dynamical systems, of which fluid flows may be but a single example (for example see Cvitanovic 1984).

A dynamical system may be loosely defined as one whose state is fully determined by its position in a suitably-defined phase-space, and whose evolution in time (i.e. its first time derivative) depends solely upon its current position in phase-space (i.e. not on external random forcing etc.). Numerous other examples of dynamical systems are found outside hydrodynamics, including non-linear optics, electronics, engineering structures, chemical reactions, and even certain processes in living organisms (for example see Cvitanovic 1984, Pippard 1985 for reviews). Of particular interest has been the identification of a number of kinds of characteristic sequence by which systems may undergo transitions ('bifurcations') from steady to irregular behaviour via regular, periodic states ('routes to turbulence', for example see Eckmann 1981), and in which irregular behaviour may initially involve only a relatively small number of the available degrees of freedom in a way first identified by Lorenz (1963) — 'deterministic chaos'. The latter is in complete contrast to earlier classical theories of the transition to turbulence (Landau and Lifshitz 1959), in which turbulence and irregular flow were associated with the excitation of a very large number of degrees of freedom.

The possible applications of these theoretical developments to real systems continues to be an active area of research activity. Much theoretical and experimental effort is currently being devoted

(a) to attempts to determine the range of possible 'routes to turbulence' and their 'universal' properties (where the term 'universal' is used in a similar sense to that used in the study of phase transitions and critical phenomena (for example see Wilson 1979), and

(b) to find the optimum ways of characterizing regular and chaotic (aperiodic) behaviour in experimental (for example see Eckmann 1981, Procaccia 1985, Eckmann and Ruelle 1985, Mayer-Kress 1986, Bell *et al.* 1986) and even certain natural systems (including climate, for example see Nicolis and Nicolis 1984, Fraedrich 1986, Grassberger 1986).

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The dynamics of rotating fluids: the internally heated annulus

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Summary

Direct internal heating of a rotating fluid annulus in the laboratory, while cooling at both sidewalls, leads to profound changes in flow structure associated with the resulting non-monotonic horizontal temperature gradient. The basic flow regimes and heat transfer properties of such flows, however, are largely unchanged from the more conventional annulus experiments which impose differential heating and cooling only at the sidewalls. Regular waves occur in the internally heated system, but take the form of compact, nearly isolated closed eddies, embedded in a mean zonal flow with strong lateral shear. The properties of the flows in the regular wave regime of the internally heated annulus are compared with those of large-scale eddies in the atmospheres of Jupiter and Saturn, and a possible analogy between the two systems is explored. The implications of such an analogy are discussed with particular reference to the role of the large-scale eddies in the atmospheres of the major planets, and theories of atmospheric predictability.

1. Introduction

In carrying out experiments in the laboratory on thermal convection in a rotating, baroclinic fluid, it is of great importance to establish which aspects of the flows observed are generally applicable to any fluid system, and which may be more specific to the particular system under study (e.g. dependent on particular means of forcing or boundary conditions). One way in which this may be investigated is by incorporating variations, e.g. into the construction of the experiment, the fluid properties and especially the boundary conditions. Here we consider some effects of variations in the thermal boundary conditions and the overall distribution of heating and cooling in the annulus. Thus, for example, by using direct internal heating of the working fluid, it is possible to investigate the properties of baroclinic waves in a zonal flow for which the horizontal thermal gradient is non-monotonic, and therefore much removed from the kind of flow considered in 'classical' theoretical analyses. A further motivation for

studying such flows has arisen recently from observations of the atmospheres of other planets, whose composition, scale and means of thermal and mechanical forcing (and their spatial distributions) may be quite different from those of the Earth. The atmospheres of Jupiter and Saturn offer some particularly intriguing phenomena which could be manifestations of sloping convection under conditions more closely similar to those which can be obtained in the internally heated annulus (for example see Hide 1981, Read and Hide 1983, 1984, Read 1986a). This potential application of the annulus experiments will be considered in sections 3 and 4.

2. Baroclinic waves with internal heating

The laboratory system considered is an annulus of conventional design, but in which heating may be applied internally via ohmic dissipation of an alternating electric current passed through the working fluid (which is a weak electrolyte) between the (electrically-conducting) sidewalls. Either or both sidewalls can be cooled in the usual way, allowing a wide variation in the effective thermal boundary conditions and distribution of heat sources and sinks (for more details see Hide and Mason 1970, 1975, Read 1986b).

The various regimes of flow obtained in such a system are found to be very similar to those in the conventional (wall-heated) annulus, with transitions between them occurring under comparable experimental conditions (again measured by a stability parameter Θ and Taylor number τ_a (see Read 1988) almost regardless of the distribution of cooling at the boundaries (for example see Hide and Mason 1970). Thus, axisymmetric flows occur at the lowest rotation rates Ω , regular waves at intermediate Ω and irregular waves at the highest values of Ω . The most significant difference between the behaviour of internally heated flows to those in the conventional annulus appears to be in the form of periodic 'vacillations'—recent work suggests that 'amplitude vacillation' rarely occurs in the internally heated annulus, while 'wave-number vacillation' is the preferred form of structural vacillation. A selection of regular and irregular wave flows for cases in which both sidewalls are at the same temperature ($\Delta T = 0$) are shown in Fig. 1.

The form of the horizontal flow pattern varies considerably in the axisymmetric and regular wave regimes, depending upon the thermal boundary conditions at the sidewalls (see Fig. 2). Internal heating forces upward-motion throughout the interior, which must match onto the horizontal boundary layers via the Ekman suction condition. Thus, the relative vorticity of the axisymmetric or mean zonal flow is anticyclonic at upper levels and cyclonic at lower levels (a more detailed analysis is given by Quon 1977, Read 1986b). In the presence of non-axisymmetric waves, this results in trains of eddies which are predominantly anticyclonic at upper levels, but with an associated meandering jet stream whose location and strength depends upon the thermal boundary conditions at the sidewalls, and hence upon the net inward or outward radial flux of heat. This may be approximately related to the mean zonal flow near the side boundaries (where the eddies are weak) by

$$H(r, t) = -(v/\Omega)^{1/2} [\bar{T}(r, z=d, t) - \bar{T}(r, z=0, t)] \bar{u}(r, z=d, t) \quad \dots \quad (1)$$

(see Hide and Mason 1970, 1975, Hide 1981), where H is the total heat flux through a cylindrical surface of height d and radius r , $\bar{T}(r, z, t)$ and $\bar{u}(r, z, t)$ are the mean zonal temperature and zonal velocity respectively, and v is the kinematic viscosity. Note that the terms multiplying \bar{u} are negative definite, so that \bar{u} may be seen to reflect directly the partition of heat flow between the inner and outer sidewalls—the result is summarized schematically in Fig. 3 for comparison with the examples in Fig. 2.

The most striking example occurs when $\Delta T = 0$, for which heat is removed at equal rates at both sidewalls. The axisymmetric flow then consists of a temperature maximum at mid-radius on horizontal

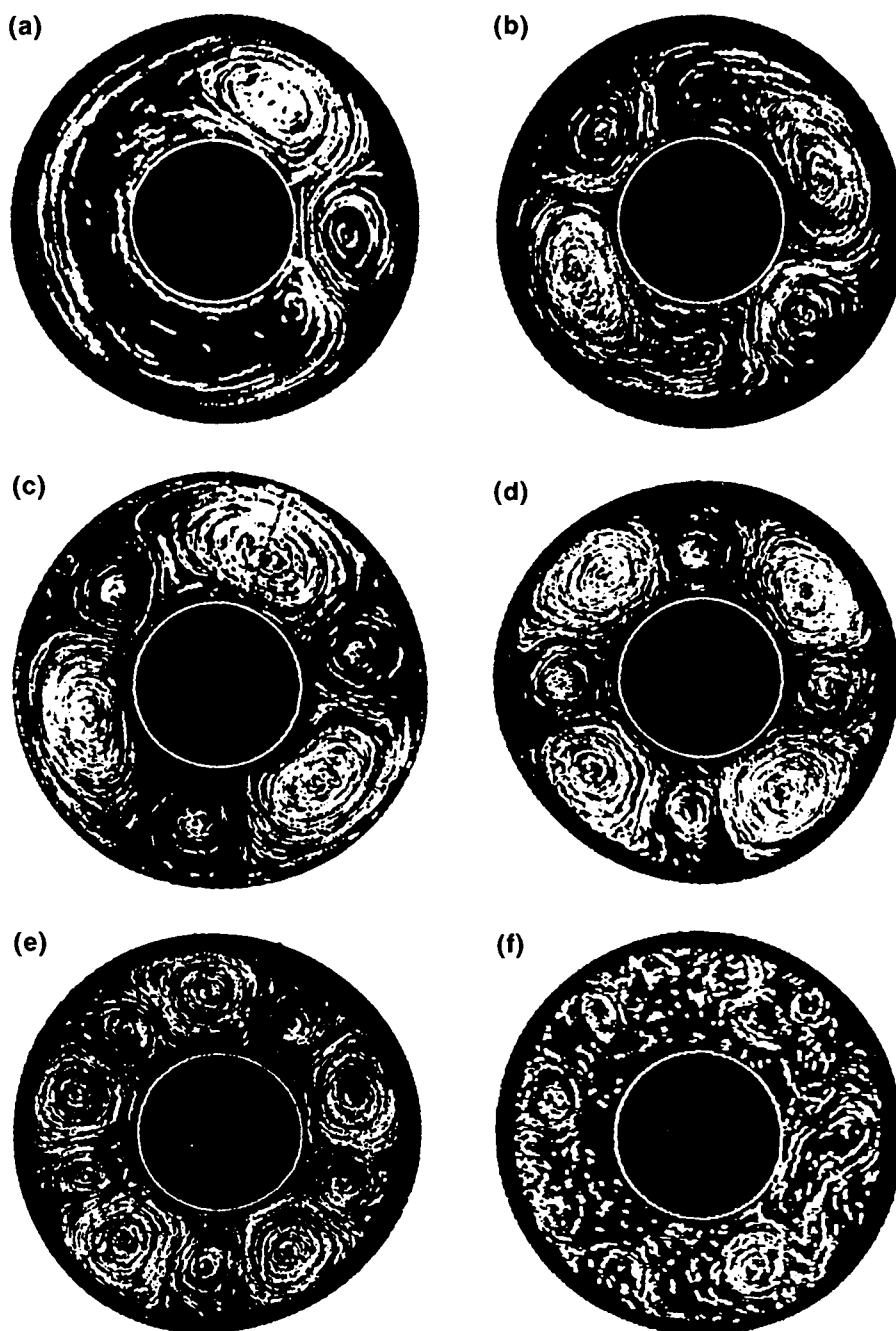


Figure 1. Streak photographs illustrating the dependence of flow type in an internally heated annulus on rotation rate. Photographs were obtained in an annulus of (radius b – radius a) 6.02 cm, cylinder height 16.1 cm, power input 100 W (except for (a) and (b) which were at 750 W and 400 W respectively), with a solution of water/glycerol as working fluid with density $\rho = 1.043 \text{ g cm}^{-3}$, and show the flow 4.5 cm below the (rigid, non-slip) upper surface. Values of stability parameter Θ are: (a) 2.92, (b) 2.84, (c) 2.16, (d) 0.72, (e) 0.48 and (f) 0.09.

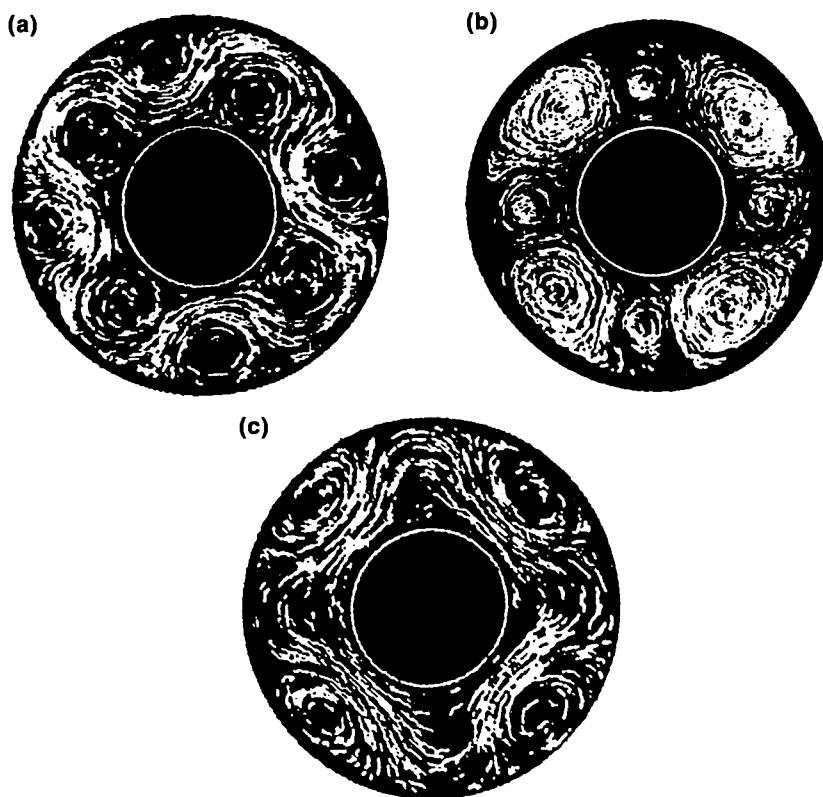


Figure 2. Streak photographs illustrating the dependence of upper-level flow pattern on the form of the impressed horizontal temperature gradient in a rotating annulus subject to internal and sidewall heating. Flows were obtained in the same apparatus as Fig. 1 at a power input of 100 W but with different values of ΔT (hence varying the partitioning of heat extraction between inner and outer sidewalls) namely (a) $T_b - T_a = -3$ K, (b) $T_b - T_a = 0$ K and (c) $T_b - T_a = +3$ K.

surfaces, with strong anticyclonic shear at upper levels between two opposing jet streams (and cyclonic shear at lower levels). Baroclinic waves take the form of trains of compact, apparently isolated oval eddies, all circulating in the same sense as the shear of the mean zonal flow (i.e. anticyclonic at upper levels). Little motion appears outside the eddies themselves, apart from a very weak meandering jet stream. The isolated appearance of the eddies is most obvious for the lowest wave numbers (m) which occur at high values of Taylor number and Θ . Fig. 1(a) shows the upper-level flow for a typical $m = 1$, in which the eddy is seen to be concentrated into a narrow range in azimuth. Although the eddy has a 'solitary' appearance, its structure is not consistent with conventional 'soliton' or 'modon' solutions, but rather has the form of a wave packet encompassing little more than a single wavelength in azimuth. Non-linear effects are therefore of great importance in setting up the flow, strongly steepening the basic wave in azimuth. Further details may be found in Read and Hide (1984).

Like the baroclinic waves in the conventional annulus, the eddies in the internally heated system contribute significantly to the transfer of heat in both the horizontal and vertical. Fig. 4 shows the variation of Nusselt number (a dimensionless measure of total heat transfer, normalized by what would occur via molecular conduction only; see Hide and Mason 1975) with rotation rate for the internally heated system, as measured in the laboratory (note that Nusselt number for an internally heated system is defined slightly differently than for a boundary-heated flow — see Hide and Mason 1970, Read

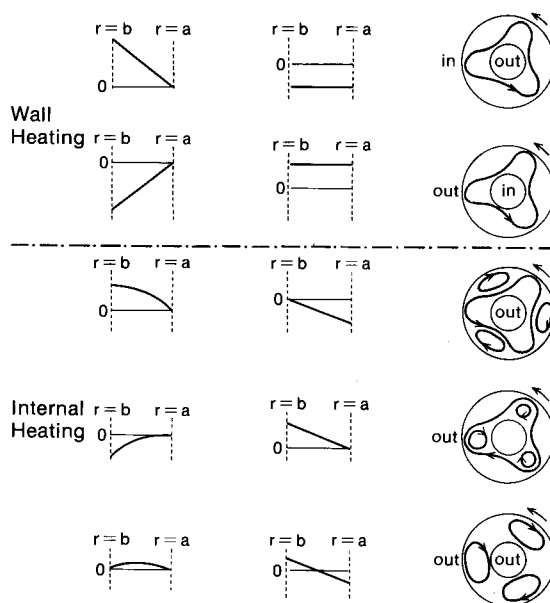


Figure 3. Schematic illustrations of the variations of the impressed temperature gradient with radius r (left column); $d\bar{T}/dr$, proportional to minus the top-surface zonal velocity (see equation (1)) (centre column); and the main characteristics of the top-surface flow pattern in the steady-wave regime based on the integral constraints expressed in equation (1) (right column) — see text and Hide and Mason (1970, 1975).

1986b). The Nusselt number which would occur if the flow were to remain axisymmetric is also shown (derived from an axisymmetric numerical model). The presence of regular eddies maintains the heat transfer close to the level in the absence of rotation until the flow becomes irregular.

Recent (as yet unpublished) studies in the Geophysical Fluid Dynamics Laboratory of the Meteorological Office have incorporated a 'planetary vorticity gradient' (similar to a β -effect) by using sloping endwalls, thereby allowing the depth of the annulus to vary with radius. Similar methods were investigated in the conventional annulus by Mason (1975). The effect of sloping boundaries on the internally heated flows is found to be very similar to that on other annulus flows, in introducing wave dispersion in a way qualitatively similar to that of Rossby waves — eddies drift with respect to the mean zonal flow at a rate inversely proportional to their wave number and proportional to the effective β ($\propto \Omega$). At higher rotation rates, the radial scale of the eddies may be reduced, so that eddies no longer fill the annulus gap. This may ultimately result in two (or more?) independent, parallel trains of waves and eddies adjacent to each sidewall, associated with a series of parallel zonal jet streams.

3. Eddies on Jupiter and Saturn

Jupiter and Saturn lie well beyond the Earth's orbit at mean solar distances of 5.2 and 9.6 AU respectively (1 AU = mean Earth-Sun distance = 1.5×10^{11} m). They are giant planets with radii $\approx 7.14 \times 10^4$ km and 6.03×10^4 km respectively, but consist largely of hydrogen (90%) and helium (10%) with small rocky cores. Both planets rotate rapidly (sidereal periods of 9h 55m and 10h 39m respectively) and are shrouded in dense cloud decks consisting mainly of ammonia ice.

Both planets exhibit a variety of eddy-like features at the level of the upper cloud-decks, some of which appear to persist for very long periods (from months to many years). The best known examples are the Great Red Spot (GRS) on Jupiter — discovered in the 17th century — and the White Ovals (also

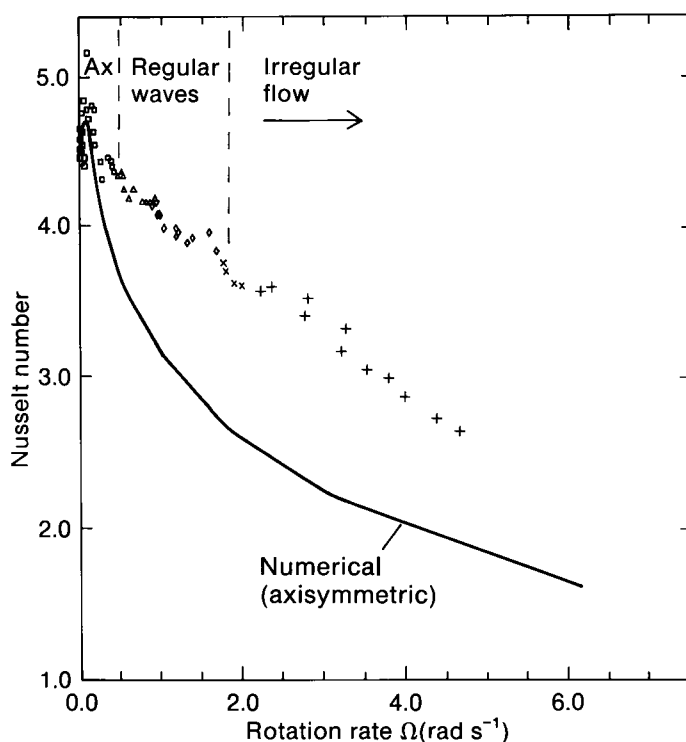


Figure 4. Variation of Nusselt number (a measure of the total heat transfer with respect to that due to conduction alone) for an internally heated annulus as a function of rotation rate Ω . Results shown are laboratory measurements by Read (1986b and unpublished) for various baroclinic wave numbers, compared with the axisymmetric heat transfer over the same range of Ω , obtained from an axisymmetric numerical model (Read 1986b). The results shown are (\square) laboratory (axisymmetric), (Δ) laboratory (wave number $m=3$), (\diamond) laboratory ($m=4$), (\times) laboratory ($m=4$ to 6, wave number vacillation), (+) laboratory (irregular flows) and (—) numerical (axisymmetric).

on Jupiter) — observed to form in 1939. Some examples are illustrated in Fig. 5. Most long-lived eddies on Jupiter and Saturn take the form of oval spots of various colours, the most common of which are found in regions of anticyclonic mean zonal shear between pairs of opposing mid-latitude jet streams, and are characterized by anticyclonic circulation at the upper cloud-levels. They include the GRS, the White Ovals and other smaller white spots at higher northern and southern latitudes on Jupiter, and some similar brown spots on Saturn. Cyclonic examples (occurring in regions of cyclonic mean zonal shear) include the brown 'barges' on Jupiter. An intriguing property of many of the smaller anticyclonic ovals on Jupiter is that they appear in almost regularly spaced trains in longitude, often interspersed with weaker cyclonic circulations.

Such features do not bear much resemblance to the more familiar baroclinic eddies in the Earth's atmosphere and in the conventional annulus experiments, and accordingly many different suggestions have been made to account for their nature and various properties (see Ingersoll 1981, Ingersoll *et al.* 1984, Read 1986a, Williams 1986 for reviews). The resemblance between these features and the baroclinic eddies obtained in the internally heated annulus, however, would suggest that sloping convection was a strong candidate to account for their nature and origin. Unfortunately, for various reasons the eddy-like features in all these different models are difficult to compare dynamically with the Jovian and Saturnian eddies:

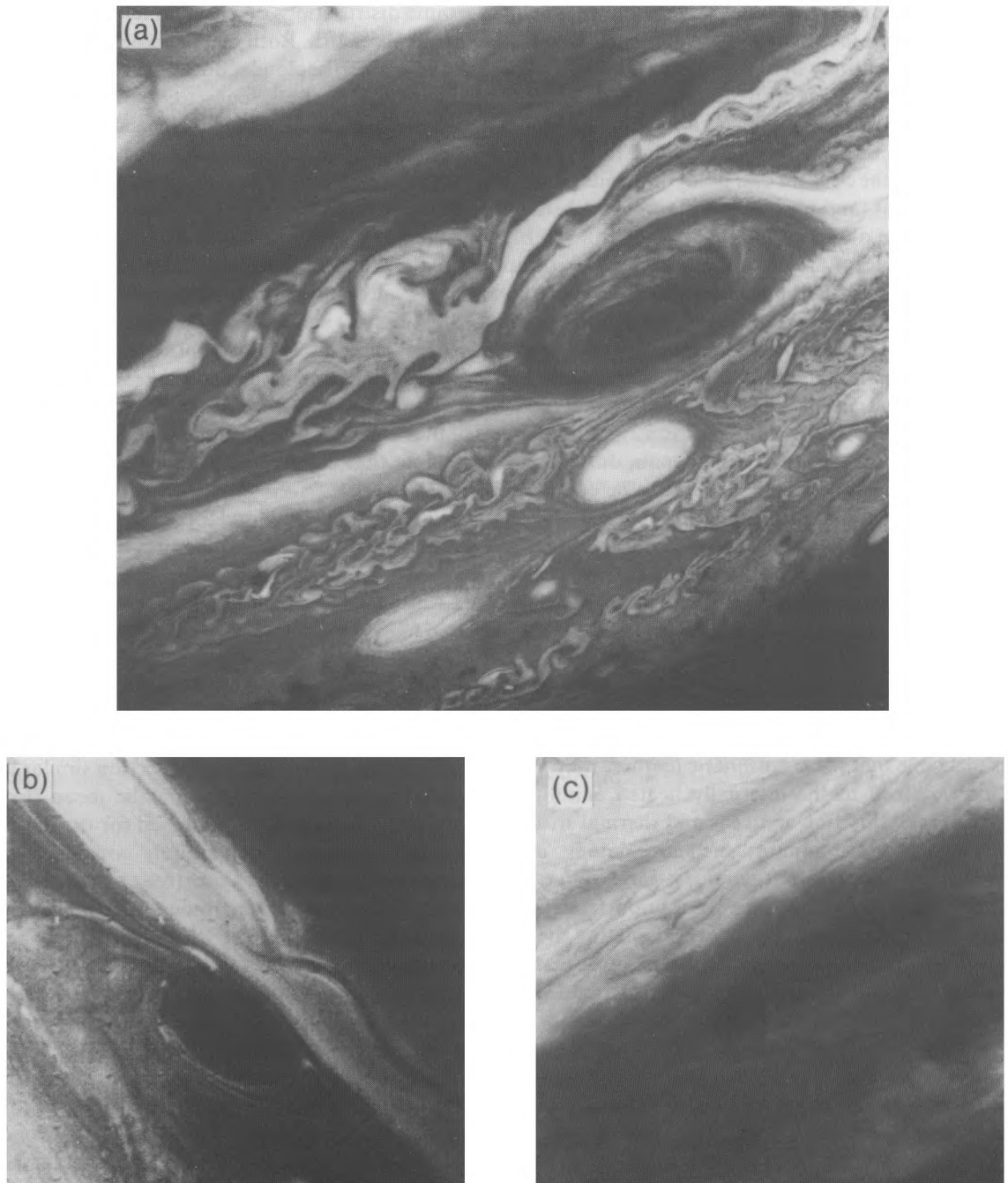


Figure 5. Some examples of long-lived oval eddies in the atmospheres of Jupiter and Saturn. (a) Voyager 2 image of Jupiter in the vicinity of the Great Red Spot (GRS), showing the GRS itself (centre right), a White Oval (just below the GRS) and other smaller features, (b) Brown Spot 1 at latitude 42.5°N on Saturn from Voyager 2, and (c) Voyager 1 image of a long-lived cyclonic 'barge', at latitude 15°N on Jupiter.

(a) The appropriate boundary conditions and background distributions of wind and temperature are probably rather different for Jupiter and Saturn than for the Earth. Both major planets are almost certainly entirely fluid throughout, with no solid surface beneath the clouds. Both generate at least as much heat in their deep interiors as they receive from the Sun. This has the consequence that the deep interior is likely to be nearly isentropic and very weakly stratified, also causing large-scale horizontal thermal contrasts to be very small (see Flasar 1986 for a review). The observed thermal contrast between the equator and poles on Jupiter and Saturn at the cloud tops is very small. At least near the cloud tops (and probably some distance below — see Flasar 1986) the large-scale thermal contrasts which are observed are associated with the banded structure of the zonal winds and clouds. The pattern of zonal winds are consistent with an application of the thermal-wind equation to the observed thermal contrasts with latitude, which are actually non-monotonic (i.e. the horizontal thermal gradient reverses several times between the equator and poles — see the laboratory experiments described in section 2). More recent analyses of spacecraft infra-red data by Gierasch *et al.* (1986) confirm an association between the pattern of zonal winds and clouds and a thermally-driven meridional circulation with upwelling in regions of anticyclonic shear (again see the internally heated experiments mentioned in section 2). Many aspects of the deep structure of the flow and the effective lower boundary conditions remain uncertain, however, so that any hypothesis for the Jovian and Saturnian eddies must continue to be controversial.

(b) The available atmospheric data refer only to a thin layer around the cloud tops. It is not possible, therefore, to determine many useful dynamical diagnostics with which to test theories (indeed this is one of the major challenges posed by Jupiter and Saturn to dynamicists — to design an observational strategy which could yield conclusive results, e.g. see Allison and Stone 1983).

4. Long-lived eddies on Jupiter and Saturn as sloping convection?

Given that the relevant similarity parameters (e.g. Rossby, Richardson and Burger numbers) are of comparable magnitude for the long-lived Jovian and Saturnian eddies and the baroclinic eddies in the laboratory (although disputes continue concerning the Burger number, for example see Read 1986a), it is plausible that the atmospheric features may indeed represent a form of sloping convection similar to that obtained in the internally heated annulus. The detailed resemblance between the mean flow structures, eddy flow patterns and thermal structures (so far as they can be determined for the major planets) serve to support such an analogy, although these factors are not entirely conclusive in themselves. The relevance of quasi-geostrophic 'free modes' to the laboratory flows (for example Read 1985, White 1986) may also be of importance in this context, since similar theoretical solutions form significant components of many competing theories of the Jovian features (see Read 1986a). Further observations tailored towards answering the many questions which arise from this hypothesis are clearly required, almost certainly necessitating data from new spacecraft missions in due course (currently planned missions include 'Galileo' orbiter and probe to Jupiter and the Hubble Space Telescope — both seriously delayed by the recent Space Shuttle disaster!).

Nonetheless, the available observations do demonstrate that eddies occur in the atmosphere of the major planets which are characterized by a high degree of symmetry in the spatial organization of the flow, and long persistence times despite the presence of chaotic small-scale features in the background flow. Laboratory studies have indicated the importance of non-linear advection in helping to sustain the regular flows, which would seem to contradict the conclusions of some theories of atmospheric predictability concerning the role of advection in promoting the breakdown of an initial pattern of flow into irregular chaotic motion. Should it ultimately be demonstrated that the long-lived eddies on Jupiter and Saturn are manifestations of sloping convection, it would serve to confirm the latter process as an important paradigm for large-scale flows in planetary atmospheres.

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The dynamics of rotating fluids: numerical modelling of annulus flows

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Summary

Comparing numerically simulated annulus flows with good quality laboratory measurements is an invaluable way of testing the dynamical formulations of numerical models. Some qualitative and quantitative comparisons of this type are described, the model being a grid-point Navier–Stokes solver and the measurements being of temperature, horizontal velocity components and total heat flux. Good agreement is found in many instances. A case in which serious discrepancies occur is investigated in detail: it is found that the numerical model generates spurious eddy motion at intermediate resolution, but not at low or high resolution. Comparison of model results with published ‘bench-mark’ numerical solutions for flow in a square cavity reveals a high level of agreement, and suggests the feasibility of using annulus measurements to verify numerical models in engineering as well as meteorological contexts. Some closing comments are made on the extent to which the various flow phenomena of the annulus are accounted for by existing theoretical models.

1. Introduction

Experience suggests that many meteorologists consider laboratory work on rotating flows to be a rather academic activity — to be regarded, perhaps, with polite indifference. To such sceptics, numerical modelling of laboratory flows may seem doubly removed from everyday meteorological reality. Read (1988) has laid out the practical and scientific grounds for the laboratory work. Here the equally strong justification for the associated numerical simulations will be given, and a selection of results presented. Some theoretical aspects will also be briefly discussed.

2. Why model annulus flow?

There are two main justifications:

- (a) Numerical-model verification — comparison of results with good laboratory measurements affords an invaluable test of numerical formulations.
- (b) Scientific investigation — good numerical simulations provide much data whose analysis may greatly assist understanding of the real flows.

Of these, (a) is the more important in practical meteorological respects (at least in the short or medium term) and it is this which will be dealt with here. In the atmosphere the forcing processes are many and various. Momentum sources and sinks arise from various types of motion — such as small-scale turbulence, cumulus convection, cumulonimbus and some gravity waves — that are not explicitly resolved in large-scale numerical models. Diabatic heating and cooling occur as a result of sub-grid-scale motions (see above), radiative effects and latent heat release/absorption in condensation/evaporation. All these processes are highly variable in space and time, and their representation or ‘parametrization’ in weather forecasting and climate models is a matter of considerable complexity and uncertainty.

On the other hand, in the rotating laboratory-annulus the only significant forcing processes are molecular viscosity and conductivity, which can be represented to high accuracy using established formulae; over wide ranges of conditions all flow scales can be resolved by tractable grids. Thus no ‘parametrizations’ are required in numerical simulations. Comparison with experimental measurements therefore enables the dynamical formulation of numerical models to be tested (‘verified’) to an extent which is virtually impossible through comparison with meteorological data because of the uncertainties concerning the atmospheric forcing processes.

3. Simulations of non-axisymmetric annulus flows with a 16-level model

In the familiar 'wall-heated' annulus system, concentric cylinders are maintained at different temperatures and the upper and lower bounding surfaces are horizontal and rigid (see Fig. 2 of Read 1988). A numerical model — the 'Met O 21 model' — of time dependent, non-axisymmetric flow in this system has been in use for several years within the Meteorological Office. It is a grid-point formulation based on the (non-hydrostatic) Navier–Stokes equations for incompressible baroclinic flow. Standard resolution is 16 (vertical) \times 16 (radial) \times 64 (zonal) points; the grid is stretched in the vertical/radial plane so that boundary layers are resolved adequately. Conservative finite difference schemes are used. Details are given by James *et al.* (1981) and Hignett *et al.* (1985). The model is similar to that described and operated by Williams (1969, 1971) and has been developed from programs originally constructed by Dr S.A. Piacsek and co-workers at the US Naval Research Laboratories, Washington DC. It is at least as tightly formulated dynamically as the typical primitive equation weather forecasting or global climate model and it runs on the Cyber 205 computer. Comparisons of the flow simulations with laboratory measurements may be made at a qualitative or a quantitative level.

3.1 Qualitative comparisons

The main flow phenomena of the wall-heated rotating annulus are axisymmetric flow, steady waves, intransitivity, wave-number transitions, hysteresis, amplitude vacillation, structural vacillation and irregular flow (see Read 1988). All of these have been produced by the Met O 21 model — although little attention has been paid as yet to structural vacillation and irregular flow. It should be noted also that the conditions (of rotation rate, temperature difference, etc.) under which a given flow phenomenon occurs in the simulations (at standard resolution) are in some cases noticeably different from those under which it occurs in the laboratory. However, the model is clearly capable of producing the phenomena that are observed, and this in itself is important information. Hignett *et al.* (1985) give a detailed survey. As examples of their results, Fig. 1 shows some upper-level pressure fields and a kinetic energy diagram from a simulated amplitude vacillation.

3.2 Quantitative comparisons

In the laboratory annulus, temperatures are measured at mid-radius and mid-depth using a ring of 32 thermocouple junctions. Total heat flux by the working fluid is calculated from the inflow and outflow temperatures of the water circulating within the inner (cool) wall. (Ideally, this measurement is made when the ring of thermocouple junctions is absent.) In a physically separate apparatus having the same dimensions, horizontal velocity components are obtained at five levels using a particle tracking technique.

Hignett *et al.* (1985) describe a quantitative comparison of a simulated steady wave flow with measurements made using these techniques. Some of their results are presented in Table I. The simulated main-wave phase speed is in very good agreement with the value calculated from the velocity measurements. Main-wave temperature amplitudes agree to better than 5% and maximum zonal mean flows differ by only about 10%. In fact, Hignett *et al.* found good agreement between simulated and measured flows as regards both the zonal mean and main-wave fields at each of the five levels of measurement. The comparison provides strong evidence that primitive equation numerical models can give good simulations of quasi-geostrophic wave motion (see Read 1988) in rotating, baroclinic fluids.

4. High-resolution simulations of axisymmetric annulus flows

An important aspect of any numerical simulation is the dependence of results on spatial resolution. As a step towards understanding the convergence (or otherwise!) of the annulus simulations as the mean

grid-length is reduced, two series of high-resolution axisymmetric flow integrations have recently been undertaken. (The storage requirements of axisymmetric flow simulation are much less than those of the non-axisymmetric case, and so fine resolutions can be readily investigated. The work has been done on the IBM 3081 computer.) The integrations offer encouraging evidence of the capacity of numerical models to give accurate results. Some of them, however, give insight into model pathology.

4.1 Heat flux comparisons

Special emphasis will be placed here on the total heat flux across the system in its steady state. This quantity may be accurately measured in the laboratory without the use of probes which might disturb

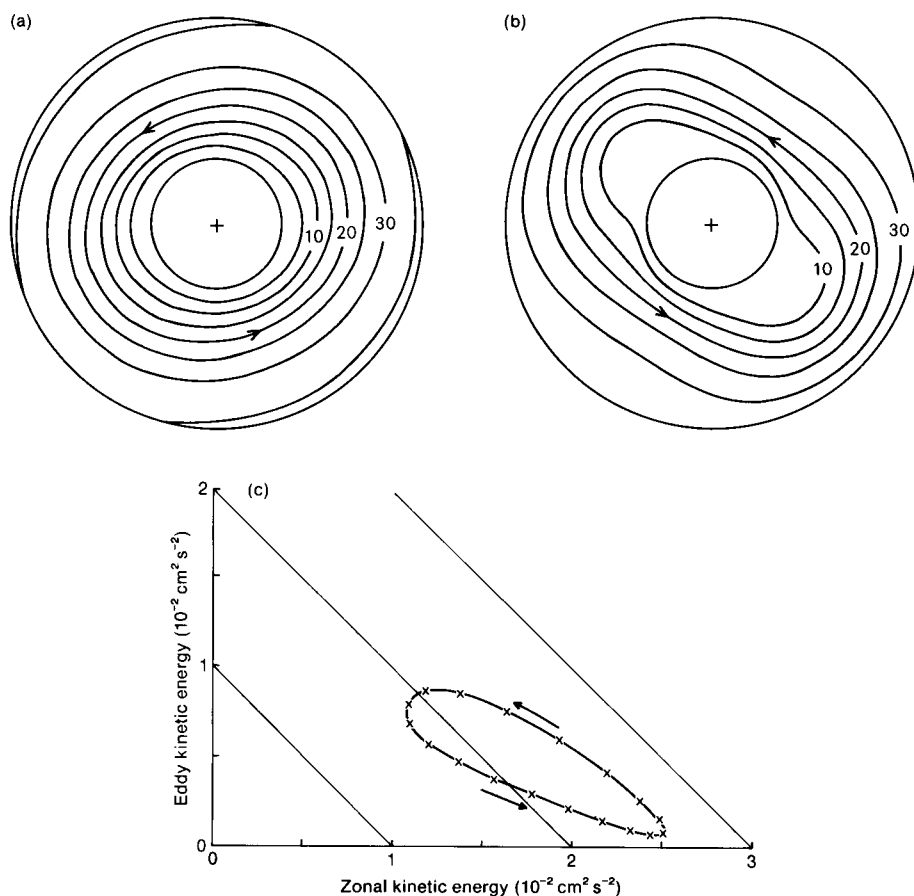


Figure 1. Numerical simulation of amplitude vacillation. (a) and (b) show pressure fields at an upper level in the flow at minimum and maximum wave amplitude respectively. Arrows indicate the direction of geostrophic flow. Quantity plotted is deviation of pressure/mean density from an arbitrary reference value; units are $10^{-1} \text{ cm}^2 \text{ s}^{-2}$. The amplitude vacillation is very regular and has been followed through six complete cycles. (c) shows the evolution of zonal kinetic energy (ZKE) and eddy kinetic energy (EKE) during one cycle. EKE is plotted against ZKE with time t as parameter; crosses are marked on the trajectory at 40 s intervals, and the arrows indicate the sense in which it is described. If the vacillation consisted solely in exchange of energy between EKE and ZKE while their total remained constant, the trajectory would simply be a straight line of slope -1 . The departure from this form demonstrates the importance of baroclinic energy conversions, and other sources and sinks of total kinetic energy, during the vacillation cycle. EKE and ZKE are here defined as the true quantities divided by the total mass of the fluid.

the flow (see above). It is also a fundamental measure of the thermodynamic activity of the system (see Hide and Mason 1975). It is probably the most important single property of the system and of attempts to simulate it.

Fig. 2 summarizes a large number of laboratory and numerical results on the variation of heat flux with rotation rate in axisymmetric flow; the heat flux is scaled by a conductive value to give a 'Nusselt number'. Measured heat fluxes have been compared with modelled values for rotation rates (Ω) of zero, 0.1, ..., 0.5 rad s^{-1} . (Near $\Omega = 0.6 \text{ rad s}^{-1}$ the laboratory flow becomes non-axisymmetric.) The laboratory

Table I. *Some results from the steady wave comparison described by Hignett et al. (1985)*

	Laboratory measurement	Numerical simulation
Main-wave temperature amplitude ($^{\circ}\text{C}$)*	0.27	0.28
Main-wave phase speed (rad s^{-1})†	7.8×10^{-3}	7.9×10^{-3}
Maximum zonal mean flow speed (cm s^{-1})	0.26	0.23

* Zonal wave 3 at mid-radius and mid-height

† Zonal wave 3; from velocity measurements

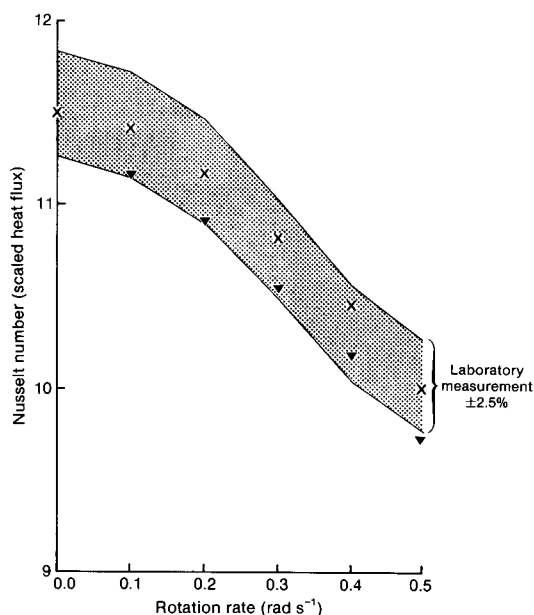


Figure 2. Measured and simulated total heat flux as a function of rotation rate in axisymmetric flow. The stippled area indicates the laboratory measurements $\pm 2.5\%$ error, low-resolution numerical model results are shown by crosses, and extrapolation to infinite resolution by solid triangles (see text for further details). The heat flux is plotted as a Nusselt number: the actual total heat flux divided by the flux which would be carried — under the same external conditions — by a solid having the same thermal properties as the working fluid. Apparatus geometry as in Hignett et al. (1985); imposed temperature difference 4°C .

measurements are ascribed an accuracy (to random errors) of $\pm 2.5\%$, and this range of values is indicated by the stippled area on Fig. 2. The general decrease of the heat flux with increasing rotation rate is well understood in terms of the concomitant decrease of the Ekman-layer thickness — see Hide and Mason (1975). The crosses on Fig. 2 show numerical model results obtained with 16×16 grid resolution. Integrations were also carried out with 24×24 and then 32×32 grid resolution at each rotation rate. Each set of three simulated heat fluxes (except the $\Omega = 0$ set — see below) was then extrapolated to notional infinite resolution using the power law method of de Vahl Davis (1983). The resulting values are shown as triangles on Fig. 2.

At rotation rates of 0.1 rad s^{-1} and above, both the low resolution and the extrapolated results lie within or extremely close to the range of the measured values (given the 2.5% error). It will be observed that the low-resolution results are generally closer to the actual measurements than are the extrapolated results. No unique explanation for this is offered. The numerical simulations may be converging to a value slightly different from the true one; or there may be some small systematic error in the laboratory measurements. Nevertheless, when all is said and done, the level of agreement shown in Fig. 2 is very good: the measured and simulated heat fluxes differ by less than 3%.

4.2 Spurious eddy motion

Fig. 2 shows no infinite resolution extrapolation at $\Omega = 0$. Considerable difficulties arose in this case. At 16×16 resolution good results were obtained (as Fig. 2 shows) but at 24×24 and 32×32 resolution time-dependent eddy motion was produced in and near the inner-cylinder's thermal boundary layer. An example of this behaviour is shown in Fig. 3(a), which is a snapshot of the streamfunction field; several

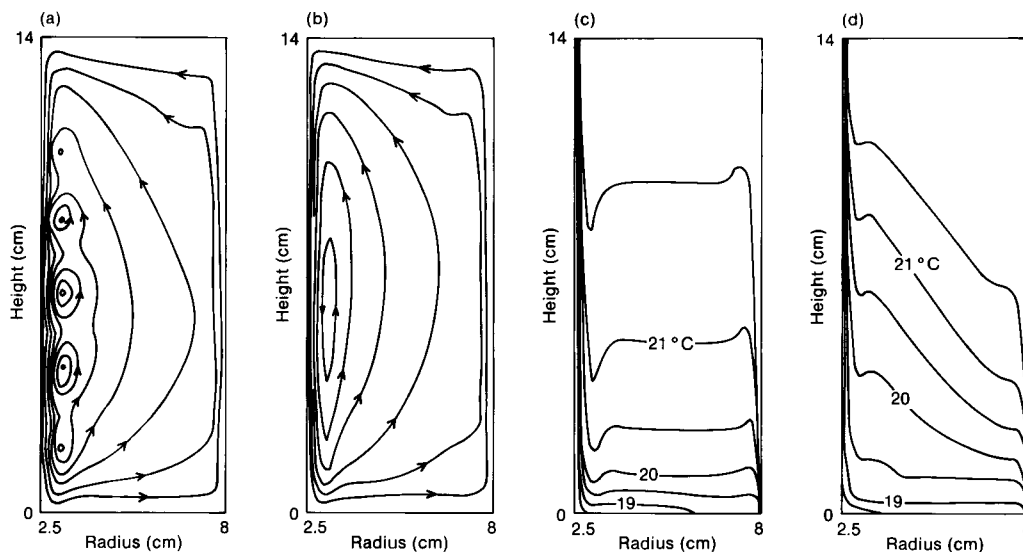


Figure 3. Cross-sections (in the height/radius plane) showing streamlines and temperature fields obtained in numerical simulations of axisymmetric annulus flow. (a) Instantaneous streamlines from an integration at zero rotation rate which developed spurious eddy motion in and near the inner cylinder; 32×32 stretched grid. (b) Steady-state streamlines from a well-behaved integration at zero rotation rate; 64×64 unstretched grid. (In both (a) and (b) streamfunction contours are plotted, and the arrows indicate the direction of flow; contour interval is the same in both cases.) (c) Steady-state temperature field corresponding to (b). (d) Steady-state temperature field obtained with a 32×32 stretched grid (as for (a)) but at a rotation rate of 0.5 rad s^{-1} . In all cases the inner and outer cylinder temperatures are 17 and 21°C , and the assumed geometry is as in Hignett *et al.* (1985).

closed circulations are seen. These eddies are spurious in that they do not appear in the real system under the conditions applied (as simple dye-injection experiments reveal). One of their effects is to increase the total heat flux by about 10% — well above the range of the measured values.

Figs 3(b) and 3(c) show the streamfunction and temperature fields in a well-behaved integration at zero rotation rate. It is clear, qualitatively, that the inner-cylinder thermal boundary-layer has the potential for instability, there being large horizontal temperature gradients as well as velocity gradients. Theoretical studies (Gill 1966) indeed show that instabilities should be expected under conditions more extreme than those applied here. What appears to be happening is that an increase in grid resolution is leading to a spurious lowering of the stability threshold. Numerous changes of finite difference scheme were tried but at the above resolutions all such variants of the model gave spurious eddies when the rotation rate was lower than 0.1 rad s^{-1} or so.

Can the effect be overcome by using still finer resolution? To investigate this, a series of integrations using unstretched $N \times N$ grids, with $N = 24, 32, 40, 48, 56$ and 64 has been carried out. Spurious eddy motion occurs at $N=40$, but all the other cases give smooth fields. Fig. 4 shows the simulated heat fluxes plotted against the resolution N ; the range of the laboratory measurements is also shown. Evidently the fluxes at high resolution are converging satisfactorily into the measurement 'corridor' (though integrations at even higher resolutions would be needed to confirm this). The occurrence of spurious eddies does indeed appear to be a pathological feature associated with intermediate resolution.

No detailed theoretical treatment of the phenomenon has yet been produced, but precedents are known. Bell and White (1987a) have established that short-wave baroclinic instabilities may be subject to spurious growth in quasi-geostrophic models having intermediate (~ 5 to 20 level) vertical resolution, while at lower resolutions they do not appear at all. Something similar concerning boundary-layer instabilities could well be happening at intermediate resolutions in the annulus model.

It might be asked why the problem of spurious eddy motion does not occur at higher rotation rates. The reason (qualitatively) is that rotation operates in several ways to stabilize the side boundary layers. It stabilizes directly through its 'stiffening' effect (the Proudman–Taylor effect — see Hide 1966, 1977

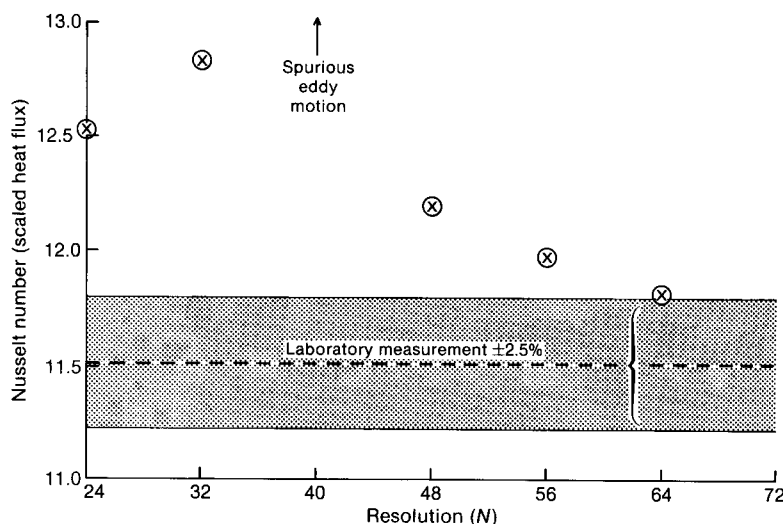


Figure 4. Variation of the steady-state heat flux with grid resolution N at zero rotation rate. Heat flux is expressed non-dimensionally as a Nusselt number — see caption to Fig. 2. Number of grid points is N (radial) $\times N$ (vertical), their spacing in each direction being even. The stippled area indicates the measured value $\pm 2.5\%$ error.

and Chandrasekhar 1961) — and indirectly (i) by weakening the meridional circulation and (ii) through the reduction of the temperature difference across the side boundary layers which occurs as thermal wind balance is attained in the interior. Fig. 3(d) shows the steady-state temperature field obtained when $\Omega = 0.5 \text{ rad s}^{-1}$; the contrast with Fig. 3(c) is clear.

5. 'Bench-mark' comparisons

Axisymmetric flow in a non-rotating wall-heated annulus is similar in many respects to a classical problem of fluid dynamics — that of convection in a cavity of rectangular cross-section (and infinite length) whose vertical walls are maintained at different temperatures. This problem is important in many engineering applications, from double glazing to nuclear reactor design. It has been used by de Vahl Davis and Jones (1983) as a basis for comparison of many different numerical models with so-called 'bench-mark' values. These values were obtained by extrapolation to infinite resolution of results from a model which the authors considered to be well-behaved and reliable. A square cavity was assumed.

By suppressing the geometric curvature factors in the axisymmetric annulus model it is possible to apply it to the cavity problem and to find how it rates against the bench-mark values. Table II summarizes the heat fluxes found in two separate comparisons. That the results are so very close is not entirely surprising since the model used by de Vahl Davis and Jones was a grid-point formulation similar in many respects to the Met O 21 model. Nevertheless, the comparison affords a useful consistency check. More important, it suggests that verification of the Met O 21 model against laboratory heat flux measurements (as described in section 3) might be considered as a provisional verification of de Vahl Davis and Jones's model and of the several models which performed well in their bench-mark comparisons. There is the clear possibility (as yet unexploited) of using annulus measurements to verify a wide range of numerical flow models used in various scientific and engineering applications.

No spurious eddy motion occurred at any resolution in any of the integrations against the bench-mark. This probably reflects the fact that most of the flows studied in Met O 21's laboratories are subjected to stronger thermal forcing (as measured by an appropriate Rayleigh number) than the flows chosen by de Vahl Davis and Jones. Annulus flows might prove to be a very stringent test-bed for the models which figured in the original bench-mark comparison!

Table II. Comparison of heat fluxes obtained in axisymmetric flow integrations using the Met O 21 model with the bench-mark values given by de Vahl Davis and Jones (1983)

Rayleigh number*	Grid type	Grid resolutions used	Heat flux at highest resolution†	Extrapolation to infinite resolution	Benchmark value
10^6	Stretched	16, 24, 32	8.940	8.820	8.817
	Unstretched	48, 56, 64	9.084	8.814	
10^5	Stretched	16, 24, 32	4.574	4.514	4.509
	Unstretched	24, 32, 64	4.564	4.519	

* The Rayleigh number is defined as $\beta g \Delta T d^3 / \nu k$, where β = expansion coefficient, ΔT = imposed temperature difference between the vertical walls of the cavity, d = side of (square) cavity, ν = kinematic viscosity, k = thermal diffusivity and g the acceleration due to gravity. In the bench-mark tests $\nu/k = 0.71$.

† The heat flux is expressed in non-dimensional terms as a Nusselt number — see caption to Fig. 2.

6. Theoretical models of annulus flows

Space does not permit more than a cursory survey of the 'scientific investigation' aspect of the numerical modelling work (see section 2). Model integrations have been used in numerous studies whose main objective has been to develop understanding of the rich variety of flows which occur in the rotating annulus; for examples from the recent literature see Bell and White (1987b), Read (1985, 1987) and White (1986), which are concerned with the construction and evaluation of various flow models based on quasi-geostrophic dynamics (see Gill 1982). Here some comments will be given on the extent to which the various non-axisymmetric flow phenomena are understood theoretically.

The transition from axisymmetric to non-axisymmetric flow is quite well explained by Eady's baroclinic instability analysis. Eady waves are unstable only for non-dimensional wave numbers (p) greater than 2.399; here $p = Nd\pi/\Omega\lambda$, where N is the buoyancy frequency, d is the depth of the fluid and λ is the dimensional horizontal wavelength of the wave. Thus, in any given annulus (and with specified values of N and Ω) the minimum possible value of p may be greater than 2.399 and so no instability occurs: the unstable waves may be too big to fit into the annulus. When the rotation rate Ω is increased, the value of p (see above definition) is reduced for a given dimensional wavelength, and instability eventually becomes possible. Calculated locations of the upper transition are in good order-of-magnitude agreement with the observed location. (A stronger statement is not supportable because the theoretical stability threshold is sensitive to the assumed zonal flow structure — see Bell and White 1987b.) To account for the lower transition it is necessary to invoke viscous and conductive effects; Hide and Mason (1975) review the relevant instability calculations.

Theoretical explanation of the regular regime is in poorer shape. Much work has been done by applied mathematicians on 'weakly non-linear theories'. These attempt to describe analytically the non-linear behaviour of weakly unstable waves: under various circumstances steady, vacillating or irregular wave solutions occur (see Hart 1979 for a review). Weakly non-linear treatments are monuments to the algebraic tenacity of their creators and they appear to account at least qualitatively for observed flows in the mechanically driven 2-layer system (see Read 1988), but their relevance to the thermal annulus is open to question. Fig. 5 shows the zonal mean flow in a typical simulated steady wave and in axisymmetric flow at the same rotation rate. It seems unlikely that any weak interaction theory can account for the radical difference in structure. Also, the theories predict amplitude vacillation at high rotation rates, whereas in the thermal annulus it occurs near the lowest rotation rate at which a given wave number can be sustained (Hignett 1985). It is possible that weakly non-linear theories are applicable, but that their usual manifestations assume an inappropriate marginally stable flow (White 1986).

Read (1985, 1987) and White (1986) have examined free-mode models for steady wave flow in the internally-heated and wall-heated annulus systems. These models have some success in accounting for the gross structure of the zonal mean flow and some of the features of the waves, but they are unsatisfactory in other respects. Representation of forcing and dissipative processes is desirable but mathematically difficult; Read *et al.* (1986) have developed a diagnostic framework.

The transition to irregular flow is broadly accounted for by the theory of Rossby wave instability (see Grotjahn 1984 for references). Behaviour in irregular flow is generally in accord with the predictions of geostrophic turbulence theory as developed by Charney (1971); indeed, the tendency of annulus flows to adopt internal jet form (White 1986, Bell and White 1987b) makes them a particularly suitable test-bed for Charney's theory.

A weak point in nearly all theoretical treatments of non-axisymmetric annulus flow is the representation of side boundary layers (see Hide 1968). The usual procedure is virtually to ignore them, but it may be that they play an important role in some time-dependent phenomena (such as amplitude vacillation).

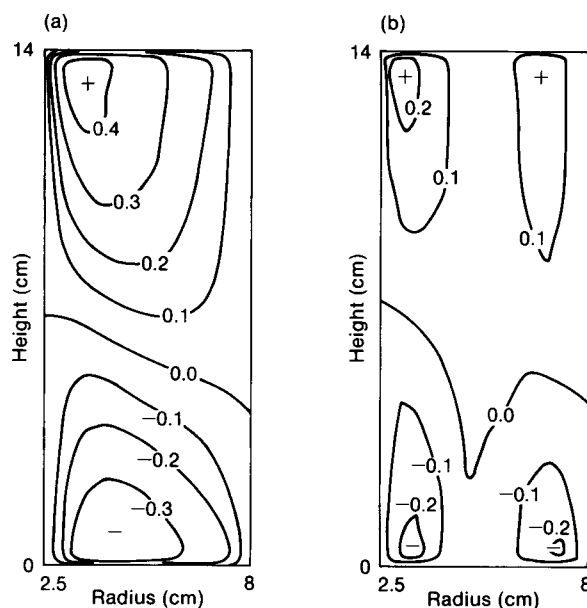


Figure 5. Height/radius cross-sections of the steady-state mean zonal flow in (a) axisymmetric and (b) non-axisymmetric numerical model integrations at the same rotation rate (1.0 rad s^{-1}). In this case the non-axisymmetric model produces a steady-wave flow, and the axisymmetric model (which, of course, does not allow non-axisymmetric motion) attains an entirely different steady state. The mean zonal flow structure seen in (b) is typical of steady-wave states. Units are cm s^{-1} . Assumed geometry as in Hignett *et al.* (1985).

7. Closing remarks

Laboratory systems are good testing grounds for numerical-flow models because the forcing processes which operate in them are physically simple and may be represented accurately using well-known formulae. In the atmosphere, on the other hand, the processes forcing the motion are complicated and difficult to represent reliably. Comparisons of real and simulated annulus flows have been described here; the results reveal generally good numerical-model performance, although some interesting spurious instabilities have come to light. Laboratory annulus measurements could be used to test and 'verify' numerical formulations in a wide range of other scientific and engineering applications.

Good numerical simulations provide a wealth of data which may be exploited in the development of theoretical and conceptual models of the flows. A brief assessment of the present state of understanding of non-axisymmetric annulus flows has also been offered in this paper.

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Books received

The listing of books under this heading does not preclude a review in the *Meteorological Magazine* at a later date.

The atmosphere — a wall chart, by K. Foley (Amsterdam, Mirage Publishing, 1987. Dfl.35.00, US \$17.50) depicts the major phenomena responsible for meteorological events. The numerous sections are in colour with their associated explanatory notes.

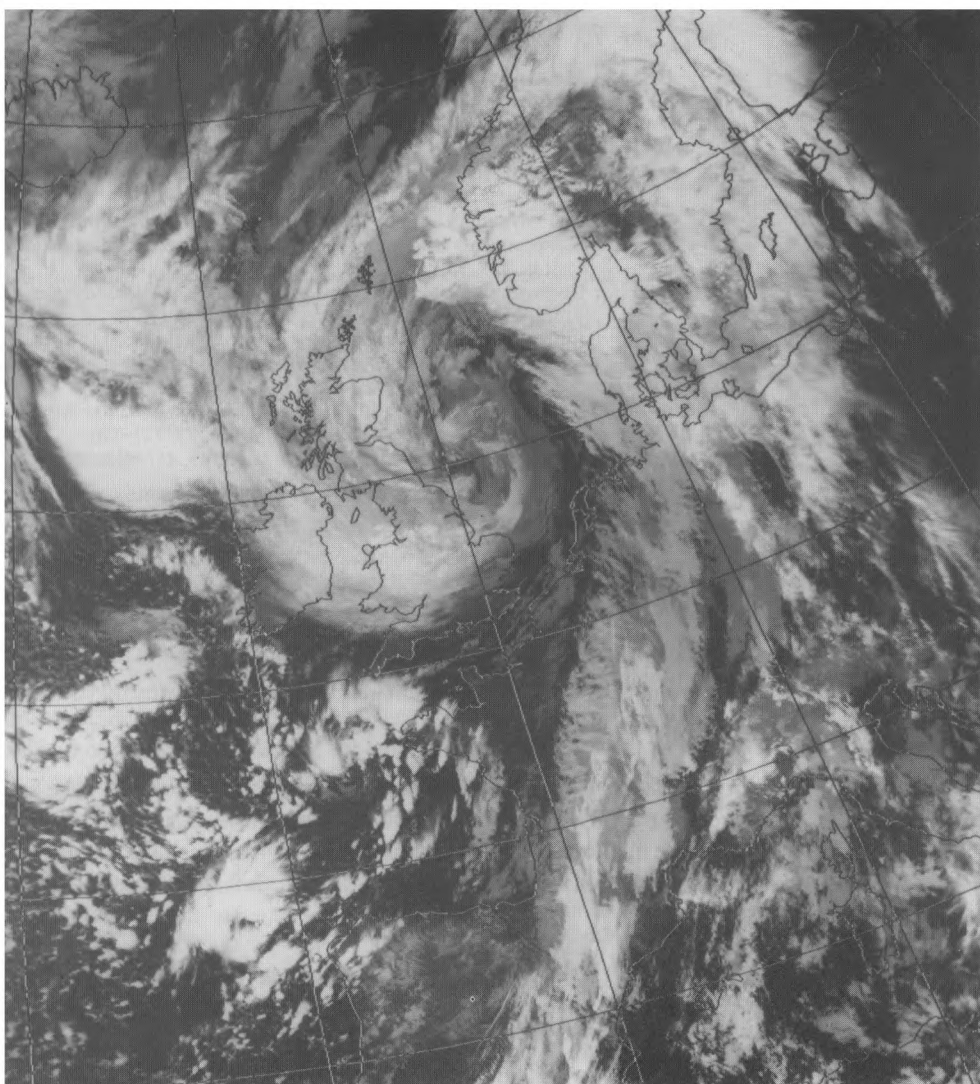
Geophysical fluid dynamics, second edition, by Joseph Pedlosky (New York, Heidelberg, Berlin, London, Paris, Tokyo, Springer-Verlag, 1987. Price DM 160.00) is a high-level, unified treatment of the theory of the dynamics of large-scale motions of the oceans and atmosphere. Included are discussions on the fundamentals of geostrophic turbulence, thermocline theory and finite amplitude barocline instability.

General circulation of the ocean, edited by H.D.I. Abarbanel and W.R. Young (New York, Berlin, Heidelberg, London, Paris, Tokyo, Springer-Verlag, 1987. Price DM 160.00) reviews the new concepts and models put forward during the last 5 years, as well as the classical theories and observations. Avenues for future study are suggested, and it is aimed at advanced students and researchers in physical oceanography, meteorology and geophysical fluid dynamics.

Satellite photograph — 16 October 1987 at 0820 GMT

This NOAA-10 infra-red image shows cloud within the circulation of an intense depression centred near 55° N, 0° W. Cyclonically curved cloud bands surround the vortex. The variation in grey shades and the generally 'smooth' appearance of the cloud indicate that a series of cloud layers is present. However, at the vortex centre a small dark area is seen, which must be either cloud free or contain only low cloud. Comparison with visible imagery (not shown) indicates the latter to be true.

South-west of the British Isles, vigorous convection is occurring due to cold air within the circulation of the low having been swept southwards over the warm sea. The cloud band extending from Norway to Spain is associated with an eastward-moving cold front.



Photograph by courtesy of University of Dundee

Meteorological Magazine

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The application of supercomputers to weather forecasting*

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Summary

The aim of this paper is to examine the architectures of large conventional computers and of the new generation of supercomputers, in relation to using these designs in operational weather forecasting and other meteorological applications. The CYBER 205 and the CRAY X-MP range of computers are covered in more detail, since they are the current operational computer systems at the Meteorological Office and at the European Centre for Medium-range Weather Forecasts.

1. Conventional computers

1.1 Basic concepts

(i) *Design.* A typical conventional computer has the general structure and constituent parts illustrated in Fig. 1. The basic idea of this design is over 40 years old and was first put forward by Von-Neumann. The control unit co-ordinates the flow of data and instructions between the various parts of the system (for example, any transfers of data between main and secondary memory) thus leaving the processor free to perform all the arithmetic and logical calculations. The transfer of information to and from secondary memory or the input/output (I/O) devices is much slower than that to and from main memory. The term 'hardware' applied to a computer system refers to the actual physical components of which it is comprised, whereas its 'software' consists of the programs which can be processed on the computer.

In the context of this discussion, the most important aspect of this design is the sequential execution of instructions, with the processor continually performing the following cycle of actions:

- fetch next instruction from memory
- decode instruction
- fetch operands from memory
- perform operation on operands
- store result

This type of computer can be classified as a 'Single-Instruction stream Single-Data stream' (SISD) computer, since one instruction operates on a single set of operands, and only one operation may be

* This article is based on an investigation undertaken as part of the 1986/87 Scientific Officers' Course held at the Meteorological Office College, Shinfield Park, Reading.

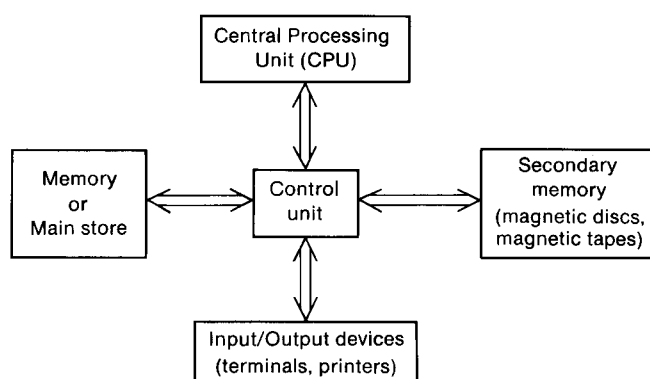


Figure 1. A simplified diagram of the basic units of a conventional computer.

performed at one time. An example of an SISD computer is the IBM 360/195, the main computer used at the Meteorological Office from 1971 to 1982. The scheme of classification used here divides computers into four general classes and is described by Hockney and Jesshope (1983). Computers in some of the other classes will be referred to later.

(ii) *The compiler.* The instructions will initially be written in a 'high-level' language such as Fortran. High-level languages have 'statements' to be interpreted by the computer, consisting of a restricted set of English words and symbols, each given a precise meaning in the language. They are designed to be hardware independent and are much easier for the programmer to understand and to use than the 'low-level' language which corresponds directly to the machine's instruction set and is therefore unique to a given type of computer. A high-level program is transformed ('compiled') to low-level machine code by a special program known as a compiler. The machine code must then be 'run' for the instructions to be actually executed. A program such as the operational weather forecast model only needs to be recompiled every few months, when changes are made to the program. The resulting program is then run twice a day (at the Meteorological Office) from its machine code form.

(iii) *The Operating System.* Every general purpose computer has an Operating System (OS), which is a set of interrelated programs. A major function of the OS is to simplify using the machine's hardware. On larger computers it provides a multi-programming environment for users and programs, in which a large number of users may appear to have 'simultaneous' access to the processor, each program being allowed a certain share of time in control of the Central Processing Unit (CPU), according to its priority. The OS also allocates resources, aids efficiency, and protects users and programs from each other.

(iv) *Operations and data.* The basic unit of data for numeric processing on a computer is the 'word' which is a consecutive sequence of binary digits, usually known as bits, of a fixed length for any one computer. A 64-bit word length is used in a number of present-day supercomputers. Operands and instructions are often an integral number of words in length. A sequence of 8 bits is normally referred to as a byte and these are typically used to store characters, one to a byte.

The main memory of modern computers can typically hold a few million words of data, stored in 'interleaved' memory banks. Accessing any one bank successively is slow, so generally consecutive words are stored in different banks to speed up their retrieval. Although secondary memory is usually provided in the form of magnetic discs and tapes, semiconductor or solid state memory, such as the

Solid-state Storage Device attached to the CRAY X-MP at the European Centre for Medium-range Weather Forecasts (ECMWF), has recently become sufficiently inexpensive to be used in this way. The semiconductor memory is much faster than the other types of secondary memory, thus going some way towards reducing the large difference between the CPU and I/O speeds of more conventional systems. Such a reduction is important because the large speed gap results in the system 'throughput' (the amount of work that can be processed by the system) being considerably less than that to be expected from the CPU processing rate.

All activities in the CPU are synchronized by a 'clock', with a clock cycle time in the range 5–50 ns ($1 \text{ ns} = 10^{-9}$ seconds) for the computers considered here. This gives the basic indivisible unit of time for the shortest operation, and gives a rough guide to the speed of the machine since the smaller the clock cycle time the faster operations can take place. If the clock cycle time is reduced to achieve greater speed, this must be backed up by correspondingly faster facilities and speeds on the rest of the system. However, one must also take account of the fact that one machine may do more or less work per clock cycle than another. The memory access time, which is usually a few clock cycle periods, gives the time to transfer one word of stored information from a memory bank to the CPU.

(v) *Comparison of performance.* There is no absolute standard for comparison of computer performance, but computer speeds are commonly measured in:

- (a) MFLOPS (millions of floating-point operations per second) or
- (b) MIPS (millions of instructions per second).

In comparing similar computer systems, it is standard practice to take a set of test programs, called bench-marks, typical of the work-load of an establishment, and run them on the different machines. It is particularly important to apply bench-marks to supercomputers since their performance varies considerably depending on the application, and may be much less than the 'peak rate' given by the manufacturer. (The performance is affected by factors such as the quality of compiler, the OS environment, the efficiency of mathematical library routines and the precision of floating-point arithmetic, and not just of the hardware.)

In scientific applications, the Fast Fourier Transform is often used to compare the performance of different computers, since it is an integral part of many scientific programs. There are also well known suites of programs which have become 'standard' bench-marks, e.g. Livermore Loops.

1.2 *Pipelined vector processors*

The computers outlined above can be described as scalar processors because one instruction is needed for each operation (e.g. adding a pair of operands).

In contrast, vector processors (e.g. CRAY-I, CYBER 205), a specialized form of the conventional computer designed to process large quantities of scientific data efficiently, operate on long vectors of data. One instruction now performs the same operation on each element of a vector in turn. In this context, a vector is just a sequence of numbers all of the same type, such as, for example, temperature values at a series of forecast model grid points. The method by which vector data are processed is known as 'pipelining'. Successful pipelining depends on being able to break down an instruction, such as an addition, into small segments, each of which can be performed several times faster than a complete operation.

Pipelining is analogous to processing an 'assembly line' of data. One pair of operands is added to the beginning of the assembly line each clock cycle and it takes a while before the line is full (the start-up time). The start-up time may be affected by the time taken to get the first operands from memory as well as by the length of the pipeline. Once the line is full, new operands are taken in, and one result is

produced each clock cycle, with intermediate operations being performed on elements 'in the middle of' the assembly line. Obviously this is much more efficient than putting one element onto the assembly line and waiting until it emerges at the other end before putting the next element on the line, which is generally what would happen in a computer that did not have the pipeline facility.

The compiler on a vector processor automatically vectorizes sections of code (i.e. it enables the data to be pipelined) where this is possible. The only type of construct that can be vectorized is a loop of some sort, such as the 'DO-loop' in Fortran, and even this is vectorizable only under certain conditions. However, a good programmer or compiler will spot ways of formulating vectorizable code which may be far from obvious in a program written originally for a conventional (scalar) computer.

A simple example of a DO-loop that vectorizes is given below. A, B and C are vectors, with A(I) being the Ith element of vector A, etc. and I takes on each of the values 1, 2, 3, ... up to a fixed integer N, in turn. For each value of I, the Ith elements of vectors B and C are added together, and the Ith element of A is given the value of this sum.

```
DO 10 I = 1, N
  A(I) = B(I) + C(I)
10 CONTINUE
```

When compiled, this Fortran loop would become a single instruction operating on a vector of length N. On the first clock cycle, B(1) and C(1) would be fed into the first part of the floating-point add pipeline. On the second clock cycle B(2) and C(2) would be fed in to the first part and the first operands would be moved to the second part of the pipeline. Similarly B(3) and C(3) are fed in on the third clock cycle, etc. After a few cycles the results A(1), A(2), etc. would start emerging from the add pipeline.

This is possible because the add operation can be broken down into several smaller operations. Firstly, the two numbers (in floating-point notation) to be added must be adjusted so that they have the same exponent. They are then added and finally the result is put back in floating-point notation before it leaves the pipeline.

Most vector processors have several such pipelined units. The main difficulty is in getting the correct instructions and data in the right place at the right time to keep the processor working efficiently. The machine is at its most efficient when the pipeline unit is kept full, i.e. for long vectors.

Numerical weather prediction models can be formulated to work with long vectors, particularly for the equations representing the dynamical processes of the atmosphere, where the same operations are generally applied at every point in the forecast domain. This is why the Meteorological Office purchased a CDC CYBER 205, and ECMWF a CRAY-1A, which has since been upgraded by stages to a CRAY X-MP/48.

Most vector processors are designed to be run in conjunction with a computer which acts as a front-end processor. In general, the front-end processor controls the preparation of input data, presentation of output data (a large task in weather forecasting systems), job preparation and other data management tasks. The vector processor is then free to spend all its processing time on processing numerically intensive work, the type of computation at which it is most efficient.

2. Supercomputers

2.1 Introduction

The term 'Supercomputer' is used by different people in various ways. It is sometimes used to denote the fastest computers currently available; this would include the CYBER 205 computer, manufactured by CDC, and the CRAY range of computers, manufactured by CRAY Research Inc. Alternatively, the term can be used to denote the advanced systems about to emerge in the next few years. These new computers typically have multiple processors and many have a completely different structure from the

conventional computer, enabling them to exploit the data structures of the problems they are designed to solve.

In some of these computers, two or more processors execute the same instruction simultaneously on different items of data 'in parallel'. The array processor discussed in section 2.2, operates in this way, an example of which is ICL's Distributed Array Processor (DAP).

In other computers, multiple processors again work together, but execute *different* functions at the same time. For example, the CRAY X-MP has up to four CPUs as its processing elements. The meteorological applications of the CRAY X-MP at ECMWF are discussed more fully in section 4, and the general characteristics of this class of computers, called multiprocessors, are covered in section 2.3.

2.2 Array processors

The array processor is designed to operate on arrays of data. It consists of a large array of processors, each with its own memory and connections to neighbouring processors. A single instruction issued by a separate control processor operates simultaneously on multiple pieces of data (i.e. each element of the array), one in each processor. Therefore this can be classified as a 'Single-Instruction stream Multiple-Data stream' (SIMD) computer.

If a scalar problem is presented, and all real problems have parts which are irreducibly scalar, then only one of the many processors can be used; this is extremely inefficient. For this reason the array processor would normally be attached to a front-end processor which would perform these scalar tasks.

In theory this type of processor is well suited to performing meteorological work because the forecast models are based on data at a grid of points. It is easy to visualize a system being applied to numerical weather prediction in which there was one processor for each grid point, with communication to nearest neighbour processors. With such an arrangement, SIMD systems are ideal for dynamical calculations where each calculation is the same at every point. However, in dealing with physical calculations, such as those due to radiation or rainfall, certain computations will only be performed at some grid points and therefore many processors will be switched off for most calculations (see section 3.4). This reduces the efficiency of SIMD machines.

Some Meteorological Centres use array processors as a cost-effective way of running dynamically based forecast models. They are particularly applicable in situations where the forecasts of physical processes, such as precipitation, are less important than those of variables calculated from dynamical processes, such as wind. However, at the Meteorological Office, this type of computer is not general purpose enough or powerful enough to handle the many models and varied applications for which it is required. In particular, there would be major problems in achieving the fast input and output of data required for the running of the operational forecast models.

2.3 Multiprocessors

These may be classified as 'Multiple-Instruction stream Multiple-Data stream' (MIMD) computers, since each processor is working on a different task using separate data.

When a computer has many users, such a multiprocessing environment can be organized so that different programs are processed by different processors, as they become free, thus increasing the throughput. The OS organizes the allocation of programs to processors and so the programmer is not concerned with this aspect of the processing, in that the work is set up as for a single-processor system. Machines of this type are quite common (an example being the two IBM 3081D computers in use at the Meteorological Office) and such computers will not be covered further in this section.

Alternatively, the processors may all be used to process one program, with the processors executing different sections of the program concurrently. This can significantly decrease the elapsed time needed

to execute a program such as an operational forecast model, but the program becomes more difficult to organize and overheads arise due to the need to synchronize the processors in order to ensure that each section is executed in the correct order. This whole area is subject to much current research.

In running an operational forecast model, the programmer can make the execution more efficient by setting up algorithms and strategies that are easy to execute as multiple processes. These processes would be large, to avoid overheads, and well balanced so that processors are idle for the minimum amount of time. If the program has been split into self-contained tasks and placed in a 'task bin', then as each processor becomes free it takes the task at the top of the 'bin' to process next, subject to task dependencies, such as one task having to complete before another one can start. In this type of multiprocessing, a 'task' is defined by Dent (1985) as, 'any block of executable code which can run independently of other blocks'. On the CRAY X-MP, a task could be a subroutine or may even be part of a DO-loop, the total number of passes through the loop being divided into several tasks.

The speed-up factor compares how much faster a multiprocessor environment is relative to a single-processor environment:

$$\text{speed-up factor} = \frac{\text{time taken for task in single-processing mode}}{\text{time taken for task in multiprocessing mode}}$$

A speed-up factor of greater than one is only achieved if, as expressed by Gibson (1985), there is:

sufficient parallelism to utilize more than one CPU to perform computations at a faster rate than could be achieved by a single processor, allowing for the extra overheads necessarily incurred by the multiprocessing control mechanism. The full benefit of multiprocessing can only be realised when the multiprocessing job has sole command of the computer. Multiprocessing should be reserved for time critical jobs which are likely to execute on the computer either in isolation, or at high priority.

It can be proved that for n processors, the speed-up factor must be less than n , since the overheads prevent the possibility of achieving a speed-up of n .

3. The CYBER 205 at the Meteorological Office

3.1 *The computer installation*

The present operational supercomputer at the Meteorological Office is the CDC CYBER 205, but this will be replaced during the next year. The CYBER, together with its two front-end processors, both IBM 3081D machines, form a very powerful processing environment. The IBM machines are general purpose machines designed to be efficient in a multi-programming environment, so they are ideal for providing the user interface to the CYBER as well as meeting much of the processing requirements in their own right. The two 3081s are identical and interchangeable but, at any one time, one of them is the control processor for both the other 3081 and the CYBER. This means that if one 3081 'goes down' it can always be replaced by the other 3081 and if the CYBER fails the combined 3081s can temporarily take over some of its processing, although global models are never run on the 3081s. The jobs given to the CYBER are those with a large amount of data which can be vectorized, since it performs this kind of processing efficiently, as discussed earlier.

Both the CYBER and the 3081s have disc storage which holds the operational forecast and climate models, as well as being used for temporary storage during the execution of programs. Magnetic tapes are used for archiving data and for back-up purposes.

The CYBER compiler has an automatic vectorizer which substitutes vector instructions for DO-loops, where such replacement cannot alter the program logic. In addition, there is an optimizer which reschedules the order of scalar instructions to make optimum use of scalar registers and pipelined scalar units without needing user intervention.

3.2 *Design features and limitations of the CYBER 205*

A vector on the CYBER is defined to be up to 65 535 contiguous elements (i.e. elements are stored in successive memory locations). This definition of a vector is rather limiting in that the elements have to be contiguous, but there are instructions to form vectors in consecutive storage locations from random elements of other vectors, and to reverse the process. This facility can be used to good effect when the required elements are defined by other data values, as in the modelling of physical processes (see section 3.4).

Execution of a vector operation consists of two phases. Firstly there is the start-up phase, which is independent of vector length and involves filling the general purpose pipelines. Secondly there is the stream phase during which the vector elements are processed. Here the time consumed is proportional to the vector length, where the constant of proportionality is the average number of clock cycles needed to produce one result. Table I, calculated from values given in Dickinson (1982), shows that for small vector lengths the start-up time dominates the MFLOPS rates. Note that the Meteorological Office's CYBER 205 has two pipes (i.e. two independent pipelines) so the figures given in Table I are directly applicable to the performance achievable on this system.

Table I. *Performance for 32-bit arithmetic operations on a two-pipe CYBER 205*

Vector length	Speed, in MFLOPS, for addition or multiplication
25	21.8
50	39.4
100	65.8
500	142.1
1 000	166.1
10 000	196.0
50 000	199.2
asymptotic performance	200.0

The use of 32-bit arithmetic (see section 3.3) gives a peak rate twice that of the standard 64-bit arithmetic on a CYBER 205. In addition, the use of a facility known as a linked triad, whereby the output of one vector unit is fed directly into the input of a second vector unit, can, where applicable, further increase speeds by a factor of two. This level of performance can be achieved only by use of careful programming, in which the code is tailored to the particular computer configuration. Such techniques can increase performance by an order of magnitude. By comparison, in scalar arithmetic program optimization can only increase performance by, say, a factor of two or three.

Once accessed, a memory bank on the CYBER cannot process another memory request for the same bank for four clock cycles. This can lead to very inefficient code, for example when there are successive accesses of the same array element or of array elements which are a multiple of the number of memory banks. There are 256 memory banks on the CYBER 205 when using 32-bit words.

3.3 *Use of the CYBER for numerical weather prediction and climate modelling at the Meteorological Office*

The time available on the CYBER is used primarily for numerical weather prediction and general circulation studies. In addition to supporting the Office's operational forecasting effort, research activities cover a wide range of topics which include such subjects as the study of climate change, the development and testing of a mesoscale model, experiments on the observing system such as data impact

studies, long-range forecasting and research leading to a better understanding of the physical processes in the atmosphere.

All the above research activities require the use of atmospheric models that can resolve the physical and dynamical processes in time and three-dimensional space. The designs of the computer programs which run two such models are discussed in more detail in the following sections. These are the global version of the operational forecast model and the climate model. Between them these models account for probably 60% of the time used on the CYBER. Descriptions of the formulations of these models are given by Bell and Dickinson (1987) in the case of the forecast model and Slingo (1985) in the case of the climate model.

Since the operational forecast models are run each day to a tight deadline, they must be efficient and the programs must be reliable, so changes to the models are thoroughly tested before introducing them. The emphasis is on producing the most accurate forecast in the time available. In practice this means running models with the highest possible spatial resolutions. In contrast, an experimental run of the climate model generally takes much longer to execute than a typical run of the forecast model, since it is simulating atmospheric events on a time-scale of years rather than days. These models, by necessity, are designed to use much lower spatial resolutions than the one used in the forecast model. Program efficiency is again important because small increases in efficiency can save large amounts of computer time, although the necessity to use modified equations to ensure the simulated atmospheric dynamics is correct in the long-term means that these equations are somewhat less efficient to solve. Also there must be provision for the amount of data processing needed in the very long program runs and for the storing of large quantities of intermediate results. The program must, in addition, have the property of being restartable in the case of a computer malfunction.

The implementation of both the forecast and climate models on the CYBER uses 32-bit words instead of the full word length of 64 bits. This gives, in effect, twice as many words of store and also has the advantage that 32-bit vector arithmetic operates at speeds up to twice that of 64-bit arithmetic. In addition, it has been shown that using only half the precision has a negligible effect on the accuracy of the weather prediction and climate models.

The CYBER is operated in 'stand alone mode' for runs of large research tasks and during operational weather forecast model runs, that is, there is only one user on the machine at once. Not only does this make the entire memory and processing power available to a single program, but it also means that no CPU time is lost in changing over to another user and bringing other files into main memory. Hence the 'wall clock' time, the time taken for the program to run, is reduced even more. Some sections of the model are 30–50 times quicker than the equivalent best coding on the previous computer, an IBM 360/195, thus demonstrating how successful the vectorization and other improvements have been.

3.4 The treatment of dynamical and physical processes

From a vector programming point of view, large-scale models of the atmosphere consist of two quite distinct parts; the dynamical and the physical processes. The dynamical processes are represented by the momentum, thermodynamic, humidity, continuity and hydrostatic equations. Both the climate and forecast models use explicit finite-difference techniques to integrate this governing set of fluid dynamic equations. The physical processes, on the other hand, occur on length scales much less than that of the grid-point system and their statistical effects are represented in terms of the prognostic variables. The schemes for modelling these processes are characterized by sets of calculations that are both conditional and intermittent. The physical processes include such processes as convection, rainfall, radiation, surface exchanges and turbulent mixing.

The integration of the dynamical equations by finite-difference techniques requires each level of the forecast area to be covered by a regular grid of points at which the current values of the prognostic variables are stored. A set of linear equations, derived from the finite-difference approximations to the governing equations, are then used to step the forecast forwards one time step at a time by modifying the values stored at each grid point and at each level of the integration domain. This means that in general the same computations are done at every point on the grid, so the solutions to the dynamical equations vectorize well and thus are processed efficiently on the CYBER.

The physical processes, however, are much more difficult to vectorize efficiently. The most important aspect of these processes, in terms of modelling, is that they only apply 'randomly' at grid points; that is, they only apply at a varying non-contiguous subset of the forecasting area. For example, areas of rainfall would be present at some grid points but not at others, and in all likelihood those points forming a developing area of rainfall would not be a contiguous set and so would not form a vector for processing on the CYBER (see section 3.2(a)). It would be inefficient to process the whole vector, since unnecessary calculations will be performed at grid points which have no rain. On the CYBER 205 there are two ways of reducing this overhead once the number of active elements in a vector becomes small. These methods use the 'compress and expand' and 'gather and scatter' instructions. Instead of suppressing the storing of the results of a calculation at unwanted points, these instructions allow shorter vectors to be first constructed from the active elements of the long vector. Once this has been done, subsequent calculations may be carried out at the shorter, faster vector length. The circumstances of any given case will determine which method is most efficient. Dickinson (1982) discusses the application of these techniques in more detail.

3.5 Data organization for vector computation

The current sizes of the grids used by two of the Meteorological Office's main models are given in Table II. Other climate models are also used, with both greater and lesser horizontal resolutions.

Table II. *The dimensions of two of the models in use at the Meteorological Office*

	Global forecast model	Climate model
No. of levels	15	11
No. of points round each line of latitude	192	96
No. of points between North and South Poles	121	72

On the CYBER 205 vector processor, long vectors are required for efficient running, so the global operational weather forecast model uses 'horizontal slices' to give the maximum vector length of $192 \times 121 = 23\,232$. The timings given in Table I indicate that this vector length, used for dynamical processes, is 99% efficient. This division of the grid also gives the longest possible vector length for physical processes, after taking into account the removal of elements that do not require processing. The physical calculations tend, in practice, to have a typical vector length of around 2000, which still gives a processing rate that is about 90% of the peak rate.

In the climate model 'vertical slices' are used to produce vector lengths of $11 \times 96 = 1056$. The flexibility given by using a smaller-sized slice compensates for an efficiency of only 84%. At present the climate model can reside entirely in main memory, but if the model were to increase in size so that it used more than this amount of store, the smaller slices, when inactive, would be more easily swapped in and out of main memory. The computations for some grid-scale physical processes are done in blocks of a

number of vertical slices placed together. Since many of the variables for these processes are derived from quantities at other vertical levels, the natural way to solve the physics is by layers over a small horizontal area.

4. CRAY computers

4.1 *The CRAY-1A at ECMWF*

At the commencement of its operational activities ECMWF purchased a CRAY-1A computer, a vector processor with one CPU, that was roughly equivalent in power to the CYBER 205 when performing 64-bit arithmetic.

The distinctive cabinet shape shown in Fig. 2 is characteristic both of the CRAY-1A and the CRAY X-MP series, with the vinyl-padded seating disguising power supply units. In this generation of supercomputers, finding the correct shape for the cabinets was important, because the wiring lengths, and hence the correct timing of the electronic signals, depended on it. Now that a whole CPU can be implemented on a single circuit board, this is becoming less of a problem.



Figure 2. The CRAY-1A situated at the European Centre for Medium-range Weather Forecasts.

4.2 *The CRAY X-MP/22 and the X-MP/48 at ECMWF*

In March 1984 a CRAY X-MP/22 was installed at ECMWF. It had two CPUs and two million words of memory, the two quantities to which the '22' in its name refers. This was double the number of processors and twice the amount of memory than there was previously on the CRAY-1A. Both the Solid-state Storage Device (SSD) and the Input Output Subsystem (IOS) were new fast devices making the running of the whole system much more efficient and the clock cycle period had also been reduced to 9.5 ns from 12 ns. It was estimated that there was an increase in throughput over the CRAY-1A of a factor of 3.

The CRAY X-MP/48, installed in January 1986, has four CPUs and eight million words of memory, another substantial increase in resources. In addition, the number of memory banks was increased, and the amount of SSD went up from 16 million words to 32 million words. It is estimated that the performance is on average 2–2.3 times better than the X-MP/22. Table III gives the speed-up of the two- and four-processor versions of the X-MP, over the one-processor version, when processing ECMWF's spectral forecast model.

Table III. *Multiprocessing timings for the spectral model on the X-MP/48*

No. of processors	1	2	4
Seconds per time step	19.3	10.3	5.4
Speed-up ratio	(1)	1.87	3.6

Since the ECMWF operational weather forecast model already contains the code to run it on a variable number of processors, it is possible to estimate the performance that would be given by greater numbers of processors, using the present multiprocessing strategy (see Dent 1985). From this, it is clear that, as in any multiprocessor system, the ratio of the speed-up against the number of processors decreases as the number of processors increases, so eventually adding more processors would make no significant difference or would actually be detrimental to the speed of the forecast model. This problem of diminishing returns is well known and is caused by communications overheads between processors and the need to synchronize tasks.

4.3 Strategies for multi-programming numerical weather prediction models

Consider a latitude–longitude–height grid as used in an operational forecast model. Suppose that the processing over this grid is to be spread over several processors. Then the grid could be split into latitude sections as shown in Fig. 3(a) with each processor being allocated its own section.

Firstly, there will need to be some transfer of boundary conditions across the dividing boundaries, in addition to the actual processing.

Secondly, there will be the same number of calculations due to dynamical processes to do at each grid point, but different amounts due to the physical processes. For example, there is more convective activity in the equatorial regions than in the other regions. Also there is more land in some latitude sections than others which means more calculations of the computationally expensive land surface processes will be necessary. This type of consideration will lead to unequal amounts of work for the various processors so one or more processor(s) may be idle while the others are still working, thus achieving less than the potential efficiency. Therefore, although the processors will keep in step overall through synchronization, there will always be inefficiencies arising from some processors being idle for part of the time.

On the two-processor CRAY X-MP, the ECMWF model is used to process one latitude row in the northern hemisphere at the same time as its corresponding one in the southern hemisphere (Fig. 3(b)). Consequently, for the two rows being processed simultaneously, effects due to latitude are more or less equal, although other more randomly distributed effects cannot be made equal. This method of processing is convenient in terms of the Fourier components and Legendre transforms appearing in the equations of the ECMWF spectral model, since they have corresponding northern and southern terms, which can be calculated simultaneously (see Dent 1985).

On the four-processor CRAY X-MP, originally two northern rows were processed at the same time as their equivalent southern rows. Although each north–south pair still needed to be synchronized when they completed a process, there was no need to synchronize between the two pairs of processors until the

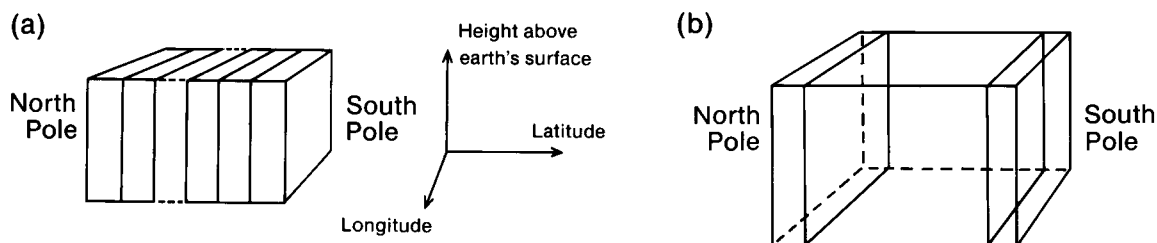


Figure 3. (a) The division of an observational grid into N sets of grid points in order to be processed by N processors and (b) the two corresponding northern and southern hemisphere latitude slices, that can be processed simultaneously in the two-CPU version of the CRAY X-MP.

complete global grid had been processed. This used a 'static' strategy in which most of the decisions concerning which task to execute in which order, the synchronization of the subprocesses and the handling of boundary transfers between subprocesses, were taken by the programmer at coding time.

Now a 'dynamic' strategy is being introduced (see Dent 1987) in which these decisions can be made at run time, processors taking on tasks as they become free. Each task still deals with a north-south pair of latitude rows but the need for these to synchronize (i.e. wait for each other) after each process is avoided by having each row updating different copies of the same files. This requires significantly more memory but reduces the time wasted when processors are idle. The dynamic method becomes more efficient than the static when using large numbers of processors because of these savings in time.

The speed-up over the single-task version of the dynamic strategy is an impressive 3.6. For this, the model executes 99% of the floating-point calculations in vector mode and has an execution rate of some 335 MFLOPS.

5. Future supercomputers and their use at the Meteorological Office

Both the speed and main memory of the most powerful computers have been increasing by approximately a factor of 10 every 5 years, a trend demonstrated by the main computers used at the Meteorological Office over the past 30 years. Present indications are that this general pattern of exponential growth will continue, at least for the next few years.

The latest generation of multiprocessing supercomputers includes the CRAY 2, from CRAY Research, of which several have already been sold, as well as the ETA 10, manufactured by a subsidiary of CDC, and the CRAY Y-MP range, also from CRAY Research, both of which are now on the market. Each of these computers is capable of giving a processing rate an order of magnitude faster than the CDC CYBER 205. The precise speed-up will be dependent on the problem being solved, the numerical precision used and the number of processors. For example, an ETA 10 with eight processors is projected to have a maximum performance of around 20 times that of the CYBER 205.

Although these are multiprocessor systems, they use only a relatively small number of CPUs, in which each CPU is essentially a vector processor 'supercomputer' such as the CYBER 205. If massive parallelism can be fully exploited, larger numbers of simpler processors could lead to cheaper and more powerful systems. Some manufacturers have already built, or are developing, systems with many processors. For example, the FPS T-series comprises, in principle, up to several thousand Inmos Transputer processor chips, which have been specifically designed to be used in multiprocessor systems.

Since an entire supercomputer CPU can now be located on just one circuit board, the physical cabinets of the newest supercomputers are correspondingly much smaller, compared to those of the early 1980s. One example of these compact machines is the CRAY 2, its main cabinet being less than a cubic metre in volume. It is possible to envisage the 'desk-top supercomputer' in the not too distant future. However, the greater heat dissipation per unit volume produced by this reduction in size has presented engineers with major design problems concerned with the development of increasingly sophisticated cooling systems which use cooling agents such as liquid nitrogen. An efficient cooling system is essential because the processors must be maintained at a low temperature to give the best performance.

Within the Meteorological Office, the supercomputer is a tool used not only to run the operational numerical weather prediction models but also to aid the research into producing even more accurate forecasts. The limited amounts of computational power and main memory available at each stage have constrained the accuracy to which weather systems and physical processes could be represented. Indications are that significant improvements in the forecasts would be gained by doubling the resolutions of the global, limited-area and mesoscale models. This would mean that the global 'coarse-mesh' model would have a resolution equivalent to that of the limited-area 'fine-mesh' model at present, with twice the number of grid points to be processed in both the latitude and longitude directions. If this was done, the model time step would also have to be halved to maintain computational stability, thus doubling again the number of necessary calculations. Hence, altogether eight times the computational power used at present would be needed to run this model within the same deadlines. Even more power and memory would be required if more vertical levels were included and if there were more runs per day.

Further planned development of the mesoscale model, which covers the British Isles, will lead to an increase in resolution, more levels in the vertical, larger areal coverage, more runs per day and runs for a longer period ahead. It has been estimated that this demand would require 50 times the power used for the present model and over 30 times the memory.

The computer is also used to support the research and development of enhancements to the operational forecast models, such as improved physical parametrizations, as well as for thoroughly testing them before implementation. Again in the research area, the climate model, which is very important for investigating long-term changes, will require increases in computer speed and memory of two orders of magnitude within the next decade. Long-range forecasting, which goes up to 30 days ahead, and the development of coupled ocean-atmosphere prediction models will both also make large demands on future supercomputers.

It has been estimated that the increase in processing power necessary for all these applications in the early 1990s would require a computer with at least 50 times the power of the CYBER 205 and about 500 million words of memory. This performance target will not be met by a single processor so, at least for the major models, it would be necessary to have a multiprocessor with probably 8–16 processors. There are several parts of the numerical forecast suite that can be made independent of each other. For example, the mesoscale and global forecasts could be run simultaneously with each integration being shared by several processors. There appears to be no intrinsic difficulty in adapting both the atmospheric and ocean models to be used on a multiprocessor, as the experience of ECMWF has demonstrated.

It would have to be possible to run the models on a variable number of processors to cater for periods when processors are not working or new processors are added to the system, and so the execution of the subprocesses needs to be independent of particular processors. Software tools are available to help users of multiprocessor systems, but even so it is likely that the Meteorological Office would still need to develop some software itself to implement a multiprocessor system fully.

During 1987 the Meteorological Office obtained approval to replace the CYBER 205 and, as a result of a competitive procurement exercise, a contract was awarded to CDC in December 1987 for supply of an ETA10 system, with June 1988 as the target date for its acceptance. The configuration is based on four processors, each of which is about twice as powerful as the current CYBER 205, and has twice the local memory. These processors also have access to 64 million words of shared memory and the overall system is expected to have a peak performance of about 3000 MFLOPS. This represents an important step towards meeting the computational requirements of the 1990s and there will also be the option of upgrading the system in the future.

In conclusion, it is clear that the accuracy of forecasts, achieved using predictive models, has progressed in stages with the available state-of-the-art computing power and this close liaison between numerical weather prediction and supercomputers is likely to be important for the foreseeable future.

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Progress in the development of PARAGON

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Summary

A description is given of PARAGON — a system developed in the Meteorological Office for the routine archiving and adjustment by gauge observations of daily rainfall totals measured by radar.

1. Introduction

The Meteorological Office requires estimates of surface rainfall amount at ungauged locations for a range of periods from five minutes to one year. The data are required for enquiry bureau use, investigations and research.

For historical studies of daily or longer rainfall totals, observations from the climatological network of rain-gauges are available. The gauge spacing in this network ranges from 3 km to over 30 km depending upon locality, with an average of about 8 km. For more urgent requirements for daily rainfalls the only observations reported in near real-time are those from the synoptic network with a gauge spacing ranging from 20 km to 100 km and an average of 40 km.

Quantitative measurements of rainfall from radar observations are now available. Because of their regular and dense spatial coverage (5 km spacing) they can be used to interpolate between gauge observations especially from the more widely spaced gauges in the synoptic network. Their operational availability every 15 minutes increases their potential for a range of advisory uses especially when prompt or detailed information is required.

On the basis of considerable experience in the non-routine processing of radar rainfall observations for quantitative studies (Palmer *et al.* 1983), proposals were made for the design of a fully automated comprehensive system for the routine processing, adjustment by gauge observations and storing of radar data (Smith *et al.* 1984). The system was planned to produce daily rainfall totals, with the computer software being developed in two phases — phase 1, off-line (non real-time) data and phase 2, on-line (real-time) data. The development of phase 1 is finished, but it now seems unlikely that phase 2, as it was originally conceived, can be made operational before 1990 because of difficulties in transferring to the Meteorological Office central computer (COSMOS) in real time the large amounts of single-site radar data involved.

This paper describes progress so far on the development of this system which has been given the name PARAGON (Processing and Archiving of RADar and Gauge data Off-line and in Near real-time). An outline block diagram of the PARAGON processing system as originally conceived is shown in Fig. 1.

2. Radar observations

Radar waves are emitted by a radar transmitter and reflected by raindrops or snow and ice particles. The strengths of these reflected signals are converted by a simple formula into rainfall rates (intensities) and averaged over contiguous $5\text{ km} \times 5\text{ km}$ squares partly to reduce their random errors and also to reduce the data to manageable amounts.

The basic rainfall intensities are measured virtually instantaneously by each radar every 5 minutes, accurately synchronized, and given an automatic real-time on-site calibration (Collier *et al.* 1983) using,

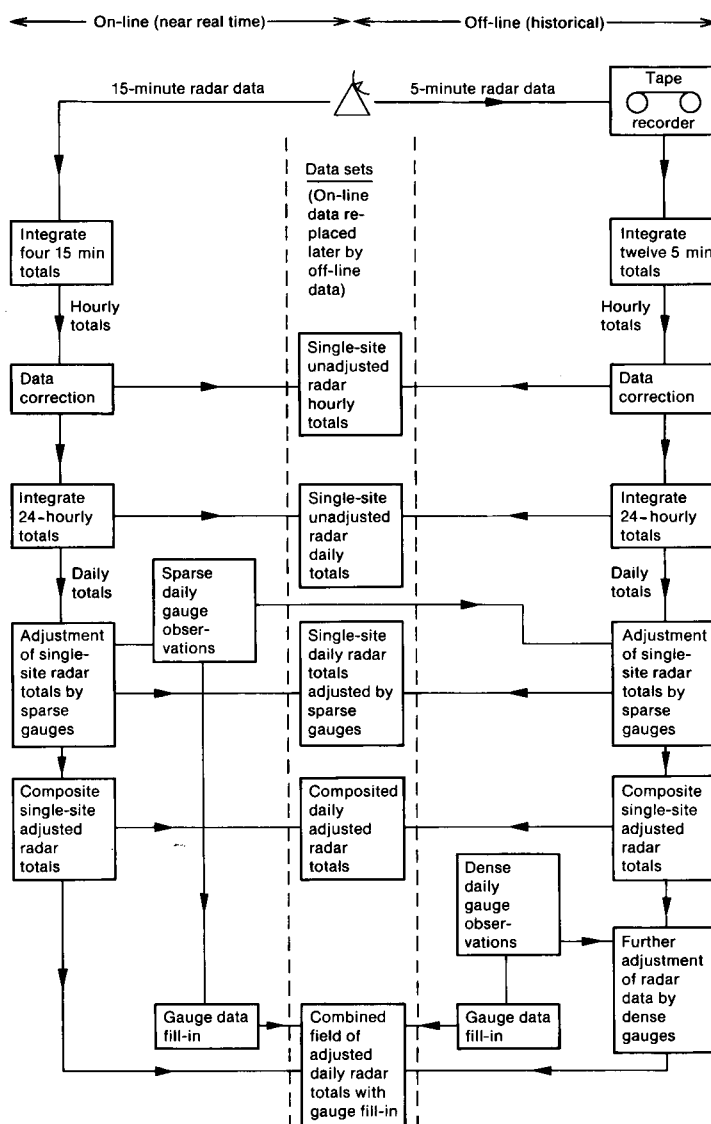


Figure 1. The PARAGON processing system.

as ground truth, observations from three–five dedicated gauges within 75 km of each radar. Areas of permanent clutter (reflections from hills, buildings, etc.) are erased on site and a correction is applied to compensate for loss of radar sensitivity at longer ranges. Currently the presence of bright band, the enhanced signal from melting snow, is detected on site but its effect on apparent rainfall rates is not yet removed operationally. The resulting rainfall intensities are regarded as the ‘raw’ radar data in the context of PARAGON.

Although the intensities or rainfall totals are areal averages they need to be ascribed to specific locations for the purposes of adjustment by gauge observations, or simply for plotting. These locations are chosen to be the centre of the squares and the spatial radar rainfall distributions are represented by a

regular array of grid-point values with a 5 km spacing. This determines the way in which all radar data (and some associated gauge data) are processed, stored and displayed by PARAGON. From these grid-point values, estimation of radar rainfall at any location, for instance of a gauge, can easily be carried out by two-dimensional interpolation.

At present, radar observations are being made at the five installations shown in Fig. 2. The coverage of single-site data is a circle of radius 210 km contained in squares of 84×84 grid points. Data from two new radars, at Castor Bay in Northern Ireland and Ingham, near Lincoln, will be available within the next year.

From the beginning of 1984 the PARAGON data sets are as complete as they can be, though data from the radar at Chenies did not start until the beginning of 1985. The data for May 1981 to the end of 1983 have also been processed but are less complete than for later years.

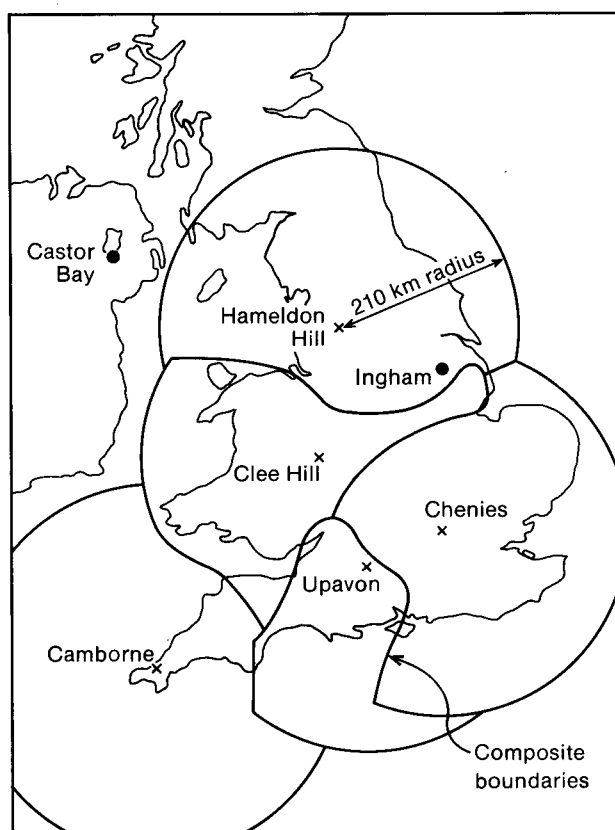


Figure 2. Radar coverages with existing operational radars. The sites of operational radars are indicated by X whereas those expected to become operational in the next years are denoted by ●.

3. PARAGON input

The basic observations required for input into PARAGON are hourly radar rainfall totals for each grid point as observed by each radar separately (single-site data), and obtained on-line or off-line as described in section 5. Much of the subsequent processing, consisting of quality control, integration to daily totals, adjustment by gauge observations and compositing, is common to on-line and off-line

working and uses the same computer programs. The main difference in the two versions was planned to be the number of gauges used for adjustment of the radar data as ground truth. The on-line version would use only the (sparse) synoptic gauge observations while the off-line version would further adjust the radar data by dense gauge observations. The timetable for the processing would be within a few hours, after the end of each day, for on-line working but after a few weeks for off-line working. The on-line products, assumed to be less accurate, are required for urgent advisory use until the more accurate off-line products become available. At present only the off-line system is operational.

4. The PARAGON processing system

4.1 Quality control and production of daily totals

Quality control of hourly radar data is carried out within PARAGON to supplement that already applied on site. Areas of partial or complete occultation (again caused by hills, buildings, etc.) are deleted completely. Areas of 'anaprop', the enhanced clutter occurring during particular weather conditions, are corrected after detection by distinguishing between the usually stationary anaprop and moving rainfalls. The data are then held as hourly totals from each radar separately, unadjusted by gauge observations, other than those used for the on-site calibration.

The 24-hourly totals for 09 GMT to 09 GMT the next day are formed for the grid points and stored as a set of single-site unadjusted radar daily totals. This particular 24-hour interval is chosen to conform with the standard rainfall day for gauge observations, which are required for the following adjustment process.

4.2 Adjustment of daily radar data by sparse gauge observations

Previous experience indicates that on-site calibrated data are still not sufficiently accurate for certain quantitative uses of surface rainfall information such as determining monthly river-catchment rainfalls. As a consequence the radar data are modified by gauge observations using a form of objective adjustment which is distinct from the more meteorologically based on-site calibration. This adjustment is a type of quality control and so is consistent with the long-standing commitment of the Meteorological Office to improve the accuracy of archived weather data.

The objective adjustment involves the calculation of daily adjustment factor g/r (g and r are daily totals measured by gauge and radar respectively) at the location of the gauge observations, interpolating between these by surface fitting to the location of each 5 km grid point and applying the estimated adjustment factors to the grid-point radar values. This alters the radar data on a scale comparable with the spacing between the gauges, but leaves the shape of smaller features between gauges unaltered. Adjustment factors outside the range 0.1 to 10.0 and ones based on too small values of r and g are rejected. The adjustment is applied to the data from each radar separately.

For both off- and on-line processing the sparse daily gauge observations used for this adjustment are those from the synoptic gauge network received a few hours after 09 GMT each day.

The result of the adjustment process is a set of single-site daily radar totals adjusted by sparse gauge observations.

4.3 Compositing

In order to reduce data storage requirements, and to facilitate the use of the data generally, a composited version is now produced to give a single field of rainfall totals by eliminating overlaps between the coverages of adjacent radars. This is done using a previously specified set of boundaries, but with alternatives if the data from a particular radar are missing altogether, to maximize radar coverage. This product is a set of composited daily adjusted radar totals.

If compositing is carried out on unadjusted data (and the raw data from two adjacent radars can be very different in the overlap area) then sharp boundaries can be produced which cannot be removed by subsequent gauge adjustment because they are small-scale features. Adjustment before compositing suppresses these boundaries, in contrast with the compositing after on-site calibration (but without any further gauge adjustment) which takes place in the production of the Network composited radar picture sent to forecasters, and is an important feature of PARAGON.

4.4 Further adjustment by dense gauge observations

Off-line hourly radar totals are received after a delay of a few weeks by which time the daily gauge observations from the dense climatological network are available. These daily gauge observations arrive at the Office by post or magnetic tape and are then subjected to a lengthy quality control. This further adjustment of the composited off-line radar data by the dense gauges is carried out exactly as described previously for sparse gauges, the intention being that the increased amount of gauge data should improve the accuracy of the final product.

4.5 Gauge-only data fill-in

Areal averages for $5 \text{ km} \times 5 \text{ km}$ squares, in areas not yet covered by radar data, or where the data have been deleted because of contamination by occultation or clutter, are estimated directly from sparse or dense gauge observations as appropriate to give completeness of data coverage. In this process the spatial distribution of average annual rainfall (AAR) is used in the adjustment, in effect, as a substitute for specific radar data for the day. Since gauge observations are always used with interpolation between them by radar data or AAR, a uniformity of accuracy of the two resulting types of fields interspersed over large areas can be obtained.

The product is stored in the final data set of combined fields of adjusted daily radar totals with gauge fill-in; gauge-only derived amounts are distinguished from gauge-plus-radar derived amounts by a negative sign.

5. Sources of hourly radar rainfalls and storage of data

Hourly radar rainfalls would be available to PARAGON from two sources for use in the two time-scales.

For off-line processing 5-minute intensity measurements are recorded on magnetic tape at each radar site independently for each grid point. These tapes are retrieved within 2–3 weeks of recording and processed into hourly totals by integrating 12 successive intensities. These totals should be the more accurate ones available from radars because this frequent sampling rate can account for more rapid changes in intensity.

For on-line processing every third set of single-site 5-minute data is also transmitted to Bracknell from each radar via direct telecommunication links to the RADARNET computer before compositing and transmission to forecasters as the Network composited pictures. Originally it was planned to transfer these 15-minute single-site observations to COSMOS in real time for processing to hourly totals at each grid point, by integration of four successive intensities. These hourly totals would be less accurate as radar data than the ones derived from the recorded data because of the lower sampling rate, but this is unlikely to be a serious source of error apart from occasions when the rainfall intensity is changing rapidly.

The general strategy of data storage is that on-line data would be automatically stored to be replaced later by the off-line data, which are expected to be of higher quality. There would be exceptions to this if for instance off-line data were partially or completely missing due to on-site recorder malfunction, in

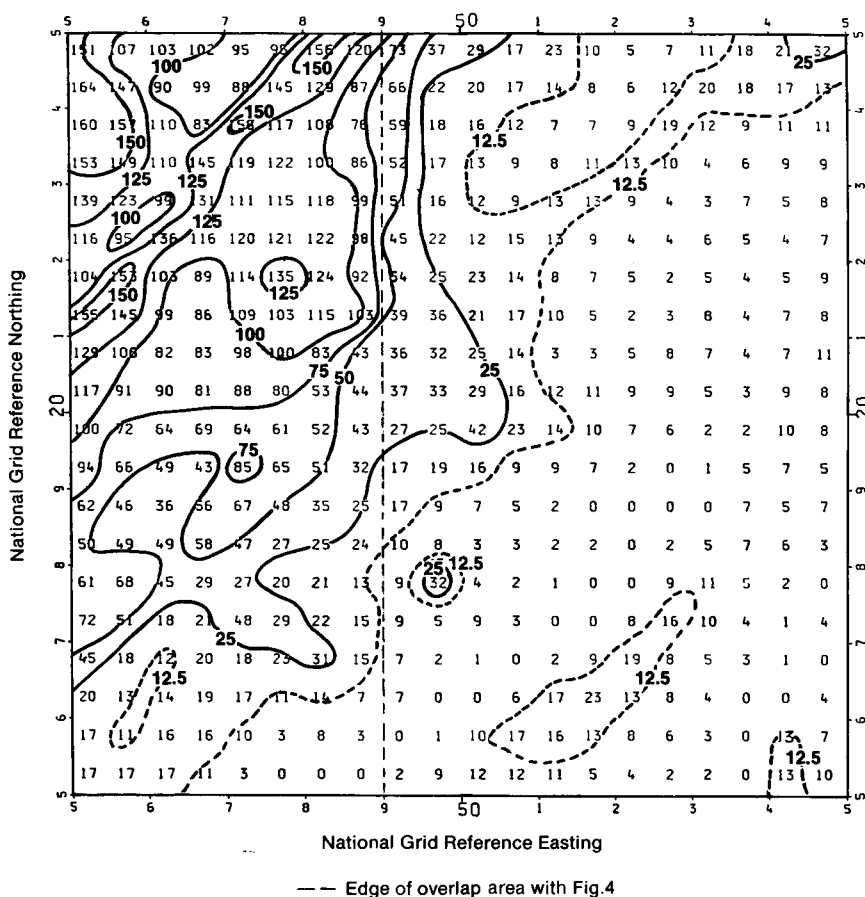


Figure 3. Unadjusted rainfall totals (units of 0.1 mm) measured by Chenies radar for the rainfall day commencing 09 GMT on 7 April 1987.

which case the on-line data would be retained for completeness. Until the on-line system is fully operational a procedure exists whereby the processing of off-line data for periods of outstanding interest can be accelerated, but this causes disruption of the routine processing of the radar-site magnetic tapes.

6. Output from PARAGON

6.1 Data output

A block diagram of the complete PARAGON system is shown in Fig. 1 with the data sets after each processing stage arranged in order down the centre. The contents of these data sets can be printed as fields of grid-point rainfall totals on fiche, page print-out or film, or produced in contoured forms. Examples of grid-point fields of radar observations unadjusted, and adjusted by sparse gauge observations with gauge fill-in (all 5 km square areas average), are shown in Figs 3 and 4. Two overlapping 100 km squares are shown such that the left-hand portion of the square in Fig. 3 coincides with the right-hand portion of the square in Fig. 4, the overlapping area being bounded by dashed lines. Fig. 3 shows the unadjusted radar data from the Chenies radar which is located at the centre of the

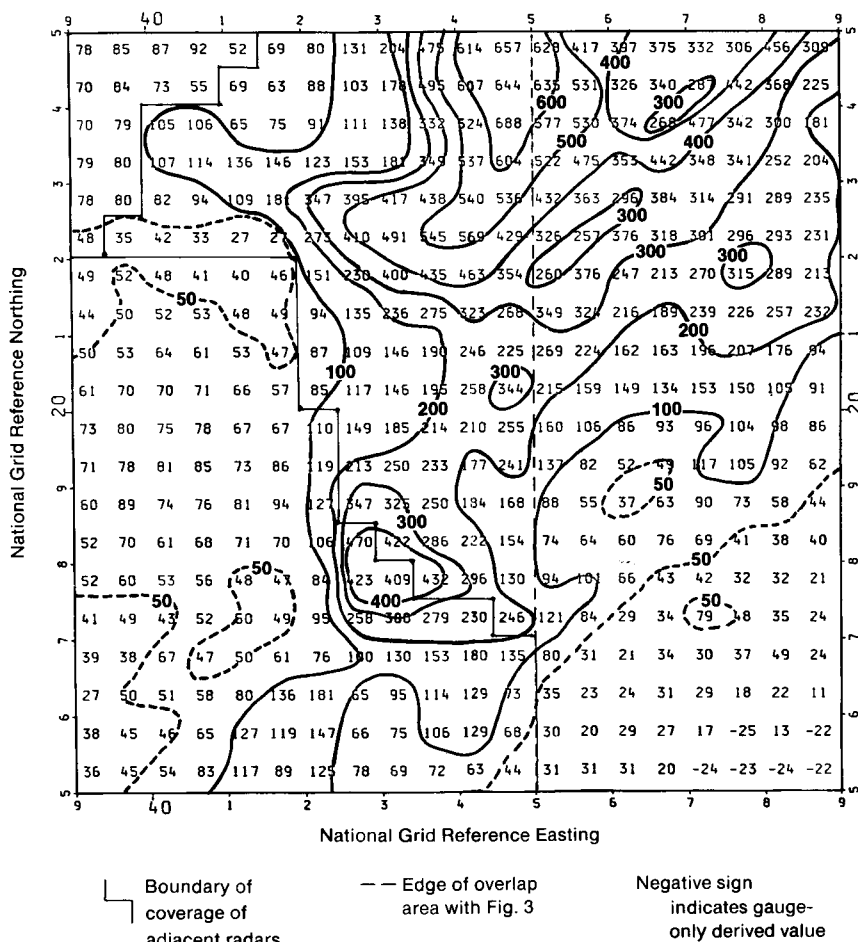


Figure 4. Radar rainfall totals adjusted by observations from sparse gauges (units of 0.1 mm) for the rainfall day commencing 09 GMT on 7 April 1987.

square. Fig. 4 shows the radar data adjusted by the sparse gauges and composited, according to the indicated boundaries, with the Chenies data to the right, Upavon data to the lower left and Cleve Hill data to the upper left of the square.

In the overlap area (all Chenies data) it can be seen that the effect of adjustment is to leave the smaller-scale detail of the rainfall field unchanged while altering the absolute values on the larger scale, in this case increasing the rainfalls by a factor of about 2 to the south but nearer 3.5 to the north. The peak of rainfall to the south-west of the centre of the square in Fig. 4 shows no influence on the isohyets of the composite boundary between the Chenies and Upavon adjusted radar data. A small area in the south-east corner of the square in Fig. 4 shows some gauge-only values which are consistent with neighbouring radar-derived values.

6.2 Diagnostic output

Information regarding the data, such as availability, quality, changes to radar-site hardware and software and its off-line or on-line status is contained in MINILOG (Banks 1985, Crummay 1984).

Quarterly Radar Data Assessment Reports are produced giving up-to-date summaries of this information (Banks and Crummay 1985). A full technical description of data sets, processes and computer programs comprising the system is contained in the *PARAGON users' handbook*.

7. Future developments

7.1 Selective use of radar data

At present, the adjustment procedure using sparse gauge observations is applied to all radar values within the area of coverage of valid adjustment factors. No consideration is made as to whether or not a better estimate of the surface rainfall at a grid point could be obtained by direct interpolation between the gauge observations without the use of radar data at all, as described in section 4.5. The choice of which is the better of the two sparse gauge-derived estimates is a matter of assessment of probability which depends on the quality of radar data and the nature of the rainfall fields in the vicinity (May 1986).

Algorithms to determine the choice at each grid point and their success are being investigated in the Advisory Services Branch of the Meteorological Office.

Investigations have been made of the differences between fields derived from dense gauges only and from radar observations adjusted by dense gauges. First indications are that the small inter-gauge spacing eliminates the contribution of radar data to a great extent and so it is possible that in future the routine adjustment of radar data by dense gauges will be omitted from PARAGON.

7.2 Use of Network composite data for on-line operation

It now appears unlikely that a system to transfer single-site radar data in near real-time to COSMOS can be implemented before at least 1990 because of data volume restrictions. Therefore on-line PARAGON processing, as originally conceived, cannot proceed before then.

The requirement for improved near real-time daily and sub-daily rainfall information is becoming more urgent, for use in MORECS (the Meteorological Office rainfall and evaporation calculation system) and in general advisory services. Consequently it is now planned, as an interim measure, to use the 15-minute Network composited radar data already available in COSMOS as the basic data for PARAGON. The benefits of the 'adjustment before compositing' feature of PARAGON would have to be sacrificed but adjustment by gauges will be retained as a means of quality controlling the radar data.

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Observations of noctilucent clouds from Ben Nevis Observatory

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Summary

Noctilucent clouds were regularly seen from Ben Nevis Observatory during part of its lifetime. Notes about the clouds were entered in the logbooks but have remained unpublicized, apart from having appeared within the log entries reprinted in the *Transactions of the Royal Society of Edinburgh*. This article brings to light the occasions when the clouds were observed from the Ben, together with descriptions, largely as the observers wrote them, of the more significant sightings.

1. Introduction

Noctilucent clouds (NLC) are tenuous, brilliant, silvery clouds visible against the twilight sky because they are being illuminated by sunlight when the sun is below the observer's horizon. At a mean altitude of 82 km in the coldest part of the atmosphere (called the mesopause) where temperatures can reach -140°C , these luminous 'night' clouds, at ten times the average height of cirrus, are the earth's highest clouds. They are believed to consist of meteor particles, or possibly ions, around which are deposited minute crystals of ice, accounting for the high reflectivity. Although NLC are regularly seen by those who enthusiastically scan the summer twilight skies, one surprising feature of the clouds' history is that they were virtually unknown before 1885. It was only in that year that they were widely recognized when



The Ben Nevis Observatory in summer.

there were extensive and brilliant displays visible from the British Isles, other parts of Europe, and Russia. But why astronomers and meteorologists did not record them with certainty beforehand is still a mystery.

One place from where NLC were 'discovered' in 1885 was the Ben Nevis Observatory. Being at a latitude of 56.8° N (almost midway within the best range of 50–65° N) it was well situated for observing them. They were recorded in subsequent years by the skilled observers of the Ben's essentially meteorological establishment which was in existence from 1883 to 1904. The observatory's altitude, 1343 m (4406 ft) at the mountain's summit, provided an excellent vantage for observation. These sightings, including any considered to be possibilities, are listed in Table I. However, in order to place the first Ben Nevis observation of NLC into perspective, it is necessary to outline when the clouds were first seen elsewhere in 1885.

Table I. *Dates of noctilucent cloud observations with notes, including possible sightings, from Ben Nevis Observatory 1884–96*

Date — night of			Notes	Date — night of			Notes
1884	July	1/2	Possible only	1888	June	30/1	Very bright
1885	June	6/7	Possible only		July	7/8	
	July	1/2	First 'pearly Ci'	1889	May	26/27	To 70° altitude
		29/30	Possible only		June	6/7	
1886	June	2/3	Almost certainly			7/8	
		17/18	Almost certainly			9/10	
1887	June	13/14	Confirmed as NLC			10/11	
		24/25				17/18	
		25/26				21/22	
		28/29	To 30° altitude		July	2/3	
		29/30	To 20° altitude			3/4	
	July	5/6				4/5	
		17/18	Not following sun	1890	May	26/27	Notes taken
		20/21			June	28/29	
1888	June	4/5			July	15/16	Notes taken
		5/6				16/17	
		15/16	To 80° altitude	1891	July	9/10	Notes taken
		17/18	To 85° altitude			13/14	
		19/20				14/15	NLC and aurora
		21/22		1892	July	13/14	
		22/23				23/24	
		23/24				24/25	NLC or aurora
		24/25		1895	July	16/17	
		25/26	Very bright	1896	May	30/31	
		26/27					

Total: 44 positive, 5 possible

The first officially recorded sighting of NLC is credited to T.W. Backhouse, a keen skywatcher from Sunderland, who saw the clouds from Kissengen in southern Germany on 8 and 10 June, and again from there on 7 July (Backhouse 1885). They were also seen on 10 June from Prague, and on 12 June the Russian astronomer V.K. Tseraskii observed them from Moscow (Bronshen and Grishin 1976). On 23 June they were noticed by various other observers, including the German astronomer O. Jesse who saw them from near Berlin (Jesse 1890). Jesse, like Tseraskii, was a pioneer in measuring the heights of

NLC. Also, on several unspecified dates during June, the clouds were seen from Dublin, and on 6 July from Southampton and London. There were numerous other occasions throughout June and July 1885 when they were observed from Europe, particularly Germany (Vestine 1934).

2. The early sightings from Ben Nevis

NLC may have been discerned from Ben Nevis in 1884 and also in 1885, earlier than Backhouse. The possible occasion in 1884 was on the night of 1/2 July when the logbook contained this entry:

At midnight long streamers radiating from the zenith were observed. They seemed to be composed of filmy cirrus, but looked almost like an auroral arch. They were about 45° long, and reached from NE to W.

And then on 7 June 1885:

At 1 h and 2 h the sky to NNE above where the sun was, was covered with very thin cirrus clouds, coloured pearly grey and pale green. Dull orange at horizon.

Was either of these two instances NLC?

The most common general description in English referred to luminous cirrus clouds; the name noctilucent clouds had not at that time come into existence. The Ben Nevis observers had their own unique name for the clouds, and they very aptly called them pearly cirrus. Thus, on the only definite occasion of their observation from the Ben in 1885, on the night of 1/2 July, the logbook records:

Beautiful pearly coloured cirrus to northward at 23 h and midnight.

No further mention was made of the clouds that night, even though the sky remained clear, but did the observer(s) wonder about them?

There was another possible sighting on 30 July 1885:

At 1 h the whole sky was dull blue above the thick haze that covered the horizon, except to the N and NNE where a distinct path of light, coloured red and pearly grey, and bounded by a sharp well-marked line, was observed. This light was probably due to the sun, and was not auroral.

In 1886 there were only two reports but these were almost certainly of NLC. On the night of 2/3 June:

At midnight the higher cirrus clouds to northward were bright, apparently with sunlight; but the lower ones were quite dark;

and on 17 June:

At 23 h and at midnight the cirri clouds to northward shone with a bright silvery light (not auroral); the brightest parts were about 15° above the horizon.

During 1886 the clouds were well observed elsewhere in the British Isles, from such widely separated places as the Isle of Wight (as early as 28 May), Sunderland, Belfast, Dublin, Bideford, Southampton, Cumberland and Edinburgh, with the last reported sighting that year from Sunderland again (as late as 11 August).

3. Sightings in 1887–89

The next three years continued to produce many reports of the clouds, both from the British Isles generally — even as far south as the island of Sark (49.5° N) — and from Ben Nevis where the weather observers saw them on 8 occasions in 1887 and on 13 in 1888.

In 1887 they were first seen from the Ben on 13 June at 23 h when filmy cirrus, which was confirmed as being NLC, was recorded to the north. Thereafter, during June and July, the words 'pearly-white cirrus' becoming 'pearly cirrus' began to be commonly used; the observers no doubt by this time realizing that these 'cirrus' clouds were something different from the familiar variety. On the night of 28/29 June 1887, the angular elevation of the clouds was noted:

Pearly-white cirrus reaching to about 30° altitude at midnight to northward.

The following night, they were seen to about 20° altitude. An interesting remark appeared with regard to the display on the night of 17/18 July:

At night bright pearly cirrus to northward, height about 12°, highest to NNW all night, not following the sun round.

NLC do not always 'follow' the sun round; their position in the sky, as seen by the observer, depends on their relative extent and actual movement, and the sun's depression angle, as well as its azimuth.

On two nights in 1888, the clouds were observed very high in the sky. On 15 June:

Pearly cirrus seen to N at night. At 23 h it reached to almost overhead, not more than 10° from zenith, and even at midnight was about 45° above horizon.

And two nights later, it was slightly higher:

At 23 h some of it was not more than 5° from zenith.

During 1888 the clouds were observed almost exclusively in June, with only two sightings in July. Having been seen both on the night and morning of 30 June/1 July, they were thus recorded on twelve occasions in June, from which there were sightings on the six successive nights from 21/22 to 26/27 June; quite a sequence. The displays of 26/27 June and 30 June/1 July were described as being 'very bright'.

Their appearances in 1887 and 1888 were summed up by the observatory's superintendent, Robert Traill Omond, in a letter dated 2 July 1888 to the British scientific journal *Nature* which, since 1885, had carried numerous reports of the clouds. This letter was published in the issue of 5 July 1888 under the heading 'Sky-coloured Clouds at Night':

In *Nature*, June 28 (p. 196), Mr Backhouse notes the appearance of illuminated clouds to northward at night. Similar clouds are seen from here on almost every clear night near the summer solstice. For the last two years special note has been taken of them. In 1887 they were first seen at midnight on June 13, and last seen on July 20; this year their first appearance at midnight was on June 4, and they are still visible every clear night. The clouds are not, as far as I have observed, coloured, but shine with a pearly or silvery lustre. I have seen them at midnight as high as 30° altitude, but they are generally confined to the first 10° or so above the northern horizon. The facts that they vary greatly from night to night in appearance, being sometimes almost absent, and that one or two photographs that have been taken of them show them simply as ordinary cirrus clouds, all seem to indicate that they really are very high cirrus lighted by the sun.

Ironically, after this letter, the clouds were seen only once more in 1888, on 7/8 July. Omond, a careful observer, had noted their 'non-colour' and he was not misled, as was easily done, by the influence of the twilight sky background which would give the impression that the clouds were sky-coloured. Even today, noctilucent clouds are usually described as a blue-silvery colour, and occasionally as yellowish when very near the horizon due to more haze lower down, but it is nevertheless the case that the cloud particles reflect blue wavelengths more strongly than any others.

The logbook in 1888 also contained two 'negative' reports of the clouds, confirming that the observers did keep a look-out for them. Thus, on the night of 16/17 June:

N horizon dusky red at midnight, but no pearly cirrus all night;

and on the night of 11/12 July:

At midnight N horizon was faintly red, but no pearly cirrus was seen.

In 1889 the clouds were observed on ten occasions, beginning on the night of 26 May at 23 h which had become the earliest date of the year that they were recorded from the Ben. On the night of 21/22 June, they were again seen high in the sky:

Pearly cirrus was seen to 70° altitude at 23 h, and a small patch to the NNW at midnight.

Six occasions were recorded in June and three in July.

4. Sightings in 1890–92

For the sightings of the clouds during 1890 and 1891 — numbering only four and three respectively — the observers supplied, in contrast to all previous years, detailed notes relating to the clouds' position, movement and structure.

In 1890 the clouds were also recorded as early as 26 May, when before midnight two photographs of them were taken. This was the first instance that the logbook recorded any photographs having been

attempted, although Omond, in his letter to *Nature* in 1888, had mentioned that 'one or two' had been taken. This display was described as having a 'ribbed' and 'wavy' appearance through which stars could be seen. The movement of the cloud mass was slowly from the east. On 27 May, another photograph was taken, but only ten minutes later:

3 h, no pearly cirrus or any kind of cloud in sky, only faint bands and streaks of haze near horizon, and pink 'foreglow' streamers.

NLC are nowadays classed into four main types — veils, bands, waves and whirls — and from the description of the display on the night of 26/27 May 1890, the Ben Nevis observer would have seen the wave or band type or a combination of both. NLC nearly always have a motion generally from east to west across the sky, which is what the observer had noted.

After that display, the clouds were not observed for over a month, until 29 June, and thereafter they were noticed only twice more, in mid-July.

The clouds were observed for the first time in 1891 as late as the night of 9/10 July, and exact angular measurements were made:

At 23 h 5 m the highest point of the pearly cirrus was $5^{\circ} 18'$ and the lowest $3^{\circ} 14'$ above the horizon.

And on the night of 13/14 July:

Pearly cirrus seen to N at midnight, stretching from NW to NE, its highest point being then $14^{\circ} 16'$ above horizon, and its lowest limit $7^{\circ} 8'$ above same.

These measurements were made with an instrument called a stephanome which the observers frequently used for obtaining the angular radii of various sections of coronae, glories, haloes, etc. More photographs of the clouds were also taken.

No increase in the frequency of the cloud sightings occurred in 1892. The first that year, however, on 13 July, contributed to a beautiful and unusual conjunction because an aurora was observed at the same time:

At 23 h and midnight pearly cirrus was seen about 10° above NE horizon. At 23 h 30 m while watching the pearly cirrus, streaks of aurora were seen, and the cirrus seemed behind these. Spectrum bands seen in N horizon at night. Photograph taken of these and of the pearly cirrus.

The reference to the pearly cirrus being behind the aurora may imply that the aurora was nearer and thus lower in altitude, but this was only an optical illusion in the same way that altocumulus sometimes appears higher than cirrus in the same part of the sky. Auroras occur at a minimum altitude of around 90–100 km. The reference to 'spectrum bands' was not to the actual spectrum of the aurora but to a description of the form of the aurora, i.e. that it was of the 'rayed-band' variety, like curtains. However, this Ben Nevis observation was not the first of aurora and NLC together. On 27 July 1886, Charles Piazzi Smyth, the Astronomer Royal for Scotland, had recorded the two phenomena at the same time from Edinburgh, although he was confused at first — unlike the observer at Ben Nevis who knew immediately of the simultaneous occurrence in 1892.

5. Height determinations elsewhere

While the Ben Nevis observers knew that their pearly cirrus clouds were at a very high altitude, they were not able to determine what that height was. In any case, the observers would not, until some years after, if at all, have been aware that such measurements had already been made as early as the clouds' year of discovery, 1885, and even before they had first been seen with certainty from the Ben. It was in late June 1885 that Vitol'd Karlovich Tseraskii in Russia had successfully obtained a range of values from simultaneous observations, resulting in an average height of 79 km (Bronshen and Grishin 1976). Two years later, Otto Jesse in Germany, using baseline photography, gave a height of 75 km, but in 1889 he was able to refine his accuracy to values of 81 and 82 km. The Ben Nevis observers may have read Jesse's account in *Nature* (Jesse 1890), but they would not have been aware of Tseraskii's work due to its lack of publicity because it was in Russian.



Photographs of noctilucent cloud taken from Ben Nevis Observatory.

6. Observation trends

It is strange that, after 1892, the clouds were reported with certainty from the Ben only once more — in 1895 — until the observatory's closure in 1904. But there was a possible occurrence on 30 May 1896:

Some brightness in northern sky at 23 h, was not distinct enough to make it certain whether it was due to aurora or pearly cirrus.

However, this dearth generally corresponds with the low frequency of sightings of NLC from elsewhere after 1895, and the reason can only be surmised in connection with the trend as a whole. 'The period 1885–94 was particularly rich in displays of noctilucent clouds which were brightest in 1885–86 and diminished in brilliance and frequency to 1894' wrote E.H. Vestine of Canada in his historical survey of 1934. Although the greatest frequency of the clouds as seen from Ben Nevis was not from 1885 to 1886 but from 1887 to 1889 inclusive, the number of sightings from an individual station in relation to others depends on the extremely variable factor of the frequency of tropospheric clouds obscuring the noctilucent variety.

Nevertheless, with the distribution of the Ben Nevis sightings fitting the overall trend, one possible reason for the high frequency from 1885 until 1894, and the low frequency thereafter, is the suspected correlation — an inverse one — between NLC and sunspot maxima. After the 1883–84 sunspot maximum, the clouds increased in frequency until after the sunspot minimum of 1889–90, but by the succeeding maximum of 1894–95, there were few reports. However, although similar inverse occurrences have been noted from then until the present time, there is still no agreement that such a correlation can be termed conclusive. Researchers believe that the heating effect of an aurora, whose presence is proportional to solar activity, may be sufficient to either prevent the formation or cause the dispersal of NLC so that the two phenomena are rarely seen together for long. It was, appropriately enough, between a departing solar minimum and an approaching solar maximum, in 1892, that the instance of coexistent NLC and aurora was recorded from Ben Nevis.

One final point of interest was a logbook entry on 29 December 1898:

Clouds like 'pearly cirrus' seen in E sky at 7 h.

From the time of year, this was probably an observation of nacreous or mother-of-pearl clouds, which form in the stratosphere at an average height of around 30 km. They occur far less frequently than NLC.

7. Photographs

The photographs of NLC reproduced here are two of several kept in the archives of the Meteorological Office in Edinburgh. However, these photographs are generally not in good condition; there is some fading and some lack of clarity. Unfortunately, the photograph of NLC with aurora has not been found.

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Conference report

Summer School on the Diagnosis of NWP Products, Meteorological Office College, Shinfield Park, England, 6–10 July 1987

This was the second such summer school to be held at the Meteorological Office College, following the successful one on mesoscale meteorology held in 1985. The principle behind the summer school is to bring together forecasters and active research scientists, from both inside and outside the Meteorological Office, in an environment where they may share and exchange ideas, thereby enriching each other's understanding of meteorology. Over lectures, in classrooms and in the bar or out on the lawns, there was ample opportunity for meteorologists from different disciplines to get together.

Over 60 people attended the summer school which lived up to its name, as may be discerned from the group photograph. The universities were well represented, particularly at post-graduate student level, and there were four participants from European organizations. Most of the Meteorological Office representation came from the research branches. There were about ten practising forecasters and a handful of others with some forecasting experience. It was disappointing to see so few outstation forecasters; those unable to attend have missed a valuable opportunity to widen their knowledge of numerical weather prediction (NWP) products.



Participants in the Summer School on the Diagnosis of NWP Products.

As in the previous summer school, lectures were held in the mornings followed by case-study sessions in the afternoons and some evenings. The speakers were drawn from the European Centre for Medium-range Weather Forecasts (ECMWF), the Meteorological Office and the University of Reading. The scene was set by Dave Burridge (ECMWF) who reviewed the progress made in NWP in recent years and the expected developments in the near future. Alan Gadd (Meteorological Office) compared the design and formulation of the global forecast models used by ECMWF and the Meteorological Office, and Stuart Bell (Meteorological Office) compared the analysis schemes at the two centres. The foundations had thus been laid for the case-study sessions in which the working groups of seven or eight people were involved in analysing and understanding the performance of the forecast models.

The first case study was one dealing with explosive cyclogenesis where the aim was to identify the main processes taking place and the ability of the models to predict such events. It also afforded the opportunity to look at some other model output diagnostics apart from those used routinely; in

particular, potential vorticity and Q-vectors as advocated by Brian Hoskins (University of Reading) in his lectures on the theory of rapidly developing systems. This case also showed the differences in performance of the analysis schemes so there was plenty of material for the working groups to analyse. The results of using the newer diagnostics were rather inconclusive. As with most methods of diagnosis, practice and familiarity are essential for effective application so that the interpretation of potential vorticity and Q-vectors was handled better by the research workers. However, the forecasters were just as effective in their use of the more familiar NWP products. This case showed the importance of higher resolution in the models for the successful prediction of explosive cyclogenesis, a factor borne out by the Meteorological Office's experience with the fine-mesh model.

The second case study was concerned with the variability of forecasts and compared the performance of the global models from the Meteorological Office and ECMWF over an 8-day period. The background to forecast variability was provided by Tony Hollingsworth (ECMWF) in his lecture on error growth and propagation. He also demonstrated how analysis differences between forecast centres could sometimes explain a major part of forecast differences. Charts of differences between models for various fields, e.g. 500 mb height difference, can be used to trace the differences back through a forecast to find the area of origin. However, the differences at analysis time are often very small and the largest analysis differences do not necessarily become the largest forecast differences. This makes the use of difference charts to estimate forecast confidence in real time rather difficult and inexact, as the working groups were to find in the case study. The case study was useful in demonstrating that the later forecast is not necessarily the most accurate. The problem of predicting the likely skill of a particular forecast was examined by Tim Palmer (ECMWF) who demonstrated three ways in which this might be achieved. The first is to identify certain regimes where forecast skill has been found to be highest, e.g. stronger-than-average Rockies ridge. Alternative ways of predicting forecast skill involve running an ensemble of forecasts from slightly perturbed initial states or using successive forecasts to estimate variability. Elements of each of these methods can be found in current medium-range forecast practice in a subjective way, but a more rigorous formalization using a combination of three techniques is eagerly awaited. Lennart Bengtsson (ECMWF) charted the improvements that have been made in medium-range forecasts over the last ten years and suggested that the gains achieved through resolution increases are becoming less marked. This also demonstrates the potential benefit in predicting the skill of a forecast.

Forecasts of a different variety were attempted by Andrew Lorenc and Mike Cullen (both from the Meteorological Office) in their assessment of prospects in data assimilation and NWP over the next ten years. These talks generated a lively exchange about the merits of automation and manual intervention. Another area of concern is that of data and in particular the likely demise of weather ships. Peter Ryder (Meteorological Office) gave a vivid account of the kinds of decision regarding cost and impact of observing systems that are having to be made now.

Reading through the questionnaires filled in by many of the participants, it appears that most found the lectures interesting and the week stimulating and enjoyable. There were some reservations concerning the amount of material in the case studies, but even so most found the exercise worthwhile and we all appreciated the amount of effort that had gone into setting these up, mostly by Will Hand at the Meteorological Office College. The summer school is certainly a forum worth continuing. Perhaps forecasters on roster duties should pencil in July 1988 in their diaries and try to get along.

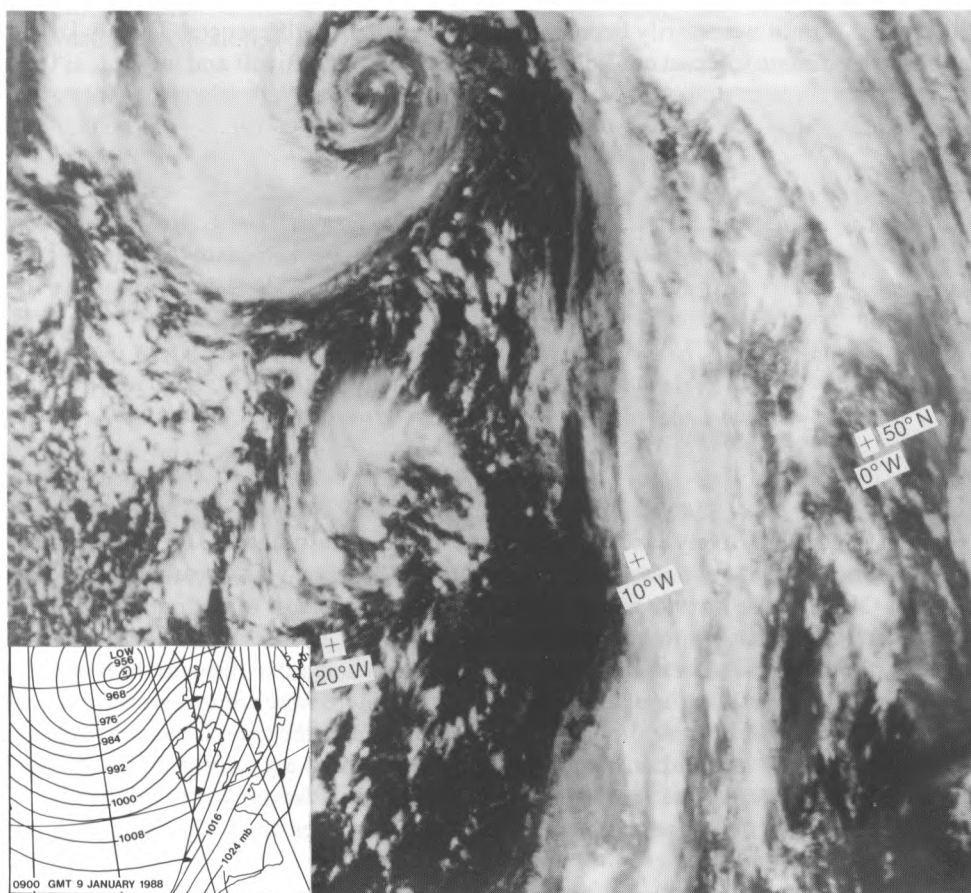
T. Davies

Satellite photograph — 9 January 1988 at 0911 GMT

This infra-red picture taken from NOAA-10, displayed on the Meteorological Office's HERMES system, has been archived as part of the Anglo-French Mesoscale Frontal Dynamics Project or FRONTS 87 experiment*. The cloud spiral near 60° N, 15° W shows an intense low that had deepened explosively during the preceding 24 hours.

At the time of the picture, the Hercules C130 aircraft of the Meteorological Research Flight was completing the second of four runs across the front (near latitude 48° N) during which dropsondes were released at intervals of 30–50 km. The measurements showed the front to be a clearly defined feature only above 800 mb. At the surface, although radar observations indicated intermittent line convection, the wind veer was only about 20° and the temperature fell by only 2 °C.

The front was the seventh of eight that were observed as part of the FRONTS 87 experiment. During the Intensive Observational Periods, considerable amounts of data were archived including measurements from three aircraft, many routine and special radiosonde soundings over the United Kingdom and France, and several high-power Doppler radars.



* Clough, S.A.; The mesoscale frontal dynamics project, *Meteorol Mag*, 116, 1987, 32–42.

Meteorological Magazine

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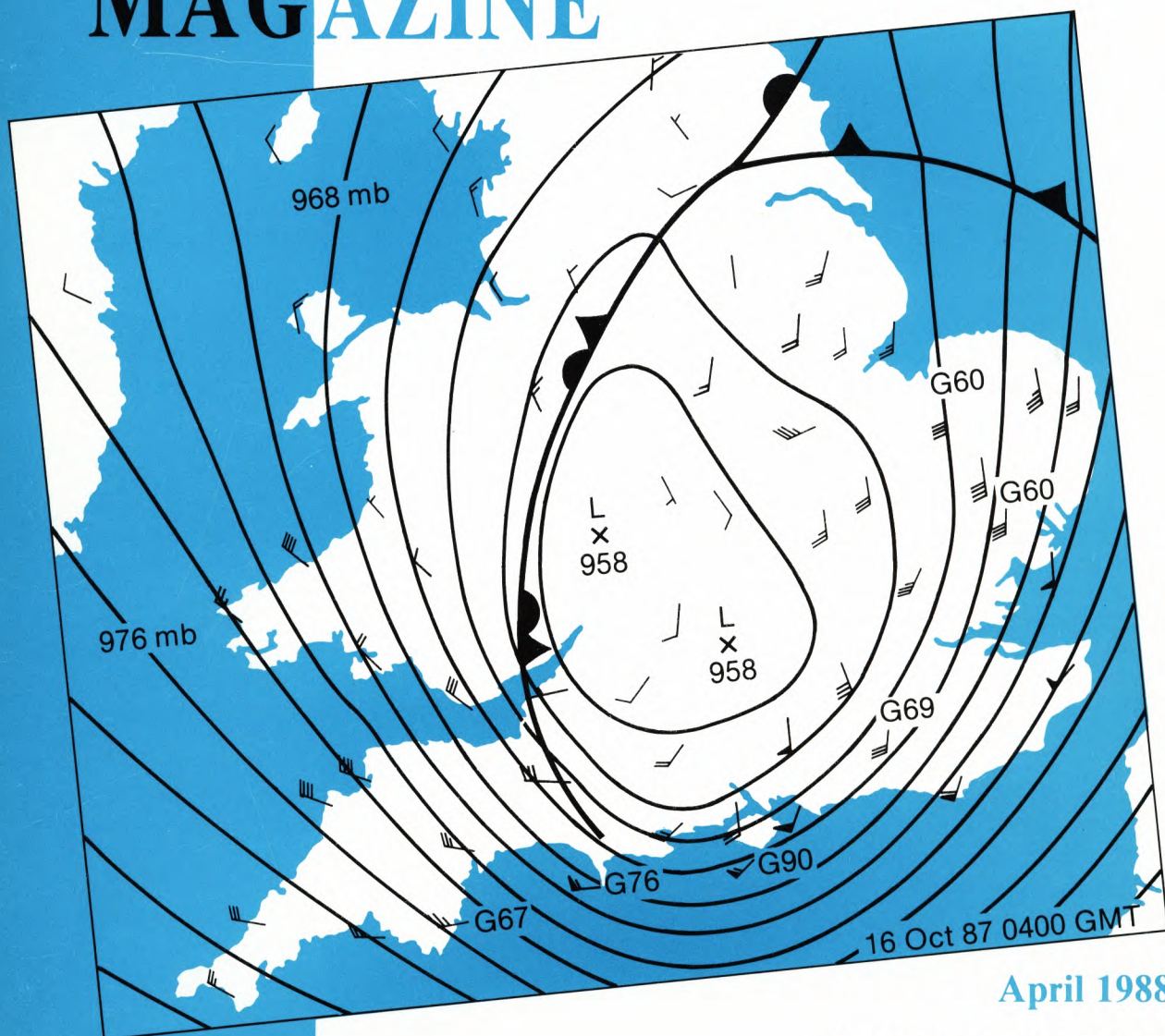
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Report on the storm of 15/16 October 1987

THE METEOROLOGICAL MAGAZINE



April 1988

HER MAJESTY'S
STATIONERY
OFFICE

Met.O.982 No. 1389 Vol. 117

THE METEOROLOGICAL MAGAZINE

No. 1389, April 1988, Vol. 117

The Meteorological Office report on the storm of 15/16 October 1987

On the 15/16 October 1987 a severe storm crossed the southern part of England and Wales, and caused much damage and disruption. In the press and media there were some criticisms of the forecasts and warnings issued by the Meteorological Office; consequently the Director-General of the Meteorological Office, Dr J.T. Houghton, set up an internal enquiry. The Secretary of State for Defence, Mr G. Younger, decided that Sir Peter Swinnerton-Dyer (Chairman of the Meteorological Committee) and Prof. R.P. Pearce (University of Reading) should consider the findings of the enquiry and report their conclusions to him. The executive summary of the report prepared by the Office is given below, and this is followed by shortened versions of the papers which appear in the report.

Executive summary

1. The situation leading to the storm of 15/16 October 1987 has been studied in considerable detail. It is clear that several discrete low centres ran north-east over Biscay before the arrival of the final low which developed into the major storm centre. Statistically the falls of pressure in front of the storm were not unusual, but the rise in pressure behind the front was exceptional, with rises of over 20 mb in three hours in places. The belt of southerly gales over land was also exceptional for the south-east in October with expected return periods of over 100 years in some areas.

2. The output from a number of relevant Numerical Weather Prediction (NWP) models was available to the Senior Forecaster in the Central Forecasting Office in Bracknell. Useful NWP guidance was given in the medium range (3-6 days) but as the time before midnight on 15/16 October became shorter the various models gave diverging guidance. The 36-hour forecasts from the European Centre for Medium-range Weather Forecasts (ECMWF), the United States and the UK global coarse-mesh model, and the equivalent 24-hour UK fine-mesh forecast, differed substantially; consequently the Senior Forecasters' guidance depended upon a compromise based on his subjective experience. In the event the emphasis was incorrectly placed on the rain and flooding problems rather than on the possibility of severe gales overland. Thus, although the guidance in the Synoptic Reviews did include gale warnings for exposed parts of southern and eastern England, the main area of severe gales was forecast for the Channel and the southern North Sea and the extreme south-east.

3. In the scientific investigations that have been carried out in the Meteorological Office following the storm, the main problems of interpretation have arisen from the paucity of data coverage, especially over the ocean areas to the south and west of the United Kingdom. The observations available during 15 October left the actual position of the storm uncertain and fell far short of providing an adequate description of the atmospheric structure in its vicinity. The prerequisites for a really accurate prediction were therefore absent. Although the general synoptic situation at the time of the storm showed conditions that strongly favoured cyclonic development, no features have been identified which would have enabled the quite exceptional character of the storm to be recognized at an early stage. Further, it was the lack of the inclusion of certain observations, which were not available at the time of the run of the fine-mesh model following 0000 GMT on 15 October, that caused that model's prediction to differ from that deduced from the run of the global model following closely after that of the fine-mesh model. The reasons for the poor predictions 12 hours in advance from the numerical model runs at 1200 GMT on 15 October have been more difficult to establish. Nevertheless, by introducing features of numerical forecasting systems at an advanced stage of development in the Meteorological Office, it has been possible to obtain good predictions of the track and intensity of the storm by selecting values of the adjustable parameters beginning from 0000, 0600 and 1200 GMT on 15 October.

4. The forecasts and warnings concerning the storm given to the public via the media began the previous Sunday (11 October) when the summary chart of the week's weather on the BBC 1 TV programme 'Weather for farmers' included a caption 'becoming very windy late in the week'. On Thursday 15 October from 0630 GMT the shipping forecasts for the Channel and southern North Sea included gale and severe gale warnings. Further warnings of severe weather were given to various authorities from 1730 GMT that evening culminating in a general FLASH message of severe gales at 0120 GMT on 16 October. Customers who could take immediate action on receipt of a warning during the night (e.g. civil and military aviation) received sufficient notice to minimize any damage that might have been sustained in severe storm conditions. Although strong winds were mentioned especially for the coastal regions in the south and south-east, the media forecasts on Thursday 15 October emphasized the rain predictions rather than the wind. No forecasts issued by the French, Belgian and Dutch weather services covered the United Kingdom; they were in line with the UK predictions as far as the Channel and the European mainland were concerned.

5. The reaction of the media in the period following the storm mostly centred on the question 'Why weren't we warned?' Press articles, based on a mistaken interpretation of remarks made to journalists both in the United Kingdom and abroad, were highly critical because they believed incorrectly that other forecasting services 'had got it right'. The TV weathermen (and the Director-General of the Meteorological Office) were put in the spotlight over the weekend, and it was only after the Press Conference given by the Director-General and his Directors on the Monday following the storm that this view subsided, giving way to the more soundly based realization that the damage to trees and property could not have been avoided however accurate the forecasts might have been. Some of the press confusion revolved around the use of the word 'hurricane' (meteorologically a 'hurricane' is a tropical revolving cyclone); the use of the word by one of the TV weathermen was particularly unfortunate, since it was picked up and exploited by the media as part of their criticisms.

Summary of weather pattern developments of the storm of 15/16 October 1987

A. Woodroffe

Meteorological Office, Bracknell

Summary

A descriptive account is given of the development of the storm of 15/16 October 1987, incorporating analyses of the surface pressure pattern prepared 'after the event' using all available data. The analyses reveal a complex evolution with a series of relatively innocuous low centres running north-eastwards across Biscay before the arrival of the final low which developed into the major storm

1. Introduction

The sequence of developments of the storm of 15/16 October 1987 will be described by a series of mean-sea-level pressure analyses. These analyses have been constructed using all sources of information, some of which were not available to the forecasters at the time — they will be referred to as the finalized analyses. The operational mean-sea-level pressure analyses produced by the Central Forecasting Office (CFO), that is those charts drawn within 3 hours of the time of origin of the data, constitute a second series of charts which will be referred to where significant differences are apparent when compared to the finalized analyses.

2. 0000–0600 GMT on 15 October

Fig. 1, which is almost identical with the CFO operational analysis, shows a complex area of low pressure at 0000 GMT on 15 October extending over several hundred miles to the west of Corunna. There were few ship reports to fix the details of the pressure pattern precisely; the analysis therefore depended heavily on the Meteosat imagery and a single ship report giving a northerly wind near 44° N, 13° W.

The Meteosat imagery indicated rapid eastward movement of the main cloud features during the next 6 hours. The finalized surface analysis for 0600 GMT (Fig. 2(a)) shows the forward low centre near Bordeaux (having degenerated into a minor feature) with a more substantial centre just to the north-

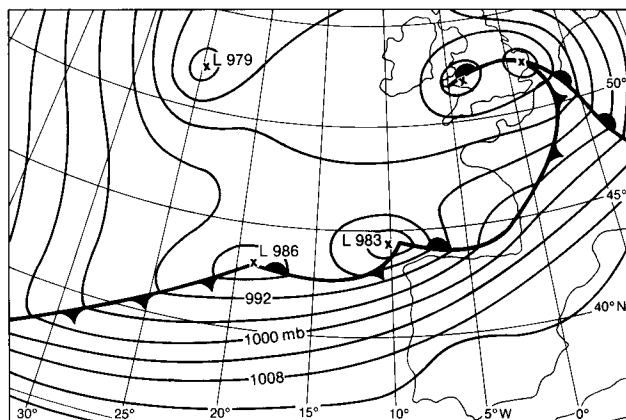


Figure 1. Finalized surface analysis for 0000 GMT on 15 October 1987.

west of Corunna. The corresponding CFO operational analysis (Fig. 2(b)) at first sight appears similar but omits the forward feature, implying only very slow eastward movement of the two low centres. Satellite imagery also suggested a further wave developing on the trailing cold front near 17° W but, with no ship reports in the vicinity, details of this feature cannot be determined with any precision.

3. 1200 GMT on 15 October

At 1200 GMT on 15 October (Fig. 3(a)), the position of the surface trough just to the south-west of Brittany was fixed reasonably well by ship reports available at the time of the operational analysis but further west the position and depth of the individual low centres were not determined very precisely. However, both the satellite imagery and the complete set of ship reports suggest that the main low centre was probably north-west of Corunna, estimated depth 968 mb, but the exact details of the analysis to the west of the centre were unclear. Comparison with the CFO operational analysis (Fig. 3(b)) reveals minor differences, the latter analysing an elongated low centre slightly further north-east, central pressure 970 mb. Pressure gradients were very strong on the south-eastern flank of this low and ahead of the trailing cold front, consistent with several reports of winds of 45–55 kn in that sector. The Meteosat imagery also showed signs of a further low pressure centre on the cold front near 42° N, 15° W; by following the imagery through it appears that this feature ran rapidly north-east and was associated with the development of the storm centre.

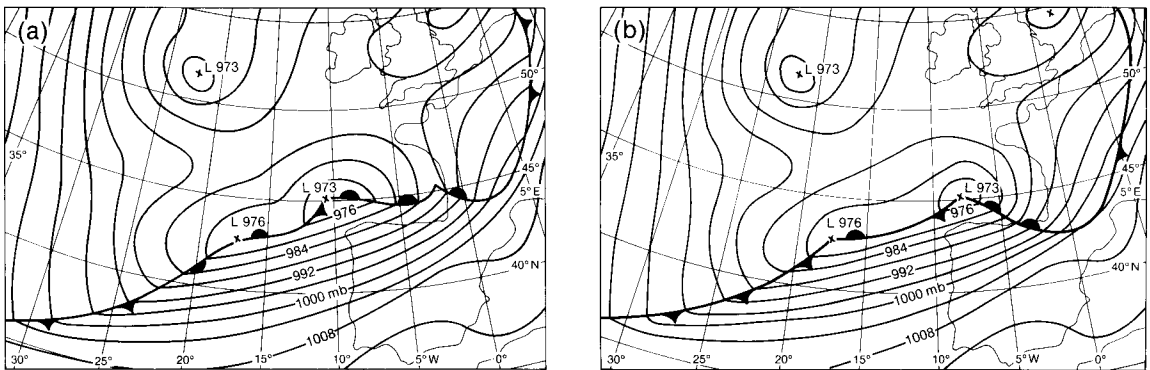


Figure 2. (a) Finalized and (b) CFO operational surface analyses for 0600 GMT on 15 October 1987.

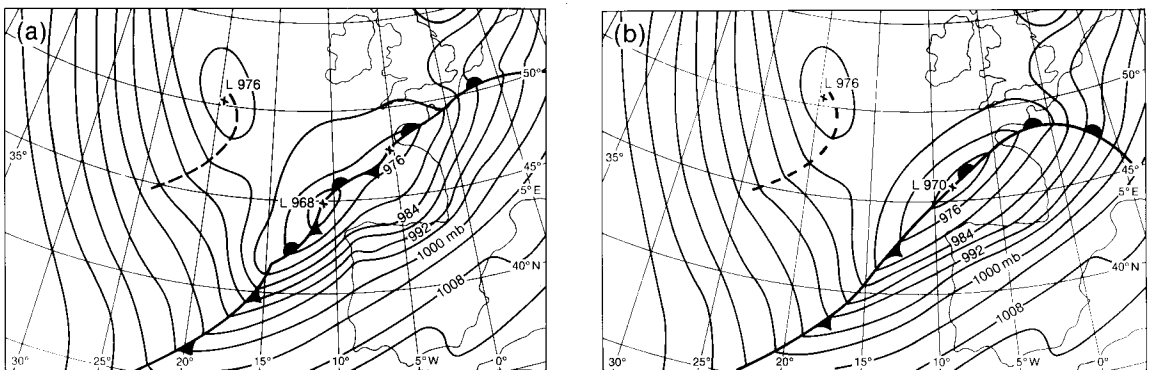


Figure 3. As Fig. 2 but for 1200 GMT on 15 October 1987.

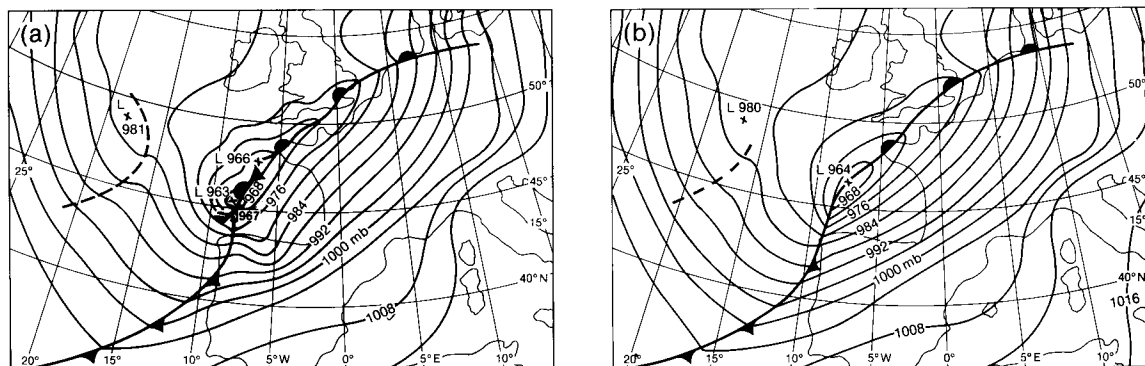


Figure 4. As Fig. 2 but for 1800 GMT on 15 October 1987. A selected ship's pressure (mb) and wind are plotted.

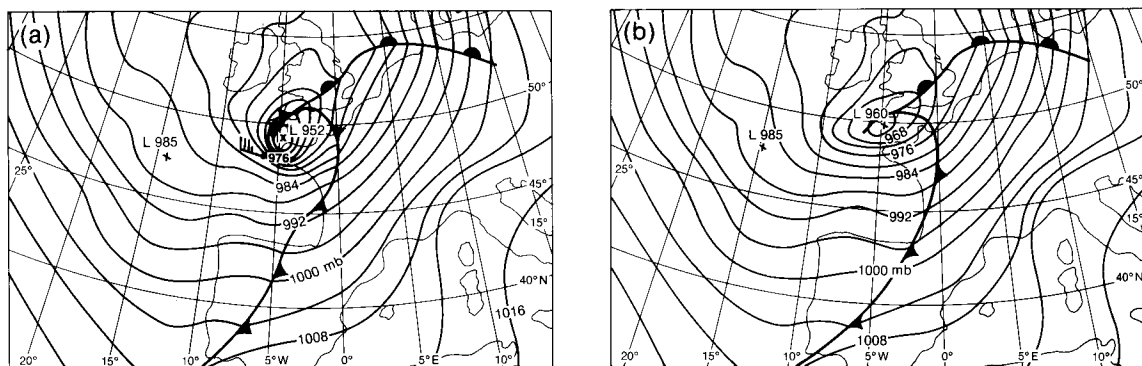


Figure 5. As Fig. 2 but for 0000 GMT on 16 October 1987. A selected ship is plotted as in Fig. 4.

4. 1800 GMT on 15 October

By 1800 GMT (Fig. 4(a)), the surface observations indicated that the low pressure centre was developing into a vigorous feature near 45° N, 8° W with winds of 60 kn ahead of the cold front. The CFO operational analysis (Fig. 4(b)) did not define the two separate centres over Biscay but again showed a single elongated centre, probably the best that can be expected given the time available for the analysis and the scale of the charts. Nevertheless the very strong gradients ahead of the cold front were well represented in the drawing.

A selected ship which was also near 45° N, 8° W at 1800 GMT has subsequently provided evidence confirming the position of the cold front deduced from satellite imagery. Although the surface pressure reports from the vessel consistently appear about 3 mb too high in relation to surrounding data, the barograph trace received well after the event shows a marked pressure minimum at 1800 GMT with a fall of about 12 mb in the preceding 3 hours. All the evidence suggests that the low pressure centre passed just north-west of the ship at that time. It should also be noted that there is evidence, from the various wind reports, of a marked trough developing in the cold air behind the front.

Although there are no ship observations in Biscay to help with the analysis at 2100 GMT, the sequence of Meteosat images shows a marked circulation developing in the cold air to the south-west of Brittany

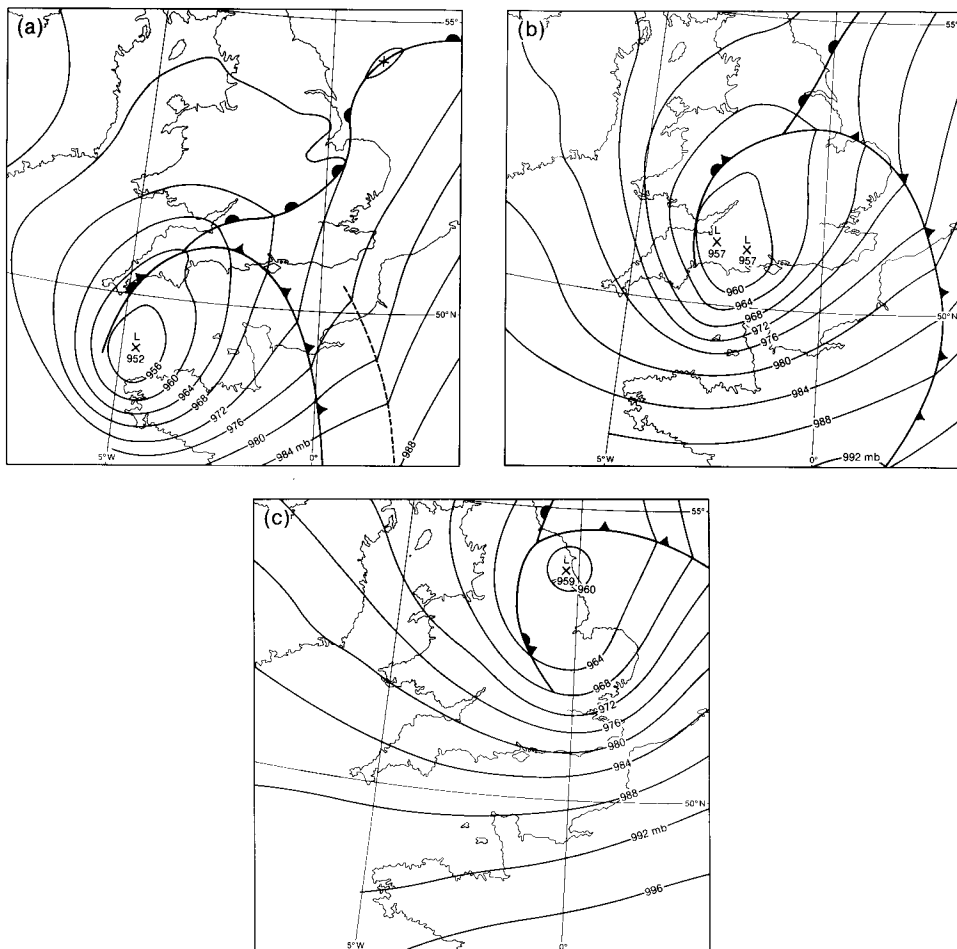


Figure 6. UK surface analysis for (a) 0000 GMT, (b) 0300 GMT and (c) 0600 GMT on 16 October 1987.

at this time with strong gusts of 72 kn being reported over Brittany ahead of the approaching cold front. Thus, although a forward low centre was evident over the western English Channel, as depicted in the UK surface analysis at the time, the main storm centre was still south-west of Brest.

5. 0000 GMT on 16 October

The finalized surface analysis for 0000 GMT on 16 October is shown in Fig. 5(a), the storm centre now being analysed in the south of sea area Plymouth, estimated depth 952 mb. This is slightly further south and 8 mb deeper than the CFO operational analysis (Fig. 5(b)), the difference arising because the crucial observations from Ushant and Ile de Batz were not received in CFO for the operational analysis. Observations at this time indicated that winds had reached 45–55 kn in the western and southern sectors of the depression and there were reports of 45–50 kn also along the English Channel to the east of the centre. Winds reached gale force along parts of the south coast at about this time. However, the lack of observations from Brittany meant that the forecasters were unaware of the exceptional gust of 95 kn recorded on the north French coast at that time.

A notable feature of the analysis in Fig. 5(a) is the exceptional pressure gradient drawn to the south of the centre with geostrophic gradients exceeding 300 kn in the strongest zone. This analysis hinges on the report from the ship at 48° N, 6° W. Although the pressure characteristic is clearly wrong (a rise of 13 mb would fit with the 2100 GMT analysis) the ship does not appear on the CFO list of unreliable ships. Later observations from the ship appeared satisfactory and with geostrophic gradients of well over 200 kn evident in the English Channel a few hours later, it seems likely that the drawing is not too far from the truth.

6. Detailed surface analyses

The detailed surface analyses (Fig. 6) over southern Britain and the English Channel show that, as the storm approached the English coast, two separate centres became apparent with relatively light winds in the vicinity of these centres and to the north of them. The very strong winds lay in a belt through the eastern, southern and western quarters, the highest and most damaging gusts being experienced around 0500 GMT some 200 miles or so to the south-east of the centre. The crux of the forecasting problem was the prediction of the location and severity of this belt of very strong winds and that problem had exercised the forecasters' minds from Sunday 11 October onwards.

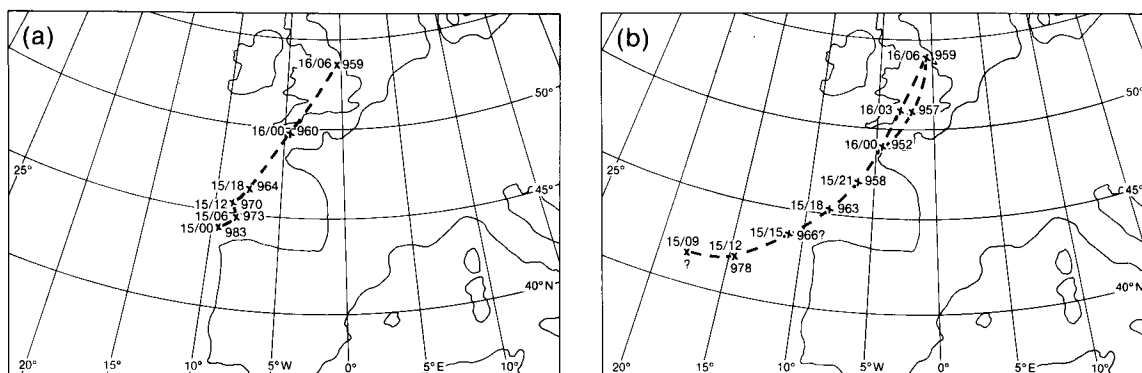


Figure 7. (a) Operational analysis and (b) finalized analysis of the storm track.

7. Conclusions

A detailed 'after the event' appraisal of all the data and satellite imagery indicates that several discrete low centres ran rapidly north-east over Biscay before the arrival of the final low which was associated with the major storm development. Tracking of the centre depicted on the CFO operational analyses (Fig. 7(a)) suggests slow north-eastward transference of the low across southern Biscay up to 1800 GMT on 15 October, followed by a rapid acceleration towards the United Kingdom. In reality it was different low centres which were being followed and this explains the inconsistent movement. In contrast the deduced track and depth of the developing low centre present a very coherent pattern (Fig. 7(b)), the chart revealing relatively steady deepening of the centre as it tracked from west of Iberia to the western English Channel. However, it must be recognized that, even now, some doubt still exists concerning the precise details of the analyses, depending as they do on subjective interpretation of the satellite imagery and the assessment of the reliability of the various ship reports.

Acknowledgement

The author would like to thank B.A. Hall of the Central Forecasting Office, Bracknell for his assistance in the preparation of the analyses.

A detailed description of wind and weather during the passage of the storm of 15/16 October 1987 across southern England

Advisory Services Branch

Meteorological Office, Bracknell

Summary

A violent storm with mean winds to hurricane force for a while in some, mainly coastal, areas, crossed southern areas of Great Britain on 16 October 1987, leaving a trail of destruction in its wake. A detailed description of the wind, pressure and temperature experienced at individual locations in southern England during the passage of the storm is given. The extreme values of wind and pressure experienced are also put into perspective by comparison with historical events.

1. Introduction

The passage of the depression on 15/16 October 1987, accompanied by violent storm force winds and heavy rain over southern England, caused chaos. An estimated 4 million cubic metres of timber were lost, many trees crashed into power lines, bringing them down and many fell across roads and railway lines, leaving a large part of southern England with no electricity, and no services on many parts of British Rail and the London Underground system. Damage and disruption caused by the high winds was reported from Dorset to Essex and travellers were advised to stay at home unless their journey was really necessary. The damage to power lines resulted in widespread loss of electricity. Seventeen deaths were reported as a result of the storm, mostly caused by falling trees or masonry. Structural damage was widespread and severe, including many chimneys and, sometimes, complete roofs destroyed. At Folkestone a Sealink ferry was grounded, at Dover a container ship capsized in the mouth of the harbour, and light aircraft in many places were moved about or overturned by the force of the wind. A detailed description of the wind, pressure and temperature experienced at individual locations in southern England during the passage of the storm on the night of 15/16 October 1987 is given.

2. Temperature

On the evening of 15 October a frontal zone was moving across south-east England. To the south of the frontal zone the air was mild, with temperatures between 14 and 17 °C, and the wind direction southerly to south-westerly. To the north of the frontal zone the air was much cooler, between 5 and 7 °C, and the winds were blowing from the north-east.

As the warm air advanced across the country there were large changes in temperature, with rises of about 5 °C at Plymouth just before midnight and rises of about 10 °C farther to the east. The temperature changes are clearly illustrated by the thermogram given in Fig. 1(a). An analysis of the rates of changes of air temperature over various time-scales based on 15 years of data* gives extreme hourly changes in one hour of 5.6 °C in London on 13 April 1969, in a showery airstream and 6.6 °C at Boscombe Down on 16 March 1972, with a ridge of high pressure across the country, the temperature rise occurring after a clear night. The rises in temperature in the early hours of 16 October 1987 greatly exceeded these previous extremes and were unusual in that they were associated with a front.

Between 0100 and 0200 GMT the temperature at Heathrow rose by over 7 °C compared with the previous highest rise in 1 hour, taken from hourly observations over 37 years of record, of 6.7 °C; this

* Laing, J.; Rates of change of air temperature in the United Kingdom in time-scales of between 1 and 6 hours, *Climatol Mem, Meteorol Off*, No. 111, 1980.

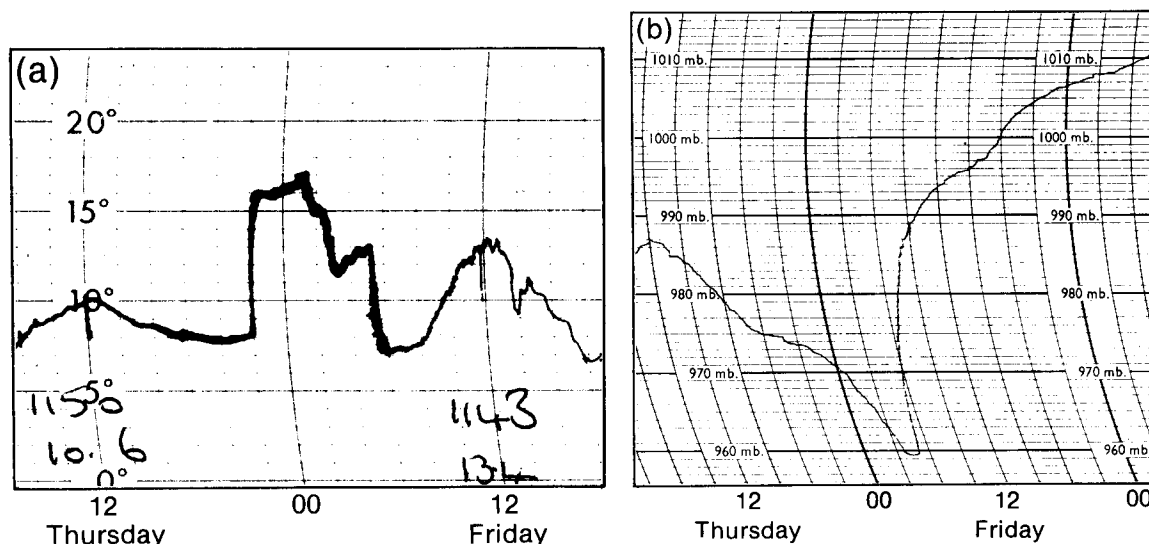


Figure 1. Autographic records of (a) temperature and (b) pressure from Bracknell for 15/16 October 1987.

was associated with strong solar heating on 26 March 1963. The previous highest frontal rise was 6.1 °C on 9 October 1951, 16 October 1952 and 7 November 1956. A preliminary study of previous rises shows that a rise of over 7 °C in 1 hour at Heathrow is a very rare occurrence.

3. Pressure changes

The hourly pressure changes in south-west England at the start of the storm show that the falls of pressure, before the front went through and ahead of the storm centre, were by no means unusually steep and looked no different on the barograph from many other pressure falls preceding strong gale or storm force winds. In fact, in the south-west the pressure fall on the previous day (0900–2200 GMT on 14 October) was greater than the fall on 15 October and more rapid. However, the rise in pressure after the passage of the front was phenomenal, with around 20 mb rises in 3 hours in a number of places. Fig. 1(b) shows a typical barograph trace in southern England.

The highest and steepest rises in the three hours to 0600 GMT were in parts of central southern England, ranging from 19.5 mb at Bristol to 25.4 mb at Portland which is believed to be the greatest rise of pressure in three hours on record for the British Isles. The rises in the three hours to 0900 GMT in more easterly parts of England were steep, but not quite as steep as in southern areas, although in most of East Anglia pressure rose more than 19.2 mb, the highest rise being 20.0 mb at Wittering at 0900 GMT.

4. Surface winds

For most weather forecasting purposes the wind is reported at hourly intervals usually using indicating-dial anemometers. The observer takes at least two readings of mean wind speed (each reading being over 15 seconds) within the overall period of the observation (approximately 10 minutes) and should report the average of these readings. A wind thus reported is usually referred to as a 10-minute wind.

Stations equipped with anemometers and a dial also report the highest gust in the previous hour using an anemograph trace if available. At main (0000, 0600, 1200, 1800 GMT) or intermediate (0300, 0900,

1500, 2100 GMT) hours the highest gust in the previous 6 or 3 hours respectively is reported in the routine synoptic report.

Details of the surface winds as reported by observing sites are shown in Fig. 2. These reports form part of the full weather observation made in the 10 minutes or so before the nominal hour of observation shown on the charts. Therefore the mean wind direction and speed refer to a 10-minute period preceding the time shown.

At 2100 GMT on 15 October most of southern England except the coasts of Kent and Sussex was covered by light to moderate north-easterly winds. Observers around the coasts of Kent and Sussex were already reporting stronger winds from the south or south-west.

By 0000 GMT the stronger winds had spread quickly northwards over southern England, backing to south-south-east to south. Gusts to more than 40 kn were reported over some inland areas and gusts to over 70 kn occurred at a number of coastal stations.

Between 0200 and 0600 GMT, most areas experienced their strongest winds. Particularly noteworthy are the gusts of 80–90 kn shown on the charts for the hours ending 0400 to 0600 GMT over the area south of an approximate line from London to the Isle of Wight. Gusts to 82 kn were recorded in London between 0200 and 0300 GMT, but stations along the coast and in the Thames estuary recorded gusts exceeding 90 kn at times, especially between 0300 and 0500 GMT.

By 0600 GMT most of England south of a line from Bristol to The Wash was covered by a broad belt of very strong winds. The wind direction had veered to south-west or west by this time as the depression moved away across Humberside. By 0900 GMT the winds had moderated over most areas except northern parts of East Anglia.

In the region of most damage, roughly south of a line from Southampton to Ipswich, maximum gusts occurred about 0300 and 0600 GMT. Gusts of 70 kn or more were reported for three or four consecutive hours during which time the mean wind veered from 180 to 230°. To the north-west there were two periods of high gust speed separated by a clear drop in wind speed. The first peak was associated with mean winds from between 170 and 190°, the second with a direction of around 230°. Strongest gusts were mostly in the southerlies between 0200 GMT (over central southern England) and 0400 GMT (over East Anglia). Over Dorset and Somerset and north of a line from Bath to Norwich the west to south-west winds were strongest, with maximum gusts around 0500 GMT in the west and 0800 GMT in the east. A separate area of strong northerly winds affected Cornwall from midnight to about 0200 GMT.

The ratio of the maximum gust to the hourly mean speed at the hour in which the gust occurred is used as an index of the gustiness of the wind. At an inland rural site, free from obstruction and at 10 m above the ground, a typical value of the gust ratio in strong winds is about 1.6 with a standard deviation of 0.10. In the storm of 16 October a number of much higher values of the gust ratio were noted (see Table 1), but in general the ratios were within the range of ratios for the relevant sectors.

Table 1. *Highest mean wind and gusts, and the gust ratio, at anemograph stations with the highest gust ratio on 16 October 1987 (Bristol's gust was very isolated and may have been a freak effect, Southampton and Ashford have non-standard exposures, and Ashford's wind speed was estimated)*

Station	Highest mean (degrees/kn)	Time (GMT)	Highest gust (degrees/kn)	Time (GMT)	Gust ratio
Bristol	270/23	0500	270/66	0530	2.9
Southampton	170/30	0200	170/75	0215	2.5
Gatwick	210/34	0400	210/86	0430	2.5
Ashford (Kent)	190/38	0400	—/92	0440	2.4

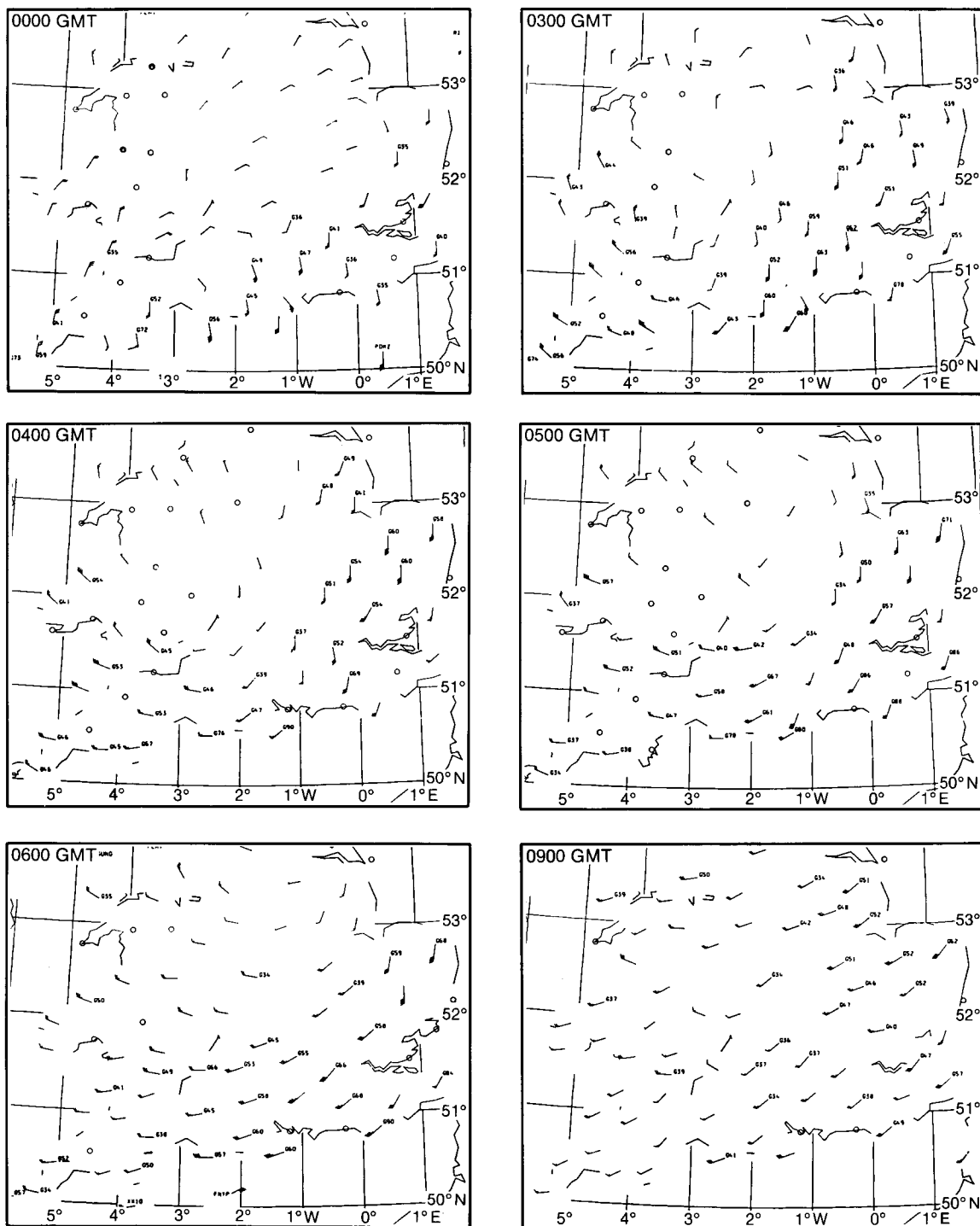


Figure 2. Mean wind speeds and maximum gusts reported on 16 October at the times shown.

5. Frequency of occurrence of wind speeds

An assessment of how unusual were the wind speeds recorded on 16 October 1987 may be reached using extreme value analyses of the past records from anemograph stations. Estimates of the average frequencies of occurrence ('return periods') of the maximum gust and maximum hourly wind speeds were made for a selection of stations within and bordering on the areas most severely affected. To enable the most reliable estimates to be made, the choice of stations should be restricted to those with long records. However, in order to improve the spatial coverage, it has been necessary to use data from some stations having less than 30 years of record. Any changes in the exposure of the anemographs during the period of analysis were accounted for by correcting all the annual maximum wind speeds used to a common effective height. The results are shown in Fig. 3. The analysis periods used were principally those ending in 1986, but further analyses were carried out for six of the stations using the maximum speeds on 16 October 1987; the influence of the speeds on 16 October resulted in relatively small decreases in return period. The following conclusions may be drawn.

- (a) At several stations, including Shoeburyness where continuous records span over 60 years, wind speeds on 16 October exceeded the previous highest recorded.
- (b) To the south-east of a line from the coast of East Anglia through southern London to Southampton Water, the return periods of both the maximum gust and the maximum hourly mean speed exceed 200 years.
- (c) There is a marked gradient in the distribution of return periods, corresponding to the line mentioned earlier from East Anglia to Southampton, so that to the north-west of London the speeds were much less exceptional, with return periods generally less than 10 years.

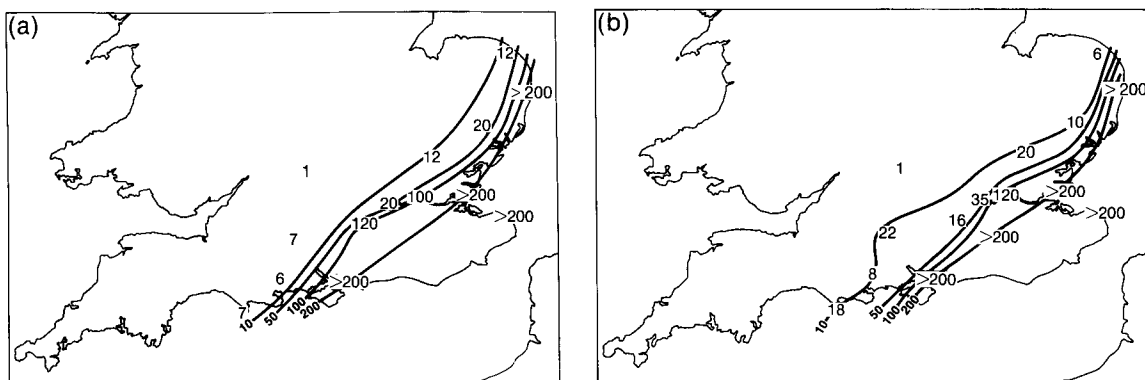


Figure 3. Estimated return periods (years) of (a) highest mean winds and (b) highest gusts on 16 October 1987.

6. Seasonal and directional factors affecting the frequency

In view of some of the damage caused to trees in leaf, it is of interest to assess the frequency with which such wind speeds occur in October. It is not statistically sound to analyse the highest speed recorded each October to produce return periods, since there are insufficient data for the analysis techniques used, but some indication of the rarity of the speeds on 16 October may be gained from a ranking of these with previous Octobers. This is done for a selection of stations in Table II. At almost all stations the speeds on 16 October were the highest ever recorded in October. The exception is Jersey, where there were localized very strong winds on 9 October 1964.

The previous highest gust in the last 50 years inland over southern England and East Anglia when trees were likely to have been in leaf was 70 kn at Boscombe Down (24 October 1945). Dover recorded

Table II. *Highest wind speeds (kn) recorded in October*

Station	Year of first record	Hourly mean speed			Gust speed	
		16 Oct.	Previous highest and year		16 Oct.	Previous highest and year
Boscombe Down	1932	39	38 1967		70	70 1945
Gatwick	1960	34	32 1967		86	56 1971
Gorleston	1913*	68	41 1926, 1955		106	68 1976
Heathrow	1959	39	34 1959		66	52 1959
Jersey	1958	55	68 1964		85	94 1964
London Weather Centre	1965	42	30 1971, 1983		82	57 1981
Manston	1967	58	42 1967		86	64 1967
Shoeburyness	1913	56	49 1967		87	74 1949

* There are gaps in the records for this station

79 kn on 27 October 1959 and 80 kn on 4 November 1957. The storm which produced a 94 kn gust at Jersey on 9 October 1964 did not affect southern England.

Since the strongest winds in the United Kingdom are usually associated with directions from about 230 to 280°, the occurrence of high hourly mean winds and gusts from directions 170 to 190° appears to be unusual. However, this is not easy to check, since no long records are available of the highest speed per year, analysed for individual wind directions. Hourly records of wind speed and direction have only been held on a computer archive since 1970. Using these data it is found that during the period 1971–83 at Heathrow, the hourly mean speed never exceeded 27 kn whilst the mean wind direction was in the sector 170–190°. On 16 October 1987 the hourly mean speed was at least 36 kn for 3 hours for a direction of 170°.

Analyses of periods of strong winds at 50 places in the United Kingdom carried out by the Building Research Establishment suggest that, for a given return period:

- (a) the ratio of the extreme in October to that for all the year is generally 0.82, with ratios for December and January close to unity (i.e. the annual maximum wind speeds normally occur in these months), and
- (b) the ratio of the extreme for sector 170–190° to that for all wind directions is generally 0.85, with ratios for 30° sectors centred on 240 and 270° close to unity, i.e. the strongest winds normally occur in these sectors.

Thus, when either the seasonal or the directional feature of the storm on 16 October 1987 is taken into account, the likelihood of having winds of this strength from these directions in October is very much rarer than the return periods of Fig. 3 might suggest.

7. Concluding remarks

There have been many severe storms over the United Kingdom causing extensive damage and with wind strengths comparable to those on 15/16 October 1987. However, winds of the reported strength are extremely rare over south-east England. Furthermore, October is not normally a month of very extreme winds, nor do extreme winds normally occur with directions between 170 and 220°. While return periods, considered on an annual basis, may have been as high as 200 years or more (e.g. Gorleston and Shoeburyness), the probability of winds of these strengths from these directions during October is a considerably rarer (and unquantifiably so) event.

Guidance available at Bracknell for the storm of 15/16 October 1987, and the forecasters' conclusions at the time

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Summary

The numerical weather prediction guidance available to forecasters at Bracknell during the period leading up to the storm is reviewed. The steps by which the forecasters reached their conclusions are explained.

1. Introduction

Forecasters in the Central Forecasting Office (CFO) at Bracknell are provided routinely with guidance from the following numerical weather prediction (NWP) models:

- (a) The UK fine-mesh regional model.
- (b) The UK global model.
- (c) The ECMWF model.
- (d) The US global model.

The two UK models are run on the Cyber 205 computer within the COSMOS computing complex at Bracknell. The European Centre for Medium-range Weather Forecasts (ECMWF) model is run on a Cray X-MP/48 computer at Reading. The US global model is used in two runs, one denoted by AVN (aviation) and the other by MRF (medium-range forecast), on Cyber 205 computers in Washington.

Certain important characteristics of the NWP guidance are summarized in Table I. The information is given separately for guidance based on 0000 and 1200 GMT starting conditions, and includes the *length* of the numerical forecast in days, the *cut-off* time for observations used to establish the starting conditions, and the time at which the numerical products become *available* in CFO.

Table I. *Characteristics of the NWP guidance routinely available at Bracknell*

Model	Guidance from 0000 GMT			Guidance from 1200 GMT		
	Length (days)	Cut-off (GMT)	Available (GMT)	Length (days)	Cut-off (GMT)	Available (GMT)
UK fine mesh	1.5	0200	0300	1.5	1400	1500
UK global	6	0320	0500	6	1520	1700
ECMWF	—	—	—	10	1930	0200–0500
US AVN	3	0345	0830–1000	3	1545	2030–2200
US MRF	10	0600	1200	—	—	—

Numerical products could also be made available from NWP models run in France and the Federal Republic of Germany. These are not used routinely at present, but some comments on guidance from the French model are included below.

During the period leading up to the storm of 15/16 October 1987, the routine NWP guidance was

available without any significant delays, and the operational work on COSMOS was run according to schedule. Some delays did occur in the early hours of Friday 16 October as a result of disturbances in the power supplies to the computers, but of course these did not affect the production of guidance in advance of the storm. Fortunately these delays were not prolonged, and did not impair the forecasters' ability to provide accurate advice during the immediate aftermath, as the storm moved away.

2. Medium-range NWP guidance

The medium range of forecasting is defined by the World Meteorological Organization as 'more than 72 hours ahead and up to 10 days'. The ECMWF and the US MRF numerical forecasts are designed specifically for this purpose. Hence they need to be run only once daily, and they use later data cut-off times to ensure that important observations are not missed. The UK global numerical forecasts are designed primarily for short-range forecasting purposes. Hence, like the US AVN forecasts, they are run twice daily with a relatively early cut-off. The UK global forecasts are, however, extended to 6 days ahead to provide additional guidance for the early medium range.

The medium-range NWP guidance for the onset of the storm was generally good. It must be borne in mind that precision is not attainable in the medium range, so the guidance is judged according to whether or not it indicates the correct general weather conditions. For example, a numerical forecast may give the wrong relative emphasis to two or more depressions moving in rapid sequence along similar tracks; this will lead to modest timing errors, but the quality of the medium-range guidance remains good.

Although it is the sequence of forecast guidance from each model run that is important in practice, attention is focused on numerical forecasts valid at 0000 GMT on 16 October. At this time the storm was fully developed with a central pressure of 952 mb in the English Channel, and the onset over southern England was imminent.

Fig 1 shows the forecast locations of the storm at 0000 GMT on 16 October and tabulates the values of mean-sea-level pressure at the storm centre according to the numerical forecasts from the UK global model, the ECMWF model and the US global model. For convenience the complete sets of forecasts, including the short-range forecasts, are given in these figures.

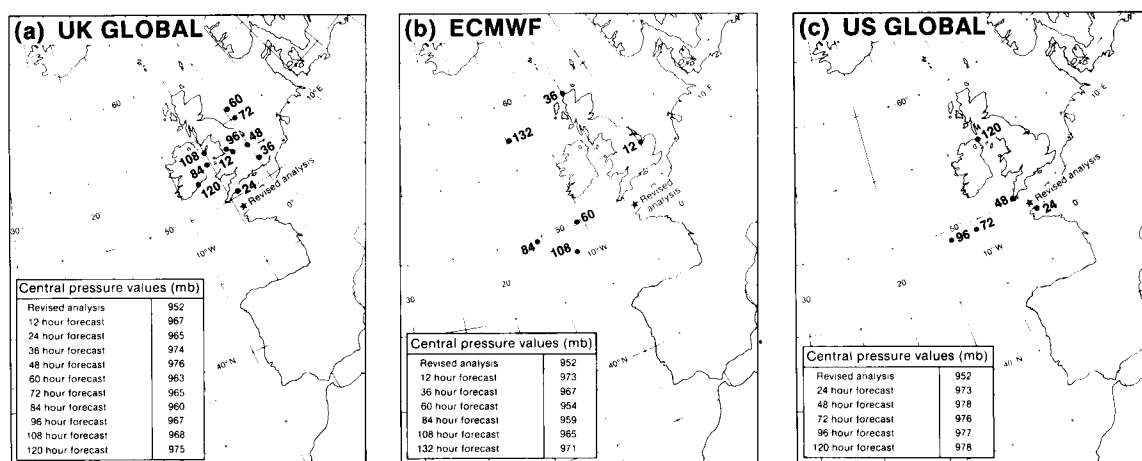


Figure 1. Locations and pressures of the storm at 0000 GMT on 16 October 1987 forecast for (a) the UK global model (b) the ECMWF model and (c) the US global model. The locations are indicated by •, and the associated numbers are the forecast periods in hours. The analysed position of the storm using all available data is indicated by ★.

The medium-range guidance from the UK global model was more consistent than that from either of the other two models. It was also more accurate, particularly with regard to the track of the storm, though it showed a slight systematic error in moving the storm across the British Isles a few hours too early.

These points are brought out by the NWP guidance from the three models available in CFO during the evening of Sunday 11 October and the morning of Monday 12 October. The two UK forecasts (108 and 96 hours ahead) are consistent in showing a deep depression, 968 mb (centred over the Irish Sea) and 967 mb (centred over Lancashire) respectively, with very strong winds implied by the pressure gradients over southern and eastern England. The corresponding ECMWF (108 hours ahead) and US (96 hours ahead) forecasts both keep the storm well south and west of Ireland at this stage. As a consequence they retain an older low as a separate feature north of Scotland, whereas in the UK forecasts this has merged with the storm circulation leaving only troughing of the pattern. The ECMWF forecast shows a vigorous low, with a central pressure of 965 mb, but the US forecast has the added disadvantage of indicating a less intense system, with central pressure 977 mb.

The medium-range forecasters in CFO accepted the NWP guidance, leaning towards the UK model in view of its consistency at 12-hourly intervals, with the result that forecasts issued from Sunday 11 October onwards emphasized the expected storm, timing its arrival for late on Thursday 15 October.

3. NWP guidance 72–48 hours ahead

The 72- and 60-hour numerical forecasts from the UK global model had slightly larger timing errors than the longer period UK forecasts, and took the centre out over the North Sea by 0000 GMT on 16 October. The 48-hour UK forecast for this time gave a more accurate location, but unfortunately the central pressure was 976 mb compared with a range 960–968 mb for the previous five UK forecasts (see Fig. 1(a)).

The ECMWF 60-hour forecast persisted with a location south and west of Ireland. However, it improved on earlier guidance by taking the central pressure down to 954 mb (see Fig. 1(b)).

The US 72-hour forecast gave a location only slightly more accurate than the US 96-hour forecast, but the location from the US 48-hour forecast was considerably better and the most accurate produced up to that stage. Both the 72- and 48-hour US forecasts continued to underplay the intensity of the low, with central pressures of 976 and 978 mb respectively (see Fig. 1(c)).

The NWP guidance during this period did not give a clear message, and the forecasters were left uncertain as to the likely track, timing and intensity of the low pressure system. The UK model had switched its story towards a shallower feature, tracking further east, and the threat of very strong winds over UK land areas seemed to have diminished somewhat.

4. NWP guidance up to 36 hours ahead

During the final 36 hours leading up to the onset of the storm, additional NWP guidance became available from the UK fine-mesh model. Senior Forecasters in CFO rely heavily on this model when preparing 24-hour prognostic charts, which they do at 6-hourly intervals, though the results from the UK global model are also available in time to be considered.

The NWP guidance for 0000 GMT on 16 October from 36-, 24- and 12-hour forecasts is shown in Figs 2, 3 and 4 respectively. The 36- and 12-hour forecasts from the ECMWF model are included for interest, though of course they are not available in time to be directly useful for short-range forecasting.

All three 36-hour forecasts are poor. The UK fine-mesh model and the ECMWF model both completely failed to develop a storm, and the main centre shown in both forecasts is the older low near the north of Scotland. The fine-mesh model has run a shallow feature (977 mb) forward over the North Sea. The ECMWF model has a very weak secondary centre (985 mb) near Brest. This is close to the

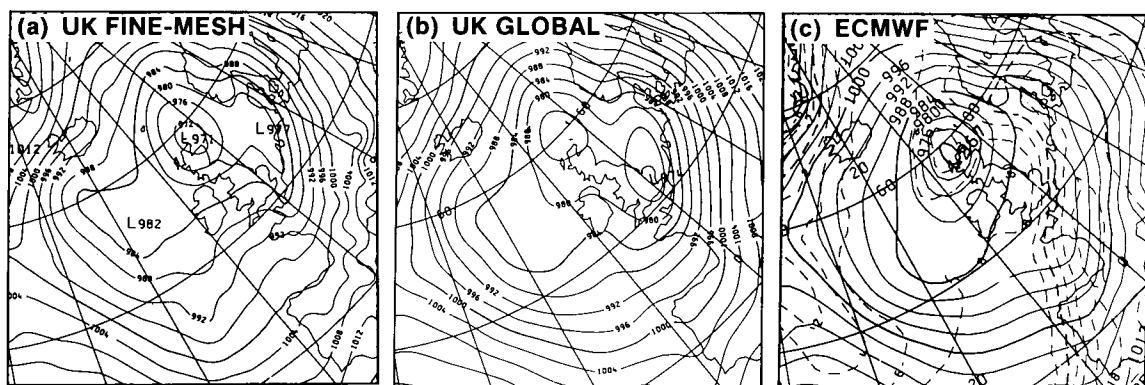


Figure 2. 36-hour numerical forecasts valid at 0000 GMT on 16 October 1987 from (a) the UK fine-mesh model (b) the UK global model and (c) the ECMWF model.

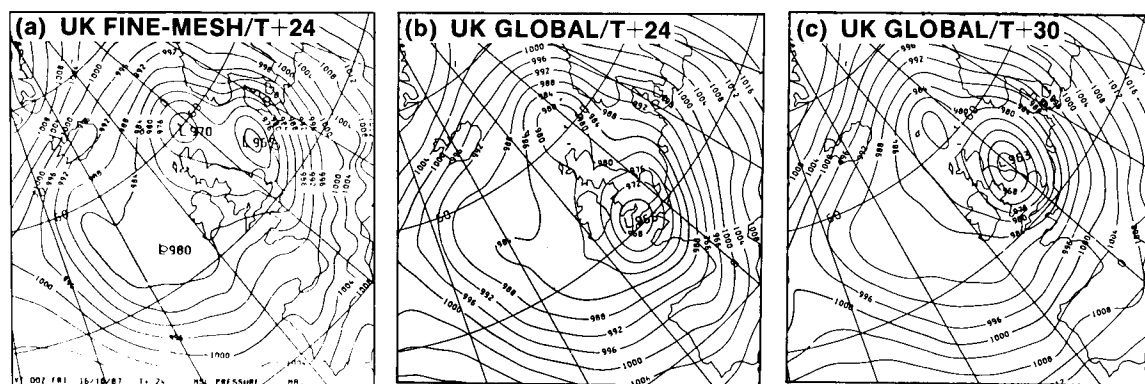


Figure 3. 24-hour numerical forecasts valid at 0000 GMT on 16 October 1987 from (a) the UK fine-mesh model and (b) the UK global model, and (c) the 30-hour numerical forecast valid at 0600 GMT on 16 October 1987 from the UK global model.

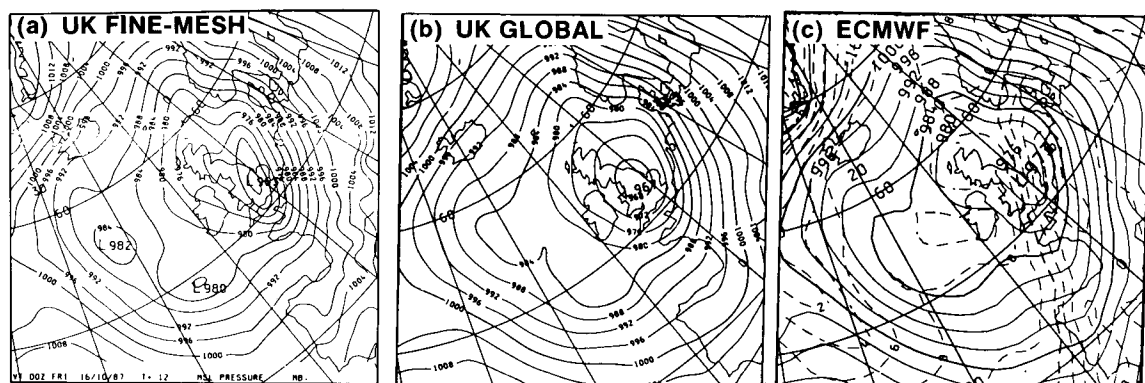


Figure 4. 12-hour numerical forecasts valid at 0000 GMT on 16 October 1987 from (a) the UK fine-mesh model (b) the UK global model and (c) the ECMWF model.

position of the storm, but with errors in excess of 30 mb the implied winds are very light (around 10 kn) over the English Channel, southern England and northern France.

The 36-hour forecast from the UK global model is only a little better, with a 974 mb centre over East Anglia. This advantage is sufficient, however, to retain strong pressure gradients and implied strong winds over northern France and the Low Countries.

The 24-hour fine-mesh forecast maintains the idea of a low centre crossing south-east England to a position over the North Sea, but the feature is now considerably deeper (967 mb) than in the 36-hour forecast. The particular track and timing are quite similar to those of the low that preceded the storm itself. A possible interpretation, then, is that this run of the fine-mesh model handled the first low well but completely missed the next baroclinic wave that developed into the storm. The accurate handling of the first low may have tended to confirm the perceived accuracy of this fine-mesh evolution as a whole, since the crucial wave developed in a data-sparse area and remained undetected for a time.

The 24-hour forecast from the UK global model stands out from all the previous guidance and places a 965 mb centre (i.e. 13 mb in error) near the south Devon coast. This proved to be the first NWP guidance that was reasonably accurate for *both* the location and the intensity of the storm. The 30-hour forecast from the same run (included in Fig. 3) is also accurate, showing the storm centre positioned just off the east coast of England by 0600 GMT on 16 October.

Comparing the global and fine-mesh 24-hour forecasts, and continuing the line of interpretation suggested above, it is probable that this run of the global model failed to capture the first low. Certainly the forecast shows no sign of the troughing into the North Sea that should be present at 0000 GMT on 16 October. More significantly as it turned out, the run seems to have succeeded in developing a baroclinic wave rapidly in about the right position to give accurate guidance on the storm onset.

Disappointingly, none of the 12-hour forecasts are as accurate as the 24-hour forecast from the global model. All three models moved centres along reasonably accurate tracks but with timing errors of around 4 hours in 12. The fine-mesh model was the most successful of the three, with a centre of 963 mb.

It is noteworthy that all of the 24- and 12-hour forecasts, despite other faults to varying degrees, maintain the belt of strong pressure gradients and implied strong winds across northern France and the Low Countries, and over adjacent sea areas.

5. The forecasters' conclusions regarding the NWP guidance on 15 October 1987

The NWP guidance for this particular event displayed characteristics that forecasters have to contend with most of the time. There are variations in the NWP advice from run to run and between different models. Quite frequently a later run proves to be less accurate than an earlier one. Small errors in track, timing or intensity of weather systems in the NWP guidance can have major consequences for the weather conditions to be expected at particular locations. Often there is the difficulty of determining whether a weather system emphasized by a numerical forecast can be identified with the system that becomes important in the real atmosphere, or whether it is merely a near neighbour that may evolve differently.

Up to about 0500 GMT on Thursday 15 October the forecasters in CFO could justifiably feel confident of the guidance offered by the morning's fine-mesh numerical forecast. This run was consistent with the guidance from the previous cycle in tracking a low centre across south-east England during the 15th and keeping the very strong winds away from UK land areas. The guidance had been supported by the ECMWF forecast, from 1200 GMT on 14 October initial conditions, that had arrived a little before the fine-mesh run.

When the UK global model guidance arrived it offered a markedly different solution with an earlier deepening, a slower movement and a track further to the west, crossing south-west England and the Midlands.

The fine-mesh model has established a reputation among National Meteorological Services throughout Europe for its ability to handle intense low pressure systems. Case studies have shown that its higher horizontal resolution sometimes permits it to represent dynamical processes that are missed by the global model. On the other hand the fine-mesh model, requiring only a regional coverage of observations, is run with an early data cut-off time. This procedure has important advantages, but it carries the known risk that on rare occasions there will be crucial late observations that miss the fine-mesh cut-off but are used by the global model, which then provides the more accurate forecast as a result.

These factors had to be weighed on the morning of the 15th. The latest observations and satellite imagery were examined for clues as to which solution was the more accurate (see next section). In the event the forecasters elected to compromise between the fine-mesh and the global-model guidance. The subjectively drawn 24-hour prognosis for 0600 GMT on 16 October, issued at 0955 GMT on 15 October, is reproduced in Fig. 5 and may be compared with the global-model evolution in Fig. 3. Compared with the fine-mesh guidance, the storm has been deepened, its movement slowed, and its track moved west, all reflecting the influence of the global-model guidance.

The next NWP advice to become available was the afternoon fine-mesh run at around 1500 GMT. This turned out to be in remarkably close agreement with the earlier subjective prognosis. The afternoon run of the global model, available around 1700 GMT, predicted a similar track and rate of movement, though it relaxed the pressure gradients around the storm a little (Fig. 4).

The story portrayed in Fig. 5, formulated after the two morning runs and confirmed by the afternoon fine-mesh run, was used as a basis for the issue of forecasts and warnings until observations finally revealed its errors just a few hours before the onset of the storm over southern England. The errors were as follows:

- (a) The expected intensification of the low was only 12 mb as it moved from Biscay (973 mb) across England and out over the North Sea (961 mb). In reality the storm had already deepened to 952 mb as it crossed the English Channel. Consequently the surface wind speeds over south-east England were significantly underforecast.
- (b) The predicted track of the low was still too far to the east as it crossed the English Channel. This had the effect of confining the expectation of strong winds over land to a too-small part of south-east England.
- (c) The expected movement of the low centre along its track was too rapid, with the result that the strong winds were predicted to arrive over south-east England about 4 hours too early.

6. Synoptic reviews issued by CFO on 15/16 October 1987

The Senior Forecaster in CFO is responsible for the issue of centralized guidance to all public service forecast offices throughout the country. These responsibilities include providing advice to the shipping forecaster, who is also located in CFO, on the issue of gale warnings for all sea areas around the UK continental shelf. The Senior Forecaster in turn receives advice from a number of other forecasters, including a colleague of equal rank who is responsible for monitoring and fine-tuning the numerical model analysis before the forecasts are made.

In association with the subjectively drawn 24-hour surface forecast chart referred to above, the Senior Forecaster issues a descriptive textual guidance routinely four times daily, although updates and amendments can be issued at any time. Each issue of the guidance, which is termed a 'synoptic review', is put into two or three parts (three parts for the early morning and afternoon issues, i.e. approximately 0400 and 1600 GMT). The guidance is designed to add value to selected numerical model products which are received by the outstations direct from Bracknell as well as containing the definitive guidance on the forecast to be followed by all regional offices.

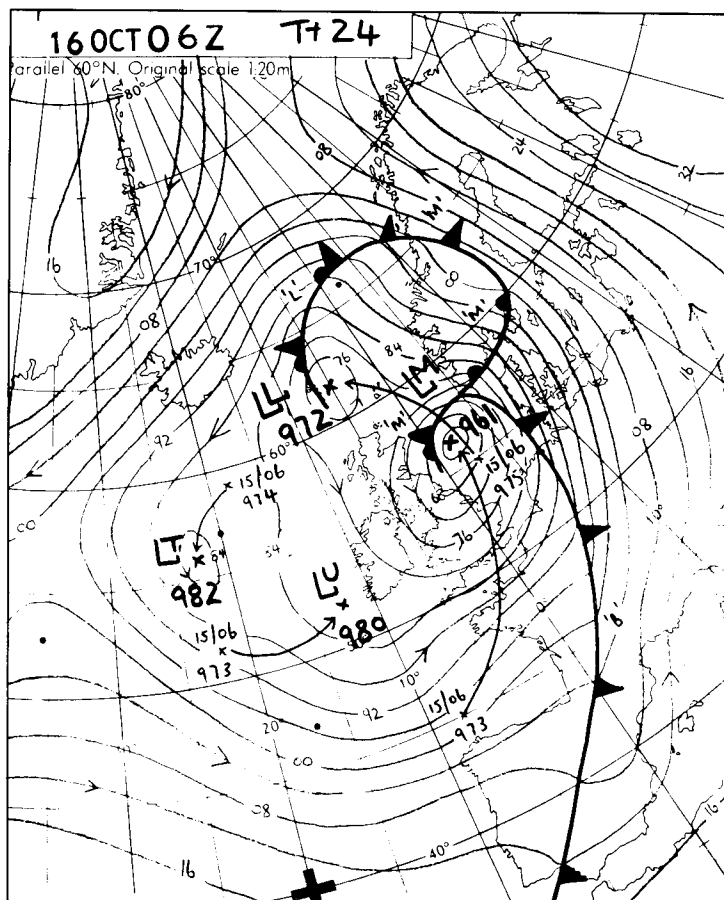


Figure 5. Subjectively drawn prognostic chart for 0600 GMT on 16 October 1987, issued at 0955 GMT on 15 October 1987.

Although outstations are required to follow the central guidance, the procedures involved in formulating the guidance include conferences and discussions with all the regional main meteorological offices at least twice daily and more frequently with the national television and radio presenters.

The early morning synoptic reviews were chiefly concerned with the likelihood of heavy rain in the south in view of recent flooding. The Part 1 (issued at 0345 GMT on 15 October) mentioned the possibility of winds reaching gale force in exposed locations especially in south-east England during the second half of the day. (At this stage, the timing of the evolution was following the latest fine-mesh guidance which proved in the event to be significantly too rapid.) The Part 3 (issued at 0550 GMT on 15 October) expressed concern about the different model solutions in a rapid developmental situation, concluding that the fine-mesh solution was preferred because of a marginally better initial state. The late morning Part 1 (issued at 1010 GMT on 15 October) included a land-gale warning for exposed parts of southern and eastern England. The Part 2 (issued at 1040 GMT on 15 October) suggested a compromise solution between the coarse mesh and the fine mesh for the position and track of the centre. This was because the available observations suggested that the fine-mesh forecast had the better pressure field

over France for 0600 GMT on the 15th, whilst on the other hand there was a suspicion that it was not developing the low quickly enough.

The Senior Forecaster was also considering yet another solution throughout the day. Satellite imagery to the south-west of the United Kingdom showed a possible 'baroclinic leaf' structure which often precedes rapid cyclogenesis and the formation of an 'instant' occlusion around a development in the cold air. This was yet another compromise solution between the coarse mesh and the fine mesh in which both models would be right to some degree, the first wave running north-east as the fine mesh predicted with the main development following in the cold air. By mid afternoon the details of the analysis (both surface and upper air) in the critical region were still unclear. The forecaster judged that the main thrust of storm force winds in the moist south-westerly flow was likely to extend over north France but the east Channel and extreme south-east England could be at risk from severe gales. There was also the possibility of severe gales around the development in the cold air, if it occurred.

The fine-mesh solution based on 1200 GMT data showed the expected slight changes of track and speed of the wave, but there was no sign of rapid development or of the formation of an occlusion. The mid-afternoon synoptic review (issued at 1535 GMT on 15 October) included a land-gale warning stating that the gales would become confined to Scotland tomorrow. This was amended at 1640 GMT in Part 2 to mention severe gale force at times in exposed coastal districts during the evening in the extreme south-east, especially in a southerly flow on the eastern flank of the depression. During the late afternoon the wave was approaching the Brest area but pressures were not as low as the fine-mesh forecast. The forecaster considered that rapid cyclogenesis could already be occurring further to the south-west or would shortly occur there; this would steer the low further north for a time but increasing north-westerly flow on the western flank would tend to recurve the low back onto a more easterly track and the strongest winds in the cold air would probably be confined to the English Channel coasts and the extreme south-east.

Part 3 (issued at 1750 GMT on 15 October) mentioned the possibility of rapid deepening of the surface circulation in the next few hours but with no specific mention of winds. The 2225 GMT synoptic review mentioned gales, even severe gales, over exposed areas of the south-east with Part 2, issued at 2235 GMT, stating that southerly gales over land could extend further westwards across southern Britain than thought earlier. The 0345 GMT synoptic review said that there would be severe land gales across much of England and Wales during the first part of the day.

The complexity of the developments which exercised the Senior Forecasters' minds throughout the 15th are well revealed in the full text of the synoptic reviews.

Numerical forecast studies of the October 1987 storm over southern England

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Summary

The dynamical structure of the storm is described with the aid of numerical analyses and forecasts. Causes of differences between operational forecasts are investigated. Excellent 24-hour forecasts with the fine-mesh model were obtained in experiments using observations which arrived after the operational cut-off. There were insufficient observations to define the detailed structure of the developing system at 1200 GMT on 15 October. However, an excellent forecast from this time was obtained using a new assimilation scheme designed to cause less disruption to the forecast model's structure.

1. Introduction

This article presents the results of investigations aimed at clarifying the reasons for the deficiencies in the numerical guidance presented to forecasters concerning the storm of 15/16 October 1987.

In section 2, the dynamical characteristics of the genesis and evolution of the storm are examined, within the limits of the evidence available, to see if they were highly exceptional. Sections 3 and 4 are concerned with the shortcomings of the operational numerical forecasts, particularly those originating from 0000 and 1200 GMT on 15 October. The objective is to determine how observations, analysis procedures or the forecast models themselves contributed to the errors. Section 5 describes the potential usefulness of systems now being developed. Some conclusions are given in section 6.

2. Dynamical structure of storm

To understand the processes which led to the development of the storm on 15/16 October it is necessary to consider the wider atmospheric conditions over the Atlantic and during the preceding days. At 0000 GMT on 14 October (48 hours before the storm affected the United Kingdom), the flow at upper levels over the Atlantic consisted of a strong, broad, westerly airstream between latitudes 40 and 50° N (Fig. 1(a)). This is fairly far south for the time of year, but not unusual. The temperature contrast between polar and tropical air was largely confined to the same latitude belt. At the surface, the depression of interest was near 40° W, with a central pressure of 1003 mb (Fig. 1(b)), well ahead of the upper trough. During the next 24 hours the depression deepened and moved quickly eastwards. In the operational computer analysis of mean-sea-level pressure for 0000 GMT on the 15th (Fig. 1(d)) there is some uncertainty because of the sparsity of observational data. Its indication of three distinct low pressure centres is probably correct, but there is some doubt over their relative intensities. The upper trough also moved quickly eastwards, but it was still to the west of the surface depression (Fig. 1(c)).

During the period 0000 to 1200 GMT on 15 October, the amplifying upper trough with its associated strong winds crossed the region in which there were surface pressure centres, and where the low-level baroclinicity and thermal contrasts were large. These conditions are especially favourable for the development of depressions, especially if the upper trough 'phase-locks' with a surface centre.

Small-scale jet streaks (areas of local intensification) may be embedded within the broad jet-stream flow, and influence the nature and intensity of subsequent surface development. This may have been important on this occasion.

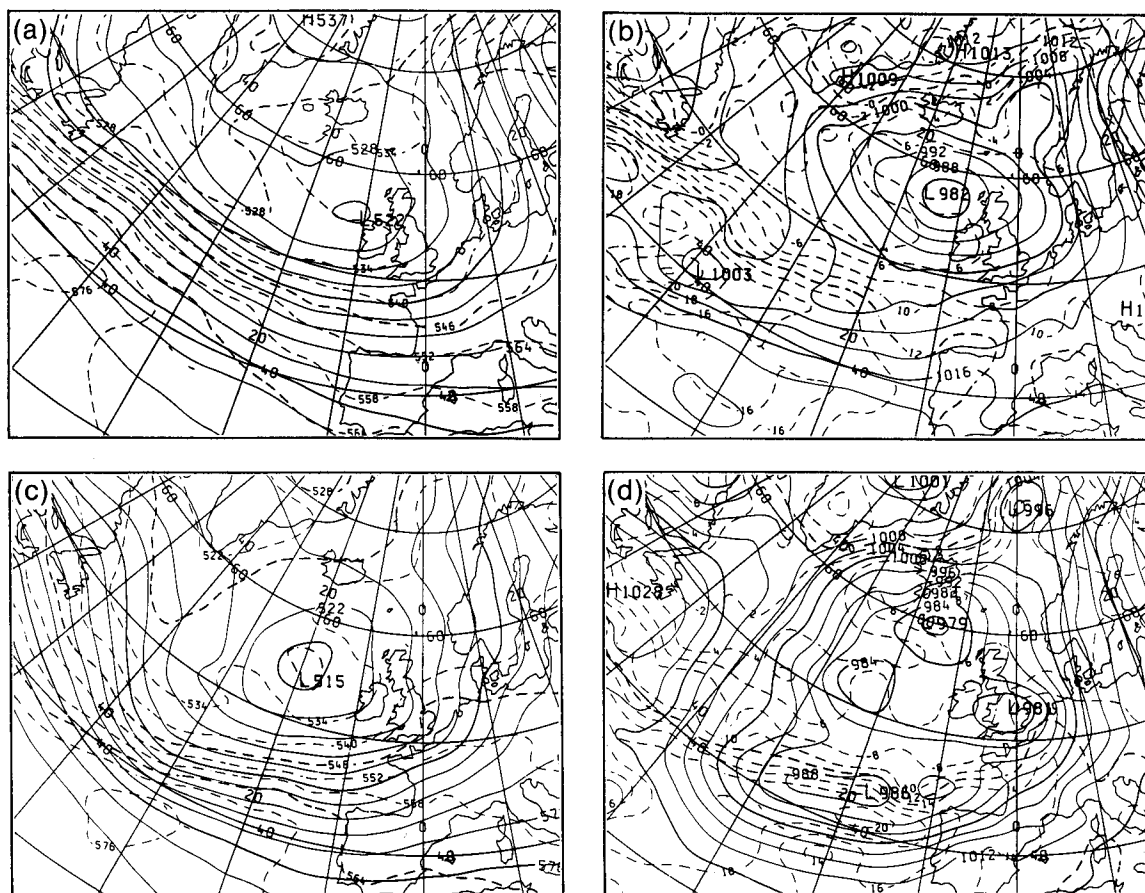


Figure 1. Operational global assimilation analyses of (a) 500 mb height (solid lines, contour interval 6 dam) and 1000–500 mb thickness (dashed lines, contour interval 6 dam) and (b) sea-level pressure (solid lines, contour interval 4 mb) and 850 mb wet-bulb potential temperature (dashed lines, contour interval 2 °C) for 0000 GMT on 14 October. (c) and (d) are as (a) and (b) but for 0000 GMT on 15 October.

In studies of a storm which developed explosively off the eastern seaboard of the USA, Uccellini *et al.* (1984, 1985) showed that a key feature was a polar jet streak which propagated, with associated stratospheric air, down to mid-tropospheric levels. Conclusive observational evidence for a similar feature is lacking, but satellite images for the UK storm indicate that a dry slot (cloud-free zone) was visible in the cloud images and more clearly in the water vapour imagery. This may have been associated with a deep stratospheric intrusion. The imagery during 15 October is essential for fixing the position of the frontal zone and the waves on the front because of the lack of surface observations. The satellite pictures also show a number of other features (for instance a cloud head) which are believed to be linked to strong cyclogenesis (Böttger *et al.* 1975). However, these qualitative observations by themselves do not provide sufficient information to enable the precise nature of the evolution of the low to be predicted.

During the mature phase, on 16 October, the depression, as represented in the most successful fine-mesh forecast (see section 3.1), had a pronounced warm core below 5 km between two zones of high baroclinicity (Fig. 2). The existence of such a feature is supported by surface observations. The

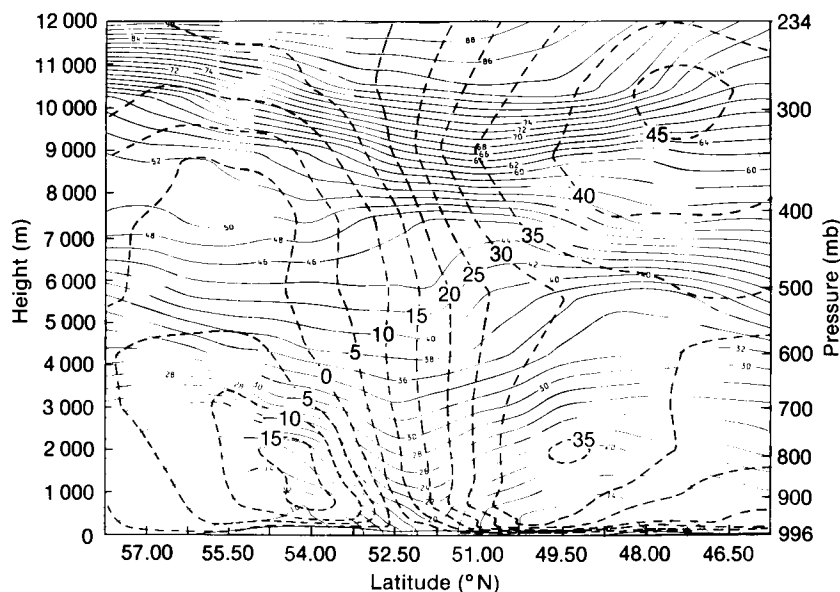


Figure 2. Cross-section of potential temperature (solid line, contour interval 2 °C) and northerly component of wind (dashed line, contour interval 5 m s⁻¹) along 1.87° W at 0300 GMT on 16 October from a forecast using the fine-mesh model from the best available rerun fine-mesh analysis for 0000 GMT on 15 October.

hydrostatic relationship and geostrophy gives the thermal wind relationship between horizontal temperature gradients and vertical wind shears. The warm core in Fig. 2 is related to low-level maxima in the winds; the model's northerly components are shown. There was also observational evidence for this low-level jet maximum.

Many intense extratropical cyclones have been observed to have warm cores, the origin of which is the subject of scientific debate at present. One possibility is that in the occluding phase of a depression some of the warm air gets extruded from the warm sector and remains trapped at low levels in the depression, whilst the rest moves upwards and ahead of the storm. Bergeron (1928) identified such a process and termed it 'seclusion'. Another explanation is that vigorous convective ascent in the vicinity of the centre of a developing depression causes compensating subsidence outside the convective areas which leads to adiabatic warming. Although there were some reports of thunderstorms from stations on the Welsh coast during 16 October, there is little evidence that convection was sufficiently widespread to contribute significantly to this process. A third possible explanation for the relative warmth is that large fluxes of sensible and latent heat entered the storm over Biscay in association with the pre-existing strong winds. Whatever the actual process is, the fine-mesh model seems capable of representing it. Further studies of these dynamical mechanisms and their role in the formation of such storms are needed to establish the nature of the mechanisms more precisely.

In summary, though the general atmospheric conditions strongly favoured cyclonic development, no features have been identified that would have enabled the quite exceptional character of the storm to be identified at an early stage.

3 Forecasts from 0000 GMT on 15 October

The Meteorological Office's fine-mesh model has an excellent record in forecasting rapid developments up to 36 hours ahead. As a result forecasters have come to put more weight on its guidance

than on the global model. Thus its failure to predict the storm's development correctly in the forecast run with data received by 0200 GMT on 15 October was unusual, and a major factor influencing the forecasts that were issued. On the other hand the global model, run with data received by 0320 GMT, gave reasonable guidance for the storm's track and intensity over England.

3.1 *Forecasts from different analyses*

The obvious most likely reasons for differences in the models' forecasts are that the analyses were significantly different. This was examined by running the fine-mesh forecast model from an interpolated global model analysis. Fig. 3 compares the 12-hour operational forecasts from the global and fine-mesh models, and from the fine-mesh forecast using the interpolated global analysis and the best available rerun fine-mesh analysis. The corresponding 24-hour forecasts are shown in Fig. 4.

The run of the fine-mesh model starting from an interpolated global model analysis differs little from the global model forecast except in the central pressure of the storm, implying that the operational

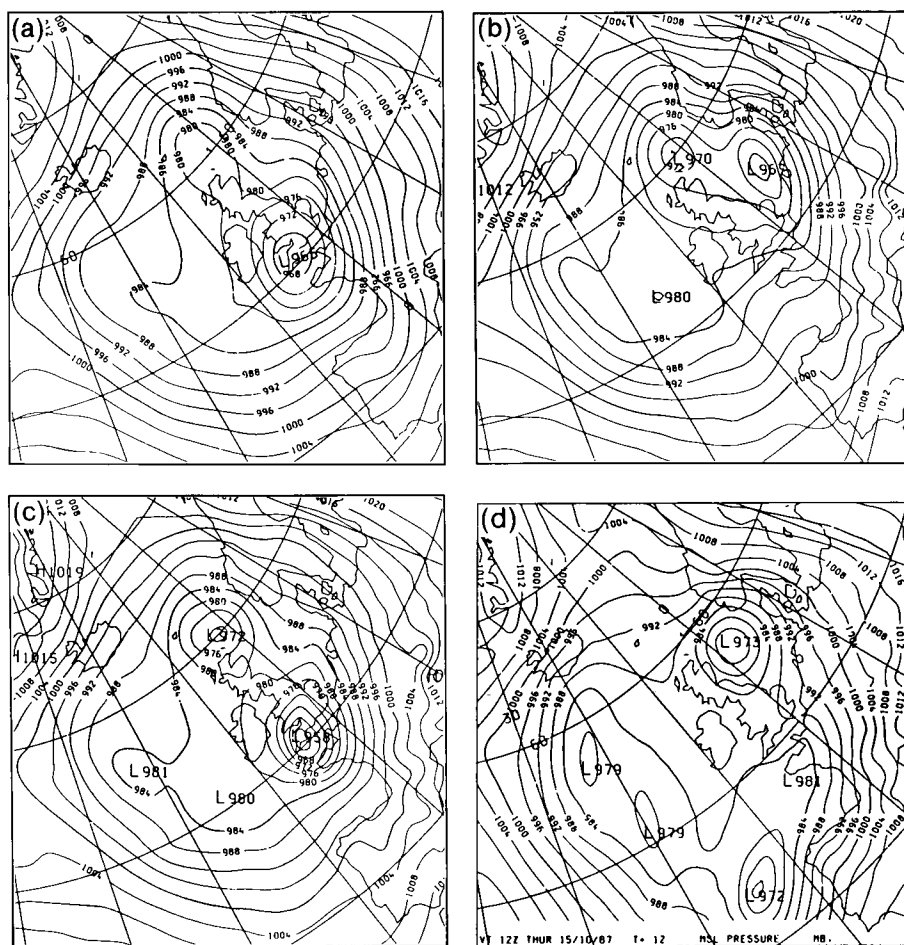


Figure 3. 12-hour forecast of mean-sea-level pressure (mb) valid at 1200 GMT on 15 October from (a) operational global model, (b) operational fine-mesh model, (c) fine-mesh model using an interpolated global analysis and (d) fine-mesh model using the best available rerun fine-mesh analysis.

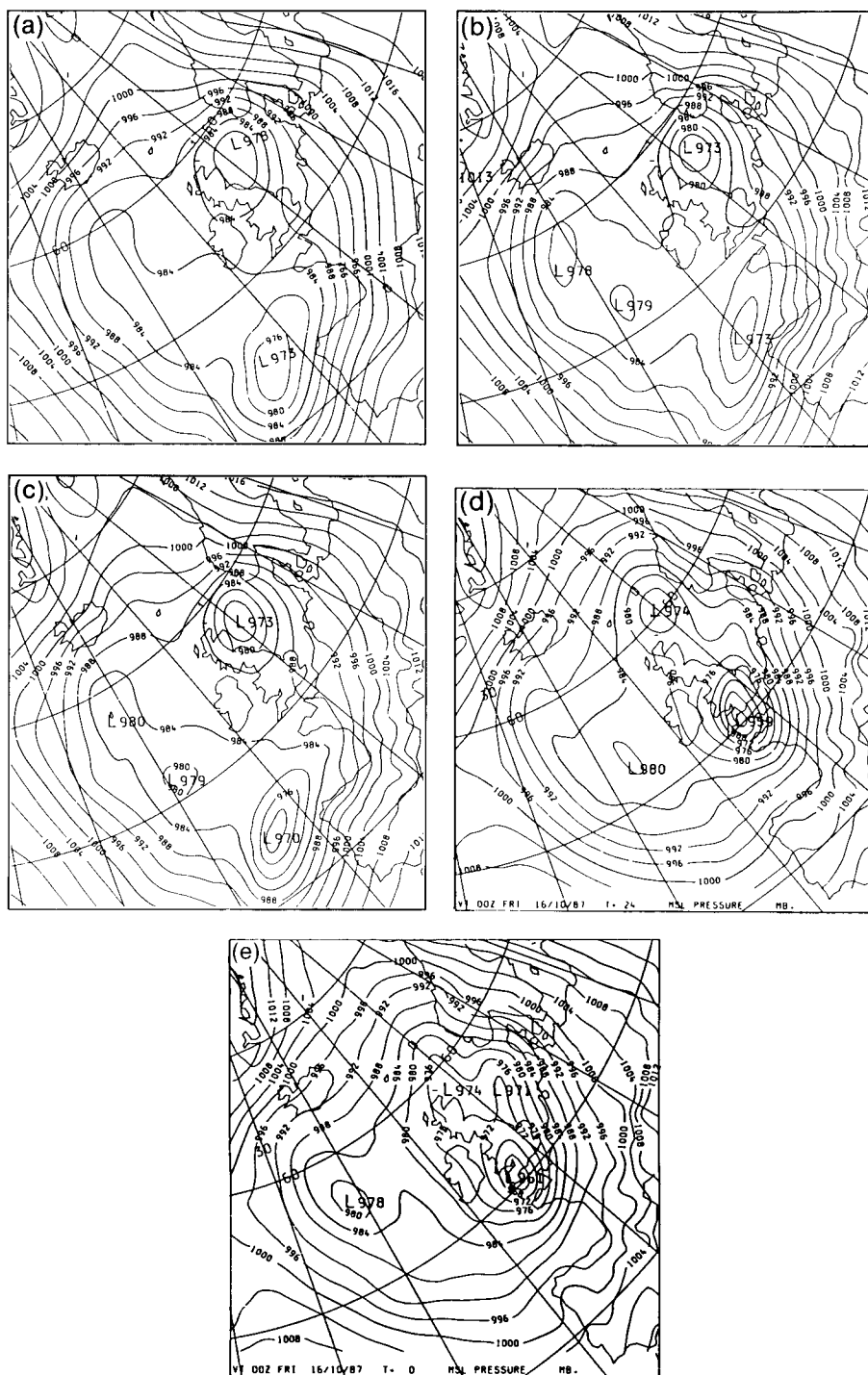


Figure 4. As Fig. 3 but for the 24-hour forecasts valid at 0000 GMT on 16 October, but with (e) the verifying analysis.

forecast errors in the track and timing of the system were caused by features in the fine-mesh analysis.

There is some uncertainty as to the correct surface pressure analysis for verifying the forecasts in Fig. 3. For instance, the fine-mesh analyses shown in Fig. 5 differ in places by over 5 mb, and various careful human analyses differed in the depth, position, and even the number of low centres. There is no doubt, however, about the existence of the elongated trough stretching approximately south-west from Brest, probably with one low centre (which did not subsequently develop) approaching Brest, and one or two others further west (one near 14° W which developed into the storm). Neither of the forecasts from the global analysis reproduce the pressure centre approaching Brest; instead they concentrate on the centre which actually did develop into the main storm. As the horizontal separation between the centres is about 400 km, and variations on this scale cannot be adequately represented in the global model with a grid length of about 150 km, the absence of detailed structure in the forecast surface pressure field is not surprising. The operational fine-mesh forecast (Fig. 3(b)) predicted a low with troughing towards Brest, in better agreement with many aspects of the actual field than the forecasts from the global analysis. However, it went on to develop this feature, moving it forward rapidly and giving a misleading forecast (Fig. 4(b)). This highlights the difficulties of reaching correct decisions on the day.

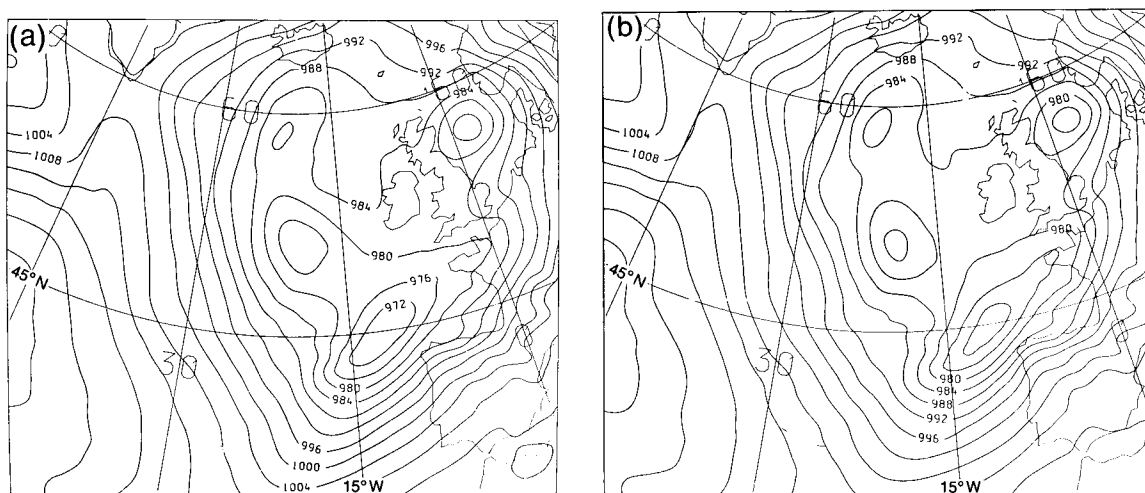


Figure 5. Mean-sea-level pressure (mb) at 1200 GMT on 15 October from (a) the test fine-mesh analysis and (b) the operational fine-mesh analysis.

A series of experiments, described below, culminated in a fine-mesh assimilation and forecast which was excellent in its prediction of the track and intensity of the storm over England. Its cloud fields were in good agreement with significant features inferred such as the dry slot and cloud head in the satellite imagery, and detailed diagnostics from it, such as Fig. 2, give a consistent picture of the dynamics of the storm. The forecasts of mean-sea-level pressure are shown in Figs 3(d) and 4(d). Like runs from the global analysis, the forecast concentrated development on the last centre though it did have significant troughing forward towards Brest, and in this aspect is superior to them. There are more substantial differences in the upper winds. The best forecast shows a series of jet streaks propagating around the upper trough, and there is no sign of the area of weakness over the Bay of Biscay which was a feature of forecasts from the global analysis.

3.2 The observations

The fine-mesh data assimilation cycle (Bell 1986) consists of four 3-hour assimilation periods starting from interpolated global model fields every 12 hours. For each cycle, data are accepted if they are within a time-window ± 90 minutes from the nominal analysis time. In contrast, the global model has a 6-hour cycle and a ± 180 -minute time-window.

The good forecast from the 0000 GMT 15 October global analysis seems to be due to observations in its last time-window; a forecast from its earlier 1800 GMT analysis had only a weak low pressure centre of 982 mb near the Dutch coast at 0000 GMT on the 16th. This window corresponds approximately to that of the last two cycles of the fine-mesh assimilation. However, most observations are nominally valid for the main synoptic hours, so Table I lists the volumes of data available to the 0000 GMT cycle of the global and fine-mesh assimilations. For the former, it consists of all observations made within the period 2100 GMT on the 14th to 0300 GMT on the 15th and received before 0320 GMT on the 15th; the equivalent period and time for the fine-mesh model are 2230 GMT on the 14th to 0130 GMT on the 15th and received before 0200 GMT on the 15th.

Table I. *Number of observations available operationally within the fine-mesh area for the 0000 GMT cycle on 15 October*

	Fine-mesh assimilation	Global assimilation
SATEMs (500 km)	4	25
SATEMs (250 km)	0	98
Ships	139	163
AIREPs	34	99
DRIBUs	8	10
SATOBs	21	41
Radiosondes	153	169

The table and an examination of the locations of observations indicate that more satellite data, and more aircraft and ship reports, were available to the global assimilation in areas where they might have affected developments in the Bay of Biscay. By deleting the SATEM data, and the AIREP reports successively, it was established that only the latter had a significant effect on this occasion. Without the benefit of the additional aircraft data, the 24-hour global forecast for 0000 GMT on the 16th was considerably less realistic.

Almost all the additional AIREPs were for the period 0130 to 0300 GMT and, importantly, they were in the strong wind belt between 30 and 40° W. (The majority of commercial transatlantic flights leave North America to arrive in Europe in the early morning, and try to fly in the westerly jet.) Additional SATEMs on the other hand were from an orbit with an overpass time of approximately 2200 GMT at 40° W. They were outside the ± 90 minute time-window of the 0000 GMT fine-mesh analysis, but they arrived too late to be included in the 2100 GMT cycle of the operational run. In order to ensure that the additional AIREPs were included in a revised fine-mesh forecast, as well as the additional SATEMs, the observation time-window of its 0000 GMT cycle was increased to match that of the global assimilation. The result was an improvement on the operational fine-mesh forecast for the storm over England but it was still inferior to the run from the interpolated global analysis.

Observations made before 0300 GMT continue to arrive at Bracknell after 0320 GMT. Table II shows the data volumes which were eventually available for repeat fine-mesh assimilations at 2100 GMT on the 14th and 0000 GMT on the 15th, as well as the volumes operationally available.

Table II. *Number of observations available within the fine-mesh area for the 2100 and 0000 GMT cycles on 14/15 October*

	Operational fine-mesh assimilation	Rerun assimilation with late data
1930–2230 GMT		
SATEMs (500 km)	20	33
SATEMs (250 km)	59	150
Ships	76	77
AIREPs	23	23
DRIBUs	11	11
SATOBs	0	24
2230–0130 GMT		
SATEMs (500 km)	4	4
SATEMs (250 km)	0	69
Ships	139	244
AIREPs	34	43 (127)
DRIBUs	8	9
SATOBs	21	123
Radiosondes	153	177

As already noted, potentially useful satellite data were missing from the 2100 GMT assimilation. At 0000 GMT, the extra satellite data were at 60° W and are probably not relevant. Additional ships' observations were received because many ships wait until morning to transmit their night-time reports. The increase in aircraft reports within the fine-mesh time-window is 9, but 93 if the window is expanded to 0300 GMT. A relatively large number of SATOBs (cloud motion vectors derived from satellite images) were received; however, it is recognized that care must be exercised if they are used operationally as they sometimes underestimate the strength of upper-level jet streams.

Various combinations of these data were tested. The best, which included all of them, gave a result close to the run from the interpolated global analysis.

Several experiments were performed to test the effect of various parameters in the fine-mesh data assimilation scheme. They showed that, in this case, a 40% increase in the weight given to the observations was beneficial. An analysis made using all the observations, and this increased weight, gave the forecasts shown in Fig. 3(d) and Fig. 4(d).

4. Forecasts from 1200 GMT on 15 October

Both the global and fine-mesh models from 1200 GMT failed to deepen the low sufficiently in the early stages, and moved it on too rapidly, leading to unhelpful forecasts. A fine-mesh forecast from the global analysis did not correct this deficiency, nor did the ECMWF forecast from an analysis with an even later data cut-off.

The forecast from the global model analysis at 0000 GMT was good, whereas that from 1200 GMT was not. It is important to find out why.

Experiments were undertaken with the fine-mesh system to establish which data contributed most to the change. The fine-mesh assimilation was started from an interpolated global analysis for 0000 GMT on 15 October, which was known to give a good forecast. Forecasts were run from intermediate analyses (data times 0600 and 0900 GMT). That from 0600 GMT gave an excellent position both at 0000 and at 0600 GMT on the 16th, with the low 2 mb shallower than the run from the 0000 GMT global analysis. In the forecast from 0900 GMT the low moved too quickly, but not as fast as in the 1200 GMT run. The

progressive worsening of the forecast from the 0600, to 0900 to 1200 GMT analyses, indicates that a single observational cause is unlikely. This was verified by other experiments.

As varying the observations available was not helpful, an alternative approach was to use manually generated 'bogus' observations. The best 12-hour forecast from 0000 GMT was used as a guide in generating them, and they were assimilated along with the actual observations. It was found that in none of the 'bogusing' experiments were the position and depth of the depression at 0000 GMT on the 16th correctly forecast.

In contrast to the experiments using the operational scheme, a test version of a modified assimilation scheme, which is being developed and is described in section 5.4, gave a fine-mesh analysis for 1200 GMT on 15 October which led to a very good forecast for the storm. The test scheme was run for two 3-hour cycles, starting from the operational fine-mesh analysis for 0600 GMT on 15 October, and using the same observations as were available operationally. The sea-level pressure from the test is shown in Fig. 5(a), which can be compared with the operational analysis given in Fig. 5(b). The test scheme gives a 969 mb low at 13° W compared to the operational scheme's 971 mb low at 11° W. The test analysis places greater emphasis on a trough near 44° N, 15° W; its pressure here is 5 mb lower. The test scheme's pattern in this region is more similar to the best forecast from 0000 GMT (Fig. 4(d)), and less similar to an independent subjective re-analysis, than is the operational scheme's pattern. However, there are very few observations and some doubt about their reliability, so the true analysis is uncertain.

Sea-level pressure forecasts obtained from the test scheme's analysis are shown in Fig. 6. The track of the forecast from the test analysis is very slightly to the north of the actual track, but the guidance which this forecast would have given a forecaster was excellent.

As the model humidities agree with the satellite cloud positions, and the computer analyses are consistent with available observations, the location of a depression near 44° N, 14° W at 1200 GMT on 15 October may indeed be correct. Despite the success of the forecast, it should be noted that in root-mean-square terms the test analysis fitted the available observations less closely than the operational analysis. It therefore cannot be concluded that the forecast was accurate in all respects, and the safer conclusion at this stage is that in the development of the storm there was a very large sensitivity to the details of the three-dimensional atmospheric structure, which were not resolved by the available observations.

5. Effect of systems currently under development

The Meteorological Office is developing improvements to its forecasting system. This case has been, and will continue to be, used to test them. In this section early tests of systems currently under development are briefly reviewed in order to give some idea of potential future improvements. It must be emphasized that the results are preliminary; considerable further work is needed before some of the systems can become operational.

5.1 Mesoscale model

The mesoscale model is for use in preparing forecasts up to 18 hours ahead, the aim being to provide guidance to local forecasters on surface temperature and wind, low cloud, precipitation and visibility. It is currently run twice a day using boundary conditions derived from the fine-mesh model forecasts starting at noon and midnight. Its horizontal resolution is 15 km and it has 5 levels in the lowest kilometre, permitting some detail in the treatment of boundary-layer structure. Fig. 7 shows the 12-hour forecast for 0000 GMT on 16 October at full resolution. As expected the general evolution follows the fine-mesh model forecast. However, the wind speeds predicted over land compare well with the general level of mean speeds reported at the height of the storm. It does not reproduce the highest speeds, but since the storm an algorithm to predict the maximum gust has been added to the model.

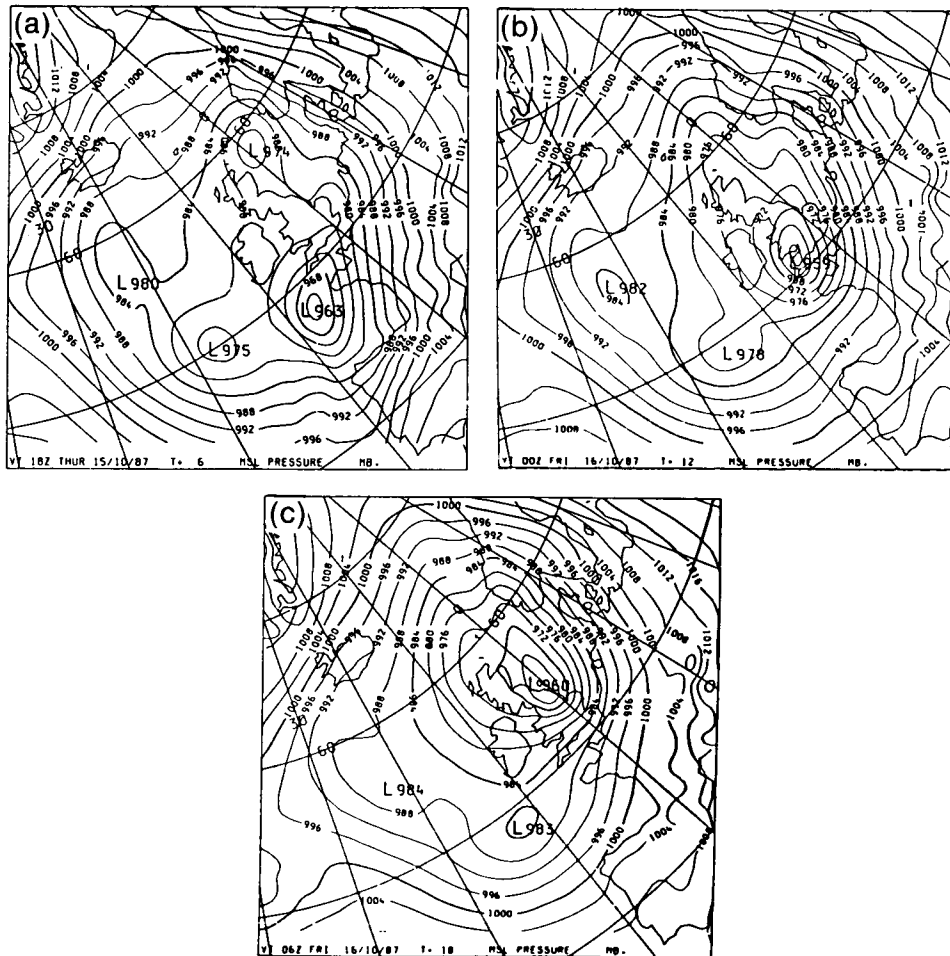


Figure 6. 6-, 12- and 18-hour mean-sea-level pressure (mb) forecasts using the fine-mesh model with the test fine-mesh analysis for 1200 GMT on 15 October.

5.2 Higher-resolution fine-mesh model

A higher-resolution version of the fine-mesh model is expected to become operational in 1988. Higher resolution should allow a more accurate description of frontal processes, and therefore the main improvement is expected to be in forecasts of precipitation. Where topographic forcing is significant, or when frontal processes contribute significantly to the dynamical evolution, improved wind forecasts should also be obtained. No data assimilation scheme is yet available for the model, so initial conditions are obtained by interpolation from the global analysis.

Forecasts were made from data times 0000 and 1200 GMT on 15 October with a horizontal grid length of 40 km, i.e. just over half that of the operational fine-mesh model. As expected, the evolutions of these forecasts were similar to those with the operational fine-mesh model using the global analysis, and with the operational global forecast; however, there is extra detail in the wind fields from the higher-resolution forecast (Fig. 8), and the depression is made more intense.

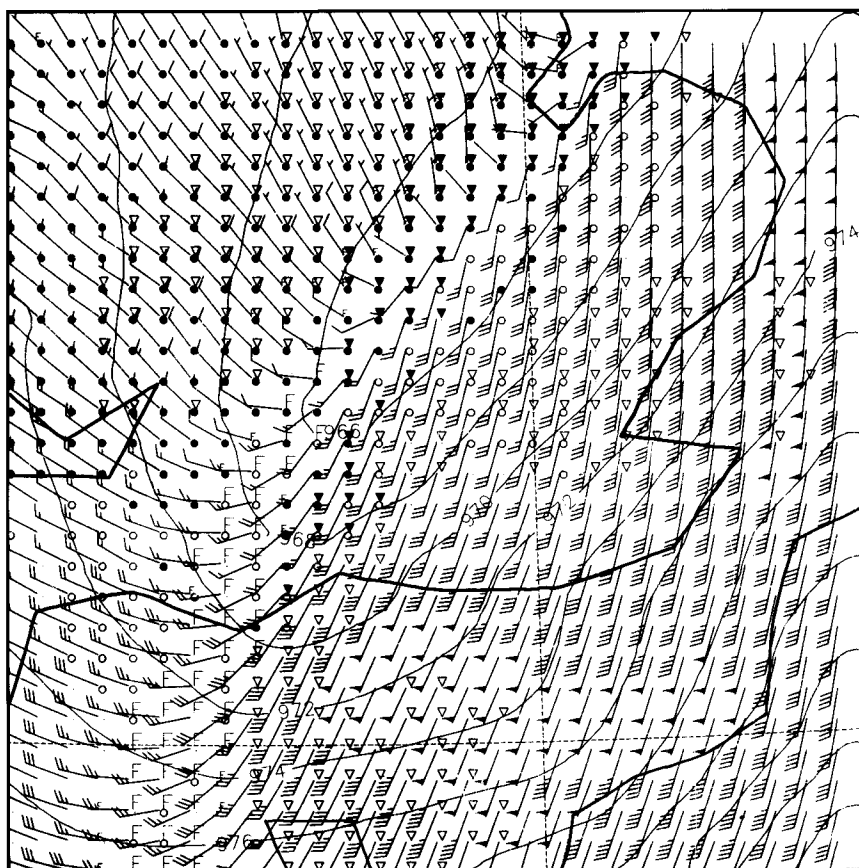


Figure 7. 12-hour mesoscale model forecast of pressure, wind and weather over south-eastern Britain from data time 1200 GMT on 15 October. Pressure in millibars, winds in knots, and weather by circles indicating precipitation from layer cloud (greater than 0.5 mm h^{-1} if solid) and triangles indicating showers (greater than 0.5 mm h^{-1} if solid). F indicates very low cloud.

5.3 Local Area Sounding System

TIROS satellite data for orbits near the United Kingdom are picked up by the receiving station at Lasham. By processing the Local Area Sounding System (LASS), higher resolution and more timely soundings can be produced than are available over the Global Telecommunication System as SATEM reports. Two processing methods are available. The first, based on techniques developed in the USA for processing TIROS data, but with locally derived calibration coefficients and other modifications, uses a statistical method and a first-guess profile based on a sample of radiosonde soundings. The second uses a physically based method with a first guess taken from a fine-mesh model forecast.

The impacts of both sets of retrievals were tested on the fine-mesh assimilation leading to the 1200 GMT 15 October analysis, but for the present case the retrievals were not helpful. Because of their high resolution, these data are potentially of great value, but improvements in methods of using them are needed.

5.4 Analysis Correction assimilation system

A new assimilation scheme, known as the Analysis Correction scheme, is being developed. Its basic

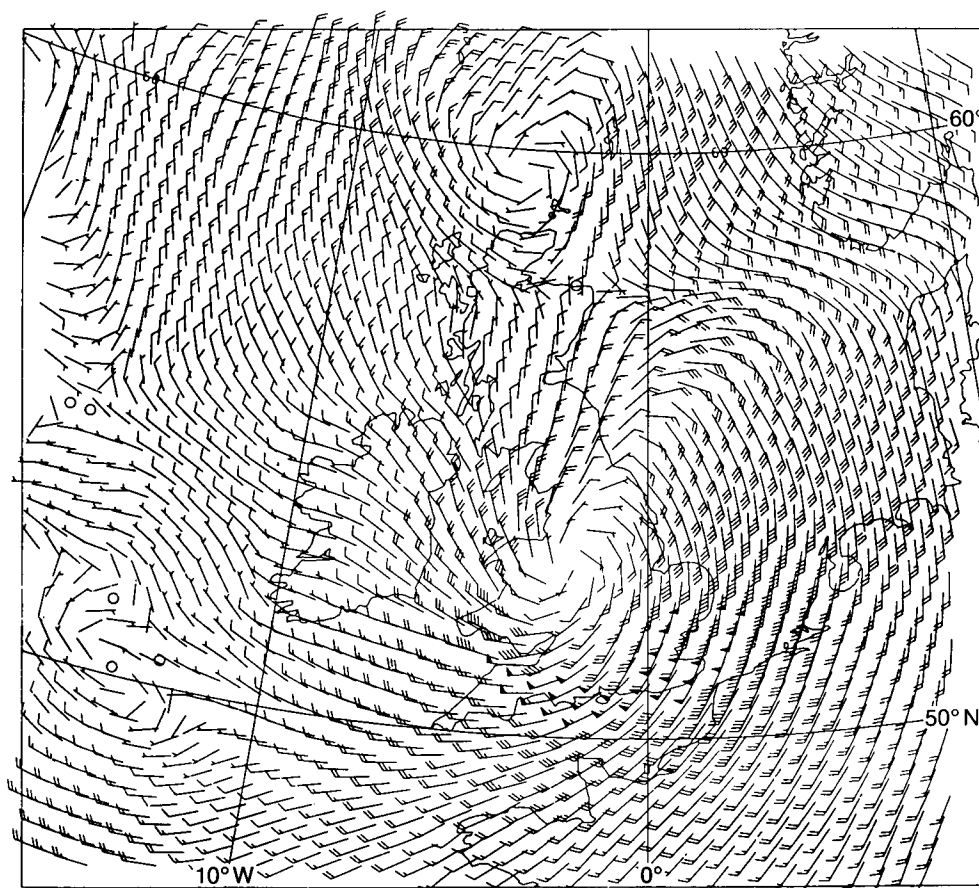


Figure 8. High-resolution fine-mesh forecast of 10 m mean winds (kn) at 0600 GMT on 16 October, run from the global analysis for 0000 GMT on 15 October.

structure is similar to that of the operational scheme, but its weighting and spreading of data are different. These differences are important in:

- (a) the handling of off-time data such as AIREPs, which are processed at their valid time rather than the nominal analysis time, and
- (b) the treatment of sparse data which should be fitted with less disruption to the detail in the forecast background.

New techniques for using the LASS retrievals discussed above are being developed as part of this scheme, but are not yet ready for testing.

A two-cycle rerun of the global version, like the operational global scheme, gave a good forecast from 0000 GMT. A fine-mesh version of the scheme which is being developed was tested on the assimilation leading to 0000 GMT on the 15th. Results were slightly worse than the corresponding run with the operational assimilation. The test of the fine-mesh version of the assimilation for 1200 GMT on 15 October has already been described in section 4. It gave the only analysis so far obtained for that time which leads to a good forecast of the storm.

6. Conclusions

The storm which crossed the south of England during the night of 15/16 October 1987 developed when an upper-level trough caught up with a strong frontal zone on 15 October. The existence of this development region was well forecast by numerical models several days in advance. Details of the features within this large-scale situation were crucial for determining the track, timing and intensity of the storm, and they were less consistently forecast. In contrast with the global model, the fine-mesh forecast from 0000 GMT on 15 October did not give a good prediction of the storm's track and intensity over England because of incorrect details in its initial conditions. Aircraft reports from the Atlantic between 0130 and 0300 GMT, which were too late for the operational analysis, would have provided much of the necessary detail; more would have come from satellite temperature soundings which arrived too late for the previous 2100 GMT analysis. A forecast based on the 0600 GMT analysis, which incorporated these late data as well as the 0600 GMT observations, would have provided excellent guidance to the development of the storm.

Neither of the two operational model forecasts from 1200 GMT predicted the storm adequately, but a fine-mesh forecast from a new assimilation scheme which is being developed did; the reasons for this are still being resolved. In the development of the storm there was a very large sensitivity to the details of the three-dimensional atmospheric structure which were not resolved by the available observations.

High-resolution models gave a better prediction of the local severity of the storm.

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Public forecasts and warnings of the storm of 15/16 October 1987

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Summary

The various forecasts and warnings issued for the storm of October 15/16 are described and the procedures in operation for warning the public and emergency authorities are discussed.

1. Introduction

Forecasts and warnings in the public sector are issued on a regional basis by the network of Weather Centres. These forecasts are based on guidance provided regularly by the Central Forecasting Office (CFO) in Bracknell. Presentations on national television and radio are carried out by London Weather Centre staff and there are routine telephone conferences with CFO to ensure that the forecast is up to date and consistent with the Senior Forecaster's views.

As regards the storm, forecasts were issued from as early as the previous Sunday and a fairly consistent picture was maintained during the week. This was reflected in the warnings issued on Thursday the 15th though the exceptional severity of the wind was not foreseen until late on Thursday evening. Many warnings were then updated a few hours before the onset of the storm. The Weather Centres at London, Norwich and Southampton were most heavily involved and several night duty staff stayed on in the morning to cover for those delayed getting into work. All in all it was a very busy period for all concerned.

2. Medium-range (2 to 6 day) forecasts

Useful forecast guidance for the 15/16 October began with the forecasts issued on Sunday 11 October.

There was mention of 'rather wet and windy weather right at the end of the week' on the BBC 1 television programme 'Weather for Farmers' broadcast on Sunday 11 October at 1258 (all times are BST unless indicated otherwise). The caption map displayed at the end of the broadcast included 'becoming very windy late in the week'. Many of the BBC television and radio forecasts from Monday to Wednesday highlighted the stormy weather expected later in the week. On the BBC 1 Wednesday broadcast at lunch-time for example, instead of opening with today's weather as is usual, the weatherman spoke of a low pressure system which 'is going to deepen like mad and head up and give us an angry spell of weather, wet and windy' on Thursday and Friday.

An example of the service that was provided to specialist users is the series of weather forecasts issued during the week to the Automobile Association. On Monday, the forecast for Thursday for south-east England was 'becoming windy, gales in places'. On Tuesday, the summary spoke of 'a major storm, crossing Britain from the south-west during Thursday and Friday'. The forecast for south-east England for Thursday was 'becoming very windy with gales or storm-force winds developing'. For Friday, the forecast was 'stormy at first, then slowly becoming less windy'.

Finally, the Meteorological Office issues forecasts for three to five days ahead on the pre-recorded telephone service, Weathercall; the relevant forecasts from Monday to Wednesday all referred to the expected exceptional strength of the wind.

3. Media forecasts issued on Thursday 15 October 1987

On the day before the storm, CFO did not anticipate the full severity of the winds. The forecasts highlighted the deep depression moving up from the south-west but concentrated on the heavy rain which was expected as a result. This was reflected in the wording used in the public forecasts issued that day. Part of the reason for the emphasis on rain lay in the weather of the previous week. There had already been copious amounts of rainfall during October, and over the previous several days there had been widespread flooding, especially in the south and east. This concern was clearly dominant in the forecasters' minds — for example, a message from Norwich Weather Centre to London Weather Centre on the afternoon of the 15th expressed the Water Authorities' serious concern at the risk of widespread flooding should the rain expected that night in their area occur.

The BBC 1 television weather forecasts at 1325, 1833 and 2128 all mentioned the likely wind in the south and east, but gave it less emphasis than the rain. Nevertheless, the wind symbols on the charts for both the early-evening and mid-evening broadcasts (symbol charts identical) showed winds of 50 m.p.h. (43 kn) for 'tonight' off the east coast and in the eastern English Channel. Note that the symbols represent mean wind speeds, not gusts.

The early evening broadcasts on BBC East and BBC South, given by staff from Norwich and Southampton Weather Centres, emphasized the wind rather more than the national forecast had done — as one would expect from a local forecast covering an area with extensive coastlines — but the national and local basic products were entirely consistent with each other.

On BBC Radio 4, the 1755 broadcast spoke in the introduction of 'an intense low pressure centre' moving across the Midlands overnight bringing 'strong winds'. The main body of the forecast for south-east England referred to expected conditions as 'quite windy with southerly winds touching gale force near south-eastern coasts for a while'.

The local radio scripts written at London, Southampton and Norwich Weather Centres, and those scripts written for the 24-hour forecast service on Weathercall for the affected areas, dealt with the situation in a similar way, tending to emphasize the unsettled nature of the weather and the rain, and making less of the wind. This was particularly the case with the forecasts for inland areas as opposed to those for coastal areas.

By midnight, however, rather more was being made of the expected winds. The live 0020 Radio 4 broadcast emphasized the severe weather to occur that night; part of it said 'just to re-emphasize, some dirty, wet weather to come, especially for England and Wales, as a really nasty depression sweeps up from Biscay, ... so some really unpleasant conditions if you are out and about on the roads and motorways tonight, some torrential rain, stormy winds eventually, especially on the Channel coast, and there will be inland gales as well'.

Finally, two television broadcasts are relevant in considering the wider area affected by the strong winds. In the BBC 2 'Weatherview' programme (pre-recorded at 2030, as usual, for broadcast at 2305), much was made of the strong winds over the sea areas and the near continent. Earlier in the day, the 1355 broadcast for the European satellite television Superchannel, which is presented by the weatherman at the BBC Television Centre, had opened with 'It's a case of batten down the hatches I think for some parts of Europe; some very, very stormy weather on the way indeed'. There was a subsequent reference to likely gales in France and the Low Countries and, later, in Scandinavia.

4. Warnings

Before going into details about the warnings issued to various authorities, it is necessary to describe the arrangements by which such warnings are given. The Meteorological Office, through its Weather Centres, gives notification of conditions expected to exceed given thresholds to those authorities requesting them. The thresholds are defined by the customer according to their operational needs.

Of particular relevance on this occasion are the arrangements by which the Meteorological Office warns emergency authorities. The London Fire Brigade has arranged to receive warnings if winds are expected to be more than 26 kn (30 m.p.h.); this is because winds of this strength curtail their use of long ladders. The London Fire Brigade has not asked to be warned of any other hazardous weather conditions, or of any wind strengths greater than the threshold. No other fire brigade has asked for warnings of any nature to be given and there are no national arrangements.

There is a national arrangement for warning police forces of fog on motorways, but all other arrangements for issuing warnings to the police are organized on a local basis. In the south-east, the local police forces receive warnings of snow, icy roads and heavy rain as well as fog, but there are no arrangements for the issue of strong wind warnings. In East Anglia, however, police forces do receive warnings of mean winds greater than 30 kn. Medical authorities only receive warnings by request and arrangement; in the south-east of England there are no such arrangements.

The Meteorological Office has organized a FLASH weather service by which the public can be warned via radio and television of the occurrence of severe weather which may cause considerable inconvenience to a large number of people and/or present a danger to life. These warnings are only issued when there is a virtual certainty of occurrence (usually based on actual weather observations) and the aim is to give immediate warnings of the onset of severe weather. The FLASH message system is important during the day since avoiding action, particularly by those intending to travel, can be taken. It is clearly much less effective at night when most people are in bed asleep, but they are not then exposed to weather hazards to the same extent. Weather FLASH messages are still issued at night, however.

FLASH warnings may be issued in cases of dense fog, heavy rain, heavy snow, widespread icy roads and severe inland gales and blizzards. They cover the 18 major urban areas of the United Kingdom (with the exception of blizzards which can refer to any area). Arrangements have been made for warnings to be broadcast through the BBC on national radio and television, and on those independent television and radio companies which agree to carry them.

Apart from receiving copies of FLASH warnings, the BBC Motoring Unit receives warnings of hazardous weather for broadcast on the BBC radio network. The criteria for these messages are less severe than for the FLASH messages; in the case of strong winds, the threshold is a mean speed of greater than 30 kn.

Warnings of exceptionally severe weather, which may call for military aid to be provided to the civil community, are issued to the Ministry of Defence at any time throughout the 24 hours. Forecasts are required when the following phenomena are anticipated:

- (a) Severe inland gales with mean wind speed of 43 kn (50 m.p.h.) or more; 'inland' means anywhere over inhabited parts of the United Kingdom.
- (b) Heavy and prolonged rain.
- (c) Snowfall likely to reach a level depth of 1 ft or more.

The Meteorological Office also issues warnings of high winds to British Rail because of problems in windy conditions with overhead lines. The requested threshold is a mean speed of 34 kn (i.e. gale force) or gusts over 60 kn. Warnings are only provided to those parts of the British Rail network where there are overhead lines; Southern Region is not covered.

On this occasion, the relevant warnings were issued at the following times:

Recipient	Time (GMT) 15/16 October
1. British Rail (Eastern Region)	1730
2. London Fire Brigade	2150
3. East Anglian Police Forces	2305
4. BBC Motoring Unit	2315
5. FLASH message of severe gales	0120
6. MOD for and to civil community	0135
7. London Fire Brigade	0140
8. All Police Forces in south-east	0145

Note that the warning to the London Fire Brigade at 0140 GMT was on the initiative of the London Weather Centre forecasters — there is no arrangement for this. Similarly the warning to the police in the south-east was beyond any agreement in respect of strong winds.

5. Forecasts for specialist purposes

5.1 *Forecasts for sea areas*

As early as 0630 GMT on 15 October, gale warnings were already in operation for all parts of the English Channel. At 1030 GMT on the same day warnings of severe gale force 9 'soon' were issued for the whole Channel except for sea area Plymouth ('soon' implies a time of validity between 6 and 12 hours after time of issue of the warning). These warnings were reaffirmed at 1710 GMT, except that it was anticipated that the gales in Portland would decrease to force 8 during the night.

The forecasts for the Channel sea areas were not revised until 2235 GMT on the 15th when warnings of storm force 10 were issued for all areas. These warnings were issued after an assessment of the 1800 GMT mean-sea-level pressure analysis. At 0135 GMT on the 16th the forecasts were increased to violent storm force 11 'imminent' (i.e. within 6 hours) for all parts of the Channel.

In addition, some forecasts for inshore waters are prepared for broadcast by local radio stations. The forecast for the inshore area from the Pool of London to North Foreland to Dungeness, issued to Radio Essex at 1631 on the 15th covering the period 1800 to 0600 on the 16th, was for winds increasing to between force 7 and severe gale 9 (30 to 45 kn) with gusts over 50 kn likely.

London Weather Centre issues many routine forecasts to the offshore industry operating in the North Sea. It is interesting to study a series of forecasts for a location off the coast of Norfolk issued between Monday 12 October and 0130 on 16 October. Apart from the high quality of the forecast early in the period, of particular relevance is the forecast issued on the afternoon of the 15th predicting winds overnight of 40 to 50 kn with gusts higher.

Generally the forecasts issued during 15 October for coastal or offshore areas, where wind is of course an important feature at all times, did include very strong winds. In particular, one major offshore contract actually began at midnight on the night of 15th/16th! Warnings issued were much appreciated by the operational staff offshore and proved to be very accurate.

5.2 *Forecasts for civil aviation*

The Senior Forecaster at London/Heathrow Airport is responsible for the forecasts for civil aviation but there are regular discussions with the Senior Forecaster in CFO. A strong wind warning was issued to 35 airfields in south-east England at 1328 GMT on the 15th valid up to midnight, forecasting wind speeds of 15 to 20 kn and gusts of 35 to 40 kn. A second strong wind warning was issued at 2300 GMT, followed at 0100 GMT on the 16th by a gale warning for wind speeds of 30 kn and gusts to 50 kn. This was quickly superseded by a storm warning issued at 0130 GMT forecasting a wind speed of 35 to 40 kn

and gusts of 55 to 65 kn. At 0450 GMT a further storm warning was issued giving wind speeds of 35 to 40 kn and gusts to 80 kn. Subsequent warnings were for gale and strong wind (depending on location) gradually moderating.

The warnings proved sufficient for most operational purposes and although damage is known to have occurred, no complaints have been received about the service provided.

5.3 Forecasts for military airfields

The Principal Forecasting Office (PFO) at Headquarters Strike Command is responsible for the forecasts issued for military airfields. The PFO produces its own forecast charts and for 0600 GMT on 16 October it forecast a depression of 959 mb near 55° N, 00° W, little different from the 0600 GMT forecast produced earlier by CFO.

Strong wind warnings were subsequently issued for military airfields south-east of the line Lincolnshire–Cornwall. Warnings of severe gales were issued during the evening, which preceded the onset of the gale at 6 stations by 3 hours or more, and at a further 5 stations by 8 hours. These warnings enabled the military authorities to take appropriate action and, apart from one aircraft parked inside a hangar which suffered superficial damage from a falling glass roof panel, no damage to aircraft has been notified.

5.4 Forecasts from other countries

A number of forecasts issued by the French National Weather Service have been obtained. It should be noted that forecasts covering the United Kingdom are not issued. For northern France, where very strong winds had always seemed likely, good warning was given. On the 14th, a message of severe weather was issued to various addresses, including the French railways, the Water Board, the Electricity Board, the national press and television stations. The message forecast winds of 43–54 kn for Thursday over some coastal areas and the English Channel, with extreme gusts of 80 kn. Sea-area forecasts and gale warnings issued by the French National Weather Service were generally similar to those issued by CFO.

6. Discussion

The medium-range forecasts issued (from the Sunday to the Wednesday) were generally very good though there is always uncertainty at this stage about the track of a depression and its intensity. Within 24 hours, the expectation is to produce a much more detailed forecast. On this occasion there was mention of strong winds in most of the forecasts, but the extreme severity of the wind was not anticipated until late on Thursday evening.

Nearly all the users of the specialized forecasts produced by the Meteorological Office were satisfied with the service provided; some, in the offshore industry for example, were very grateful. It should be noted, however, that actions are geared to wind speeds which are not as extreme as those that occurred (for example, a gale force wind of 34 kn or greater). Further, when the notice of a very severe event is given, such action as can be taken in the circumstances may often be carried out at relatively short notice and there are staff available throughout the 24 hours. The general public is not in this position and while the short period FLASH weather warning system is effective by day, it is inevitably less so at night (although messages are still issued). Further ahead, warnings to the public may be put out via the standard radio and television presentations (both national and local). On national BBC television there have been increases (in recent years) in both the number of broadcasts and the time allotted. Nevertheless, there may be scope for further action here.

One area where there will be changes of procedure concerns the warnings provided to the emergency

authorities. The warnings required by the Ministry of Defence, in cases which may call for military aid to be provided to the civil community, are well defined. These go to a single point in the Ministry of Defence and work well, even though warning of exceptional conditions is usually given with only a few hours notice. A similar arrangement with police and other emergency authorities may prove to be necessary. This will be discussed, at the initiative of the Meteorological Office, with the bodies concerned. At the same time it would be useful to review the wider requirements the emergency services have for weather information. Current procedures, with the police for example, have developed over many years, mainly on a local basis. One exception to this is the arrangement for issuing warnings of dense fog to the police; this was set up in 1965 by the then Minister of Transport following a series of crashes on motorways in foggy conditions. Although on 15/16 October warnings were passed to emergency authorities in accordance with arrangements made (in some cases exceeding the agreed requirements), extension of this nationally organized scheme may well be needed. Information would still be provided on a regional basis by the Weather Centre most closely in touch with the local weather; ideally it would be issued to a few key national and regional centres for onward distribution within the organization.

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Media reaction to the storm of 15/16 October 1987

D.M. Houghton

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F.R. Hayes and B.N. Parker

Meteorological Office, Bracknell

Summary

The media reacted strongly to the storm, and in particular to the supposed failure of the forecast. This article summarizes the main points made and the response of the general public.

1. Introduction

During the period following the storm, there was an unprecedented level of interest from TV, radio and the press, most of it centred on the question 'Why did the forecasters get it wrong?', though there were many subsidiary issues. The majority of items were critical of the Office, some extremely so, but about a quarter provided a more or less balanced view of the situation. As time progressed there was a growing body of press opinion (though never in the majority) which expressed a more sympathetic view. An increasing proportion recognized that the south-east of England could not have escaped the damage, however accurate the forecasts might have been. Many letters were received from members of the public; the vast majority expressed support for the Meteorological Office in the face of what was perceived as undue criticism in the press.

2. Survey of reports and interviews

A survey has been conducted to ascertain the reactions of the media both before and after the storm. A major source of data for the survey was the set of press articles extracted routinely from the national daily and Sunday newspapers. Weather Centres in the south of England have supplied copies of items that have come to their attention in the other national and local papers. The other major source of data has been a series of transcripts of radio and TV programmes, supplied by an agency.

Every item available has been examined, but it must be stressed that there are gaps in the coverage — notably many of the local papers and the *Daily Mirror*. It is also rather unlikely that no comments on the subject were included in any of the weekend radio or TV programmes, as stated by the agency. However, it is felt that, given the repetitive nature of much reportage, the points mentioned are likely to be a good representation of most of those made even in the areas not examined in the survey.

3. Summary of reactions of the media

3.1 *Before the storm*

During the weekend prior to the storm, much media attention had been given to the widespread flooding which had occurred in the south-east of England following a period of very heavy rainfall. Reports of 'torrential rain' were quoted, and photographs of flood damage appeared under front-page headlines in many national newspapers on Monday 12 October. Meteorological Office spokesmen were quoted as saying that the worst of the rain had passed. There were no reports recorded in the media concerning the gales forecast for the end of the week.

3.2 *Friday 16 October*

By daybreak on Friday 16 October, the majority of TV and radio services were in chaos. Breakfast-time television and radio were disrupted, with only skeleton services being transmitted. These transmissions almost exclusively reported facts as they became available, together with warnings and guidance for householders, travellers, schoolchildren, etc.

As the morning progressed, services were re-established, and attention began to shift towards forecasts issued the previous day. At 11 a.m. Nigel Gait of London Weather Centre was being faced on the 'Jimmy Young' programme (BBC Radio 2) with such statements as 'I don't recall being told in advance to expect weather like this'.

During the day, radio and TV picked up many of the issues that were to be expanded and reiterated later:

- An assertion that the ambulance services did not receive a warning.
- An assertion that the London Fire Brigade was paying for a warnings service.
- A comment by Michael Fish on his BBC TV lunch-time forecast that there would not be a hurricane. Subsequently, this term was used in virtually all media reports and articles to describe the event.
- Bill Giles's BBC 2 TV presentation pre-recorded at 8.30 p.m., broadcast at closedown on the 15th, in which, pointing to tight isobars with 50 m.p.h., he said 'it will be very breezy up through the Channel and on the eastern side of the country'. (Note that this comment was followed by a description of very strong winds to be expected. Subsequent viewing of the transmission makes it clear that this was intended to be conveyed as a deliberate understatement.)
- The opinion that the Meteorological Office and the weathermen might be sued for negligence. This was particularly highlighted in the BBC Radio 4 programme 'PM' at 5 p.m.
- Opinions that the warnings came 'too late, no effective warning.'
- The view that meteorology needs more upper-air stations and weather ships.
- The view that the Office was only as good as its forecasts of extreme events.

3.3 *Saturday 17 October*

The Saturday papers were emblazoned with reports concerning the storm. The typical front page headline was something like 'Why weren't we warned?' The *Times* printed a report that the Meteorological Office had disregarded information from ECMWF, and that the French and Dutch had got the forecast right. This point was subsequently taken up by many newspapers as a key issue.

3.4 *Sunday 18 October*

By now, many newspapers were seeking stories which concentrated on the personalities involved. The Director-General of the Meteorological Office and the TV weathermen — notably Michael Fish — were besieged at their homes by reporters and cameramen. In addition, the BBC TV Centre was inundated with press enquiries concerning the weather and the forecasts broadcast prior to the storm.

The *Sunday Telegraph* reported the Environment Secretary as condemning an 'unbelievable failure to get it right'. Most papers concentrated on the French/Dutch/ECMWF forecasts. There was a complaint from one private meteorological consultant that the distribution of ECMWF forecasts was unfairly controlled by the Office, and a statement from another that he used forecasts from the Office, ECMWF and Offenbach!

3.5 *Monday 19 October*

Monday's papers produced a number of new points:

- A virulent attack on the Cyber supercomputer (*The Guardian*).
- The possibility of privatization (*The Daily Telegraph*).
- The view that power officials 'could have coped if we'd been warned' (*The Daily Telegraph*).
- Bengtsson's (ECMWF) comments: '(the Met Office) trying to be too exact' (*The Daily Telegraph*).
- The *Sun* called for the Director-General's resignation. Reports of interviews with the Director-General in the *Daily Mail* and *Financial Times* tempered the acidity a little.

The evening TV and radio carried reports and reactions to the Director-General's Press Conference, the views of ITN's 'News at Ten' being particularly condemnatory despite broadcasting an interview with the Director-General. The whole issue was trivialized in the TVS 'Question' programme ('Weathermen always forecast for the part of the country you're not interested in').

3.6 *Tuesday 20 October*

On Tuesday 20th most of the papers gave full accounts of the Director-General's Press Conference, some with later interviews, and the whole tone was very considerably changed for the better, although the *Guardian* still talked of the Office as 'top of everyone's list of duffers'. The evening TV and radio were also by this time coming down to a very low key, with most references being to the setting up of an enquiry. In the course of the 'Tuesday Call' programme (BBC Radio 4) the head of the Dutch company, Meteocast, agreed that reports that they had forecast with greater precision were misleading.

3.7 *Wednesday 21 October*

On Wednesday the papers produced a variety of views. The *Daily Express* had some irate language — 'complete, shameful devastation of the credibility of those smugly useless TV weather people', and most papers reported details of the Swinnerton-Dyer-Pearce inquiry, but the real interest lay in the letters. These ranged from the first mention of 'What could we have done even if the forecast had been correct?' to 'Do without them!'. There was a more supportive air generally, with letters from Brian

Hoskins and Ian James (both from the Department of Meteorology, University of Reading) suggesting probabilistic forecasting, and Norman Lynagh (Noble Denton Weather Service) saying that it could not have been forecast in detail more than a few hours before. His letter, however, went on to ask why the warnings had not been issued until after midnight. Several other letters backed probabilistic forecasting, usually by suggesting the use of 'may', 'could', 'might', etc. as well as 'will'.

Media interest was revived at this stage as severe flooding occurred in South Wales and the south of England. Merton Council was reported as complaining of the Meteorological Office's supposed inadequate warnings, to be rebutted by an interview with Roger Hunt (London Weather Centre) on 'Thames TV News' later in the day. There was a fair amount of further TV coverage, mainly on ITV. During the morning Norman Lynagh was interviewed on the 'Jimmy Young' programme.

3.8 Thursday 22 October

In Thursday's papers there were fewer articles but more interest. John Gribbin in the *Daily Mail* blamed it all on the greenhouse effect, Arthur Blackham in the *Independent* celebrated 'dead silence from the frog-spawn watchers' and recommended the Noble Denton Weather Service method of giving confidence levels. An article in the *Sun* was headed 'Twenty things you didn't know about Weather Wally Fish'.

On television, Professor Pearce in the 'Breakfast Time' interview was fair but neutral despite rather leading questions from the interviewer. In the evening 'Tomorrow's World' produced an 'explanation' of the forecast failure based on a theory that the 0.2 °C global rise over the last ten years had been greater over the oceans than the land.

3.9 Friday 23 October

In Friday's *Daily Telegraph* an article concluded that if it were not for the Ministry of Defence the Office could be the next to be privatized and rationalized. The other papers only carried letters of interest, among which was one from Hugh Cumming (spokesman for the Institution of Professional Civil Servants) and another demanding more weather ships, a comment that was to be repeated fairly often. There was little on TV.

3.10 Saturday 24 October and afterwards

On Saturday 24th the *Times* third leader was asking why the Office should be in the Ministry of Defence, suggesting that the Office was being asked to do too much, highlighting conflict between the Office's role as a National Meteorological Service and its commercial roles, and hinting that we penalized the airlines in comparison with the shippers.

The *Sunday Times* went back through all the early comments without adding anything significant.

Tuesday's *Guardian* carried a blatant advertisement in the guise of an article about Metecast (Europe's satellite-TV weather channel) saying that it was better than the BBC forecasts or teletext because it was continually updated.

On Friday 30th it was discovered that BBC's Ceefax had been carrying a highly critical article entitled 'MEGA-BLOOMER' for a period of at least a week.

On Saturday 31st an article by Brian Hoskins and Ian James (Department of Meteorology, University of Reading) appeared in the *Guardian*, giving some very good background and making more clearly than anyone else the point that a 300 km wide storm can easily be missed by an upper-air observing network that has an average spacing of 270 km only over the land.

Thereafter the issue dropped out of the limelight, in the wake of continuing problems in the Stock Market.

4. Interviews, News Releases and Press Conferences

Many interviews were given by members of staff to the media. Also, during the period, two News Releases were issued by the Press Office:

- (a) Friday 16 October at 3 p.m. issued from Bracknell. This gave a very brief summary of the key facts known at the time.
- (b) Saturday 17 October at 3 p.m. issued from London Weather Centre. This concerned responsibility for Meteorological Office public service forecasts, and also stated that an internal inquiry on the storm was to be held.

On Monday 19 October, a Press Conference was held at London Weather Centre at 5 p.m., with the Director-General and senior members of the Directorate in attendance.

5. Reactions of the general public and customers

Not surprisingly, there was a considerable volume (several hundred) of letters and telephone calls from members of the public, as well as a smaller number from customers and representatives of various organizations.

The overwhelming majority expressed support for the Office and appreciation of its services. Many correspondents believed that the Office had been unduly criticized by the press.

Among the commercial customers, there has been hardly any negative reaction. Two customers for medium-range forecasts complained about the failure to predict the intensity of the storm although, as stated earlier, the forecasts issued a few days before the event were in fact very good; the situation has been explained to these customers. The Office also received a complaint from the BBC who said that the lack of warning of the storm given in the TV forecasts reflected upon their own credibility.

6. Summary of principal issues in the media

Many comments and criticisms appeared in the media, notably in the press. There was a mixture of informed and uninformed opinion, as well as perceptions which in retrospect seem distorted. The central issues were:

- Whether the forecasts had been 'wrong'.
- Whether other meteorological agencies, particularly those in The Netherlands and France, had issued more accurate forecasts. At present, no meteorological agency is claiming this; indeed there have been public assertions by such agencies to the contrary.
- Whether there had been any negligence, and whether any information (e.g. from ECMWF) had been disregarded.
- The comments made during TV forecasts during the previous day. The interpretation of these comments is a matter for judgement. Clearly, they were intended to be part of the style of delivery of the forecasts, aimed at making them more interesting rather than a dry repetition of the facts.
- Whether warnings had been too late.
- Whether emergency services had been given adequate warning.
- Whether commercial customers had received a better service than the general public.
- Whether there are sufficient upper-air stations and weather ships.
- Whether the Meteorological Office should be privatized.
- Whether anything could have been done had there been more warning.
- The difficulties of forecasting such extreme events and weather systems of such small size.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

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References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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April 1988

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Editorial Board: T. Davies, W.H. Moores, P.R.S. Salter, P.G. Wickham

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Swinerton-Dyer/Pearce Report
Noise assessment model
Llanthony experiment
Summer of 1987



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Summary and conclusions from the Secretary of State's enquiry into the storm of 16 October 1987

Sir Peter Swinnerton-Dyer

University Grants Committee, London

R.P. Pearce

Meteorology Department, University of Reading

Summary

The Secretary of State for Defence invited Sir Peter Swinnerton-Dyer (Chairman of the University Grants Committee) and Prof. Robert Pearce (University of Reading) to consider the findings of the internal enquiry carried out by the Meteorological Office into the storm of 15-16 October. A summary of their report and the conclusions about the internal enquiry are given.

1. Introduction

Following the storm of 15/16 October 1987, the Director General of the Meteorological Office instituted an internal enquiry into the weather forecasts that the Meteorological Office made in the period preceding the storm over southern England. The Secretary of State for Defence invited us to consider the findings of the internal enquiry (a shortened version of which appeared in the April issue of the *Meteorological Magazine*) and to report our conclusions to him. Our report was published in February 1988 and the following is the summary and conclusions taken from that report.

2. Summary

The lack of adequate public warning of the storm of 16 October arose from two direct causes, both related to the production of the forecast for that day at the Central Forecasting Office of the Meteorological Office (MO).

- (a) The computer forecasts available to the MO on 15 October were not in agreement, and all, including that from what is usually the most reliable model, underestimated the winds over south-east England.
- (b) The duty forecasters followed the guidance of their model too closely and did not recognize a situation in which the model was likely to underestimate the strength of the winds.

The presenters and the media cannot be held responsible for failing to issue warnings with which they were not supplied. But it must be said that on this occasion the television forecasts played down the winds over land even more than the forecasters' guidance did.

2.1 *The computer forecasts*

The main underlying factors responsible for 2(a) were as follows:

- (a) The usually more reliable high-resolution model is particularly sensitive to error under conditions of rapid storm development where sufficient observations are lacking.
- (b) There were, as usual, rather few observations over the sea, particularly to the west of Spain where the storm developed on Thursday 15 October. Because the coarse-mesh model is run later than the fine-mesh model it was able to take account of more observations; this seems to be the reason why the coarse-mesh model, which should in principle be inferior, performed better on this occasion. Subsequent analysis has shown that wind observations in this area from transatlantic aircraft would have been particularly crucial; more surface ship reports received in good time would also have helped.

These aspects of model failure are recognized in the MO report, and the recommendations made there provide sound guidance for attacking these problems. The computer forecasts available at the French Meteorological Service were somewhat more consistent than ours, mainly because they have access to a more powerful computer, but they equally underestimated the storm's intensification.

The MO fine-mesh model has a well-deserved reputation; indeed, when we visited the French Meteorological Service, they went out of their way to praise it. We believe both the mathematical formulation and the computer simulation to be as good as any in the world — though we trust that both of them will continue to be improved by incorporating the results of continuing research. But the model does suffer from one unnecessary handicap. The computer on which it runs (a Cyber 205) is significantly less powerful than the Crays available both to the ECMWF and to the French Meteorological Service, and in particular it has a smaller memory. One consequence is that the French fine-mesh model uses a mesh twice as fine as that of the MO.

In this context we would stress the importance of ensuring that the Meteorological Office always has at its disposal the most powerful computer available. Underprovision of computing power would indeed be a false economy, because it would undermine the campaign to increase the MO's commercial income — and this campaign is essential to the MO's future funding strategy. We are relieved to hear that the MO will be provided with an ETA 10 supercomputer in the Spring, even though the cost has had to be found by internal economies. We are not in a position to comment on the damage done by these economies beyond saying that it will have to be endured because the new computer is essential.

The computer models, and their enhancements, are among the major products of the Research Division of the MO. That Division provides good value for money, and without it the MO would rapidly fall behind its competitors in other countries. There is a continuing need for research, both in the MO and in universities. The division between the two is about right, research and development in the MO being closely motivated by operational needs and research in universities being more fundamental — though that too will eventually be reflected in better forecasts. In atmospheric science, the MO's links with university departments have recently been strengthened. We regret, however, that it has not been possible to interest academic numerical analysts in the (probably very difficult) problems related to weather forecasting, including the fundamental problems of atmospheric predictability. This is particularly true of the 'spin-up' problem — the problem of transforming initial observations to initial conditions on the grid on which the computer calculations are done. If the MO were to fund one or two CASE studentships in this area, that might create useful links at inconsiderable cost.

2.2 *The issued forecasts*

So far as 2(b) is concerned, no individual should be seriously blamed for the failure to forecast the severity of the storm. There are two main reasons for this. One is that the demands on the forecasters on this occasion were unusually heavy. Whoever happened to be on duty on 15 October was going to face what was likely to be the severest test of his career. The interpretation of computer forecasts is largely a subjective process and the model's guidance was, on this occasion, unusually confusing. Although most forecasters would have stressed the possibility of severe land gales, as indeed did the French, it seems to us possible to defend the failure of the senior forecaster actually on duty to do so.

The other reason relates to the senior forecaster's work schedule. His first task on taking up his duty is to assess the meteorological situation. He then prepares his 'synoptic review' describing his assessment and this is subsequently used, with periodic updating, as guidance for the detailed forecasts issued to the public and subscribers. The senior forecaster taking up duty at 0800 is expected to issue his review by about 1000. Under normal conditions this gives him reasonable time in which to study the charts and computer forecasts and to identify and deal with any tricky aspects of the situation. Under exceptional weather conditions, however, his assessment needs more information than is at present readily available, and more time. Consultation with senior colleagues could also help. This was an occasion when none of these conditions could be met.

3. Conclusions

The question then arises 'What steps need to be taken to enable our forecasters to cope more effectively with exceptional conditions?' The general public understandably expects forecasters nowadays, with computer and weather satellites at their disposal, to be able to predict the weather more accurately than in the past and, in particular, give due warning of exceptionally severe events. The experience of this storm shows that, if forecasters are to meet these expectations, they need improved computer models. But, equally important, they also need sufficient background knowledge and experience to not only interpret computer forecasts but also assess their reliability. We are therefore led to recommend a re-examination of certain aspects of training and organization within the MO. The ones that particularly concern us are as follows:

(a) The training which our forecasters receive needs to be improved and lengthened. Compared with the French forecasters, the training which ours receive is shorter (and therefore cheaper) and lays less emphasis on meteorological theory. French forecasters complete two years of a first degree course, usually in mathematics or physics, followed by a three-year course at the meteorological college at Toulouse. In effect, when they start work they already have a Master's degree in Meteorology. Our forecasters are recruited on the basis of a first degree, again usually in mathematics or physics. During their career they will take a number of short courses at the Meteorological Office College, but their training relies extensively on on-the-job training — in effect an apprenticeship system. This does not give them the background of theory which they need if they are to take the fullest advantage of the strengths and weaknesses of the computer models at their disposal. It also puts them at a disadvantage when they are faced with exercising judgement in a situation that has no precedent within the collective memory of the MO. We recommend that the training of our forecasters be reviewed, and that the review should include a more detailed comparison with what happens in other countries than we have had time to carry out.

(b) The duty senior forecasters carry on their shoulders the full responsibility for forecasts and warnings issued by the Meteorological Office. Their rank of Principal Scientific Officer is below that of senior research scientists (and senior administrators), who however have no responsibility for issuing forecasts. These disparities reflect the relatively lower status of the senior forecasters within

the hierarchy which, in view of their ultimate responsibility for the successful performance of the organization, is inappropriate. At least the best of them should have the opportunity of being promoted to Senior Principal Scientific Officer on merit, without thereby being forced to move to other jobs within the MO.

(c) It is our impression that, as a result of the economies imposed on the MO in recent years, the staff on duty in the Central Forecasting Office has been cut to the minimum needed to do the work in normal circumstances. Any increased staffing would be in a sense a diseconomy; but the effect of the cuts is that when exceptional problems occur there is no spare effort that can be devoted to thinking them through. An alternative, and probably better, way to remedy this would be to provide better display facilities and more interactive computing; this would need considerable extra programming effort.

(d) There seems to be no formal arrangement within the MO under which, when there is a situation of unusual uncertainty with a possibility of particularly severe conditions, the senior forecaster on duty can consult more widely than usual. That this was such a situation should have been obvious very early on 15 October when it became clear that different computer models were giving diverse guidance; also fewer than usual midnight observations were being received from France. Wider consultation on 15 October would have enabled decisions, possibly different ones, to have been made at a high level as to whether the threat of an exceptional storm was sufficient to warrant alerting the public and, if so, at what stage.

(e) Similarly, when there are conditions of unusual uncertainty that uncertainty should be allowed to come through to the general public. The senior forecaster's synoptic reviews issued during 15 October reflect some uncertainty — though less than he probably felt at the time — but little if any of this came through in the radio and television forecasts. Part of the senior forecaster's responsibility should be to assess the degree of uncertainty that should be presented to the general public.

(f) There are times, particularly when the weather situation is complex, when the time allocated to the presenter is inadequate if the public is to be provided with sufficient detail, particularly of weather hazards. The media should be prepared to introduce sufficient flexibility into their programme scheduling to allow, at short notice, more time to the weatherman on such occasions.

Our first three conclusions are not reflected in the MO report. The report does, however, contain a recommendation concerning instructions to Senior Forecasters in dealing with critical situations, i.e. to provide more information to the public on alternative possibilities. This recommendation, which we support, relates to our fourth and fifth conclusions but we perceive the need for a more radical initiative.

The Larkhill noise assessment model. Part I: Theory and formulation

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Summary

Noise forecasting is a routine task performed operationally for a number of Ministry of Defence ranges in support of artillery training exercises and explosives testing. The forecasts are produced using a numerical model which is run on a desk-top computer. This paper, Part I, describes the current operational model and discusses the theoretical background. Part II of the paper (Turton *et al.* 1988) assesses the model and describes its use, and also presents a simplified technique for providing noise assessments for remote sites using synoptic data.

1. Introduction

Since the First World War, it has been well known that the sound generated by gunfire and explosions can travel long distances in the atmosphere. There are many recorded instances when the bombardments preceding the major battles in northern France were heard in south-east England. Generally such incidents were attributed to freak atmospheric conditions. During the last ten years there has been a steadily growing requirement for some assessment of when the noise from gunfire and explosions is expected to be unusually loud. This requirement has come mainly from the military ranges in southern England where a combination of newer and more powerful guns, an increasing population living close to the ranges, and a growing awareness of the environment have combined to produce numerous claims against the Ministry of Defence for causing 'noise nuisance' and sometimes actual structural damage to buildings.

The task laid upon the Meteorological Office was to predict the level of noise expected to reach various centres of population within about 20 km radius of the ranges. This work was undertaken by the Meteorological Office at Larkhill and some earlier results were published by Sills (1982).

Part I of this paper discusses the theoretical background and describes the current operational model. In Part II (Turton *et al.* 1988) the accuracy, sensitivity and limitations of the model are assessed, and some empirical results that allow noise assessments to be prepared using synoptic data are presented.

2. An overview of the theory

The speed of sound depends on both the temperature and the wind speed, but the wind speed is the dominant parameter. On a calm day, assuming isothermal conditions, sound rays travel in almost straight lines (Fig. 1(a)). However, in windy conditions the sound rays are bent (Fig. 1(b)), the degree of bending depending upon the vertical wind shear. This produces the well known effect of the noise from a gun being heard more loudly downwind than it is upwind.

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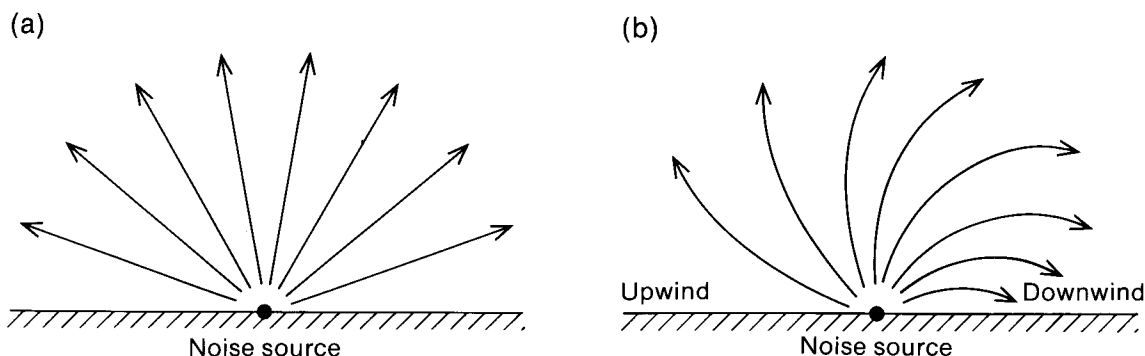


Figure 1. Illustration of the propagation of sound for (a) calm and (b) windy conditions.

2.1 Effects of wind

Let c be the speed of sound in an isothermal atmosphere at rest. Now consider a small section of a shock wave as it spreads out from an explosion in a region where the wind speed, v , increases with height (see Fig. 2). The top of the element has a speed relative to the ground of $c + v_2$ and the bottom of the element a speed of $c + v_1$. If $v_2 > v_1$ then the top of the element travels faster than the bottom and the inclination of the section to the horizontal changes as shown — the process is very similar to the way in which light waves are bent as they pass through a water-air interface. The result is that the sound rays are bent towards the region of lesser wind speed. The mathematical theory is outlined below.

The speed of sound relative to the ground, V , at a height z above a reference level z_1 is given by

$$V = V_1 + G(z - z_1). \quad \dots \dots \dots (1)$$

where $G = dV/dz$ is the gradient of the speed of sound, and V_1 is the speed of sound relative to the ground at height z_1 . Fermat's principle, which states that the path of a ray between two points is that which has the least propagation time, gives rise to Snell's law of refraction. Thompson (1972) discusses the various approximations that can be made to Snell's law for the case of a moving atmosphere, the simplest generalization being

$$\frac{V}{\cos \theta} = \frac{V_1}{\cos \theta_1}, \quad \dots \dots \dots (2)$$

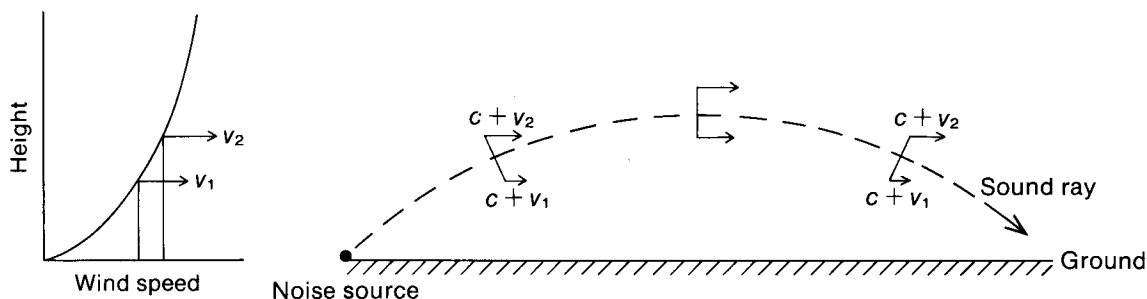


Figure 2. Illustration of the way in which a sound wave is refracted by a wind speed gradient. For explanation of symbols see text.

where θ and θ_1 are the inclinations of the sound ray to the horizontal at z and z_1 respectively, which allows equation (1) to be written as

$$z = \frac{V_1}{G} \left(\frac{\cos \theta}{\cos \theta_1} - 1 \right) + z_1. \quad \dots \dots \dots (3)$$

Differentiating with respect to θ and using $\tan \theta = dz/dr$, where r is the horizontal coordinate, gives

$$\frac{dr}{d\theta} = - \left(\frac{V_1}{G} \right) \left(\frac{\cos \theta}{\cos \theta_1} \right), \quad \dots \dots \dots (4)$$

and integrating gives

$$r = - \left(\frac{V_1}{G} \right) \left(\frac{\sin \theta}{\cos \theta_1} \right) + r_1 \quad \dots \dots \dots (5)$$

where r_1 is a constant of integration. Combining equations (3) and (5) gives an elliptic equation which describes the trajectory of a sound ray

$$\left(z - z_1 + \frac{V_1}{G} \right)^2 + (r - r_1)^2 = \left(\frac{V_1}{G \cos \theta_1} \right)^2. \quad \dots \dots \dots (6)$$

Two special cases are worthy of mention. Firstly, if the speed of sound is constant with height (i.e. in a homogeneous atmosphere) then $G = 0$ and the right-hand side of equation (6) approaches infinity, and the sound rays travel in a straight line. Secondly, if $G = \text{constant}$, then the right-hand side of equation (6) is constant so the equation becomes of the form $z^2 + r^2 = \text{constant}$, and the ray path is circular.

Thus, if the atmosphere is divided into a number of uniform layers, the ray paths through each layer describe an arc of a circle. The complete trajectory can then be built up from a series of arcs, and is relatively simple to determine. The use of this approximation was discussed by Suggitt (1978).

Further examination of equation (6) reveals some general characteristics about the propagation of sound in the atmosphere. For rays which have a shallow elevation, $\cos \theta \approx 1$, and the radius of curvature approximates to V_1/G ; thus for a value of $G = 0.1 \text{ s}^{-1}$ (15 m s^{-1} over 150 m — a typical atmospheric value) the radius of curvature is of the order of 3000 m . The curvature is shallow and therefore it is only rays with an initial elevation of less than about 20° which are brought back down to ground downwind of the source. Higher elevation rays will bend but are unlikely to come back down to the ground, except perhaps in mountainous terrain. Upwind, the rays are bent away from the ground, as illustrated schematically in Fig. 1.

Wind shear may also result from directional changes, rather than from changes in wind speed. This can also lead to the bending of sound rays back down to the ground.

2.2 Effects of temperature

The speed of sound also varies with temperature

$$c = (\gamma R T_v)^{1/2} = 20.05 (T_v)^{1/2}, \quad \dots \dots \dots (7)$$

where γ is the ratio of the specific heats of dry air at constant pressure (c_p) and constant volume (c_v) ($\gamma = c_p/c_v = 1.40$), R is the specific gas constant for dry air ($R = 2.87 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$) and T_v is the virtual temperature. Equation (7) gives $c = 331.4 \text{ m s}^{-1}$ at 0°C and 337.4 m s^{-1} at 10°C . Therefore in adiabatic conditions $G = -0.006 \text{ s}^{-1}$ and the rays are bent away from the ground. If the temperature increases with height, i.e. in an inversion, G is positive and the sound rays are bent back towards the ground.

Note that, whereas the presence of wind shear gave a preferred direction for noise enhancement, the presence of a low-level inversion bends sound rays towards the surface in all directions, giving noise enhancement uniformly around the source.

2.3 Combined effects of wind and temperature

Fig. 3(a) shows the trajectories of the sound rays in both the upwind and downwind directions for typical daytime conditions with light winds; the meteorological profiles are shown in Fig. 3(b). In the downwind direction, the effects of the winds are sufficient to overcome the effects of the lapse rate and the sound rays are bent back down to the ground. Upwind, the wind and temperature effects combine in bending the sound rays away from the ground. The fact that the winds have a stronger influence on the sound rays than do the temperatures can also be seen by differentiation since $dV = dc + dv$. Considering only the effect of temperature gives $dV \approx 0.6 dT_v$ for $T_v \approx 280$ K, whereas for wind only $dV = dv$. Typically the effect of wind shear is an order of magnitude greater than that of temperature.

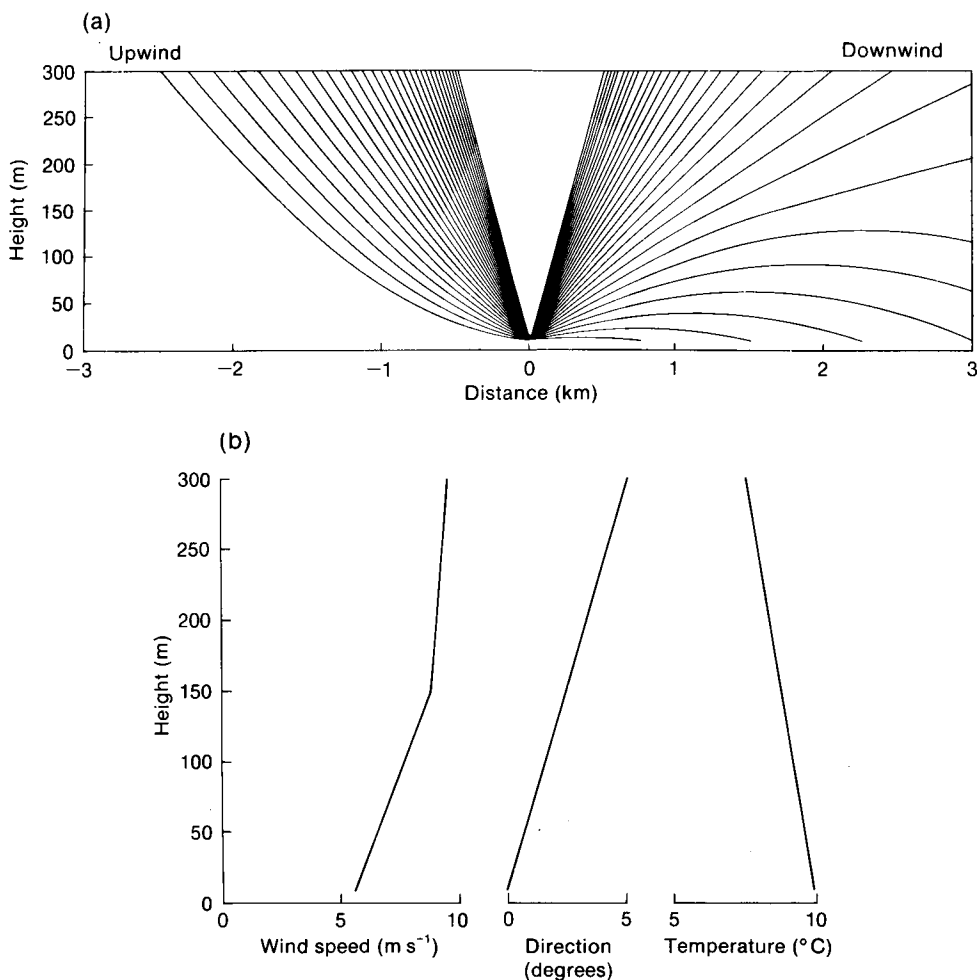


Figure 3. (a) Predicted sound-ray trajectories for typical daytime conditions with rays drawn at 1° intervals and (b) profiles of wind speed, direction and temperature specified in the model.

At night, the situation would be expected to be rather different as the presence of a nocturnal inversion (of typically a hundred metres or so depth) would tend to increase the bending of sound rays back towards the ground.

Also, elevated inversions associated with areas of subsidence or frontal systems may occur, and the presence of these may indicate regions of significant wind shear. Clearly such features will influence sound propagation. In particular, sharp inversions are often found capping cloudy layers, e.g. the inversion capping stratocumulus can be as large as 10 K over a distance of less than 10 m, and nearly horizontally inclined sound rays may be reflected by such inversions.

2.4 Behaviour in the atmosphere

From a consideration of the above effects it might be expected that the noise from gunfire would be loudest in a downwind direction on days when there is a marked low-level inversion, and quietest in an upwind direction on convective days. Although this is generally true, the situation is seldom that straightforward.

Consider, for example, the conditions for 1100 GMT on 20 August 1985 at Larkhill. The wind and temperature profiles are given in Fig. 4, and show the warmer air aloft and veering of the winds associated with a warm front which was approaching from the south-west. These profiles were used to calculate the trajectories of sound rays emanating from a point source. A plan view of the density of sound rays returning to the ground is shown in Fig. 5, which illustrates the three distinct regions for sound propagation that can occur. The first of these, marked A in Fig. 5 occurs in the downwind direction (035°). In this region only shallow rays of less than 12° initial elevation are brought back down to the ground. This is also shown by Fig. 6(a), which shows a cross-section with the ray trajectories for 035° (note that the scales are different from those in Fig. 3(a) in this example). In the upwind direction (Fig. 5 region B and Fig. 6(b)) no rays return to the surface, as they are all bent away from the ground. A third region also occurs (Fig. 5 region C), where a number of rays come to ground over 10 km from the source over a range of directions, particularly between 090 and 180° . Fig. 6(c) shows the ray trajectories for 150° , where a number of sound rays are brought back down to the surface around 10–15 km from the source.

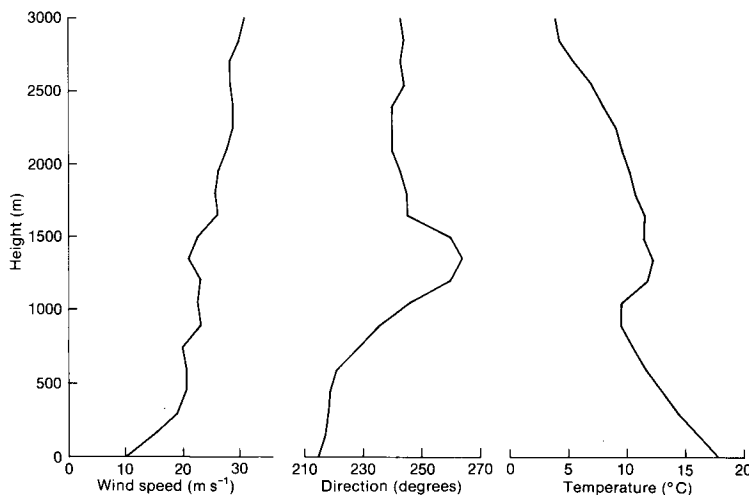


Figure 4. Profiles of wind speed, direction and temperature at Larkhill for 1100 GMT on 20 August 1985 as used in the model assessment.

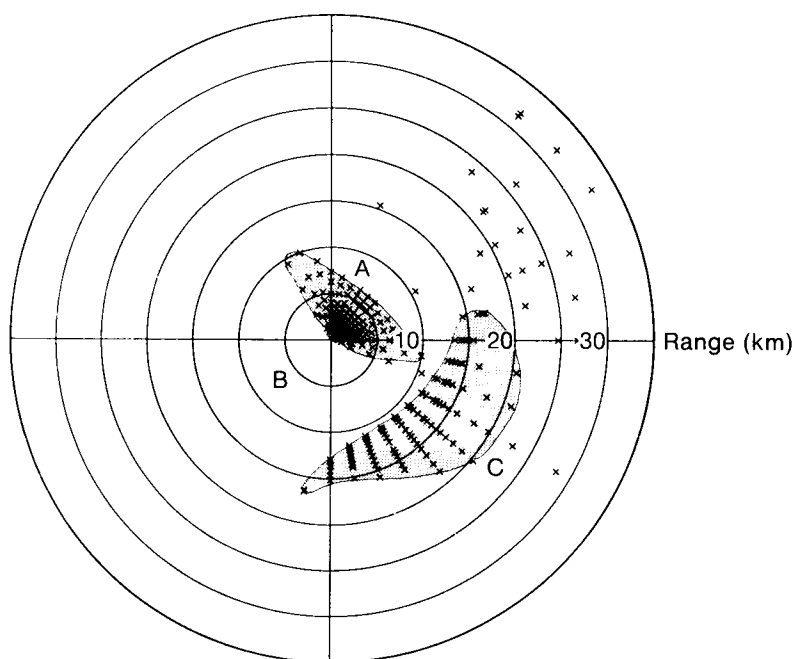


Figure 5. Polar diagram for Larkhill at 1100 GMT on 20 August 1985 showing the predicted locations at which sound rays return to the ground.

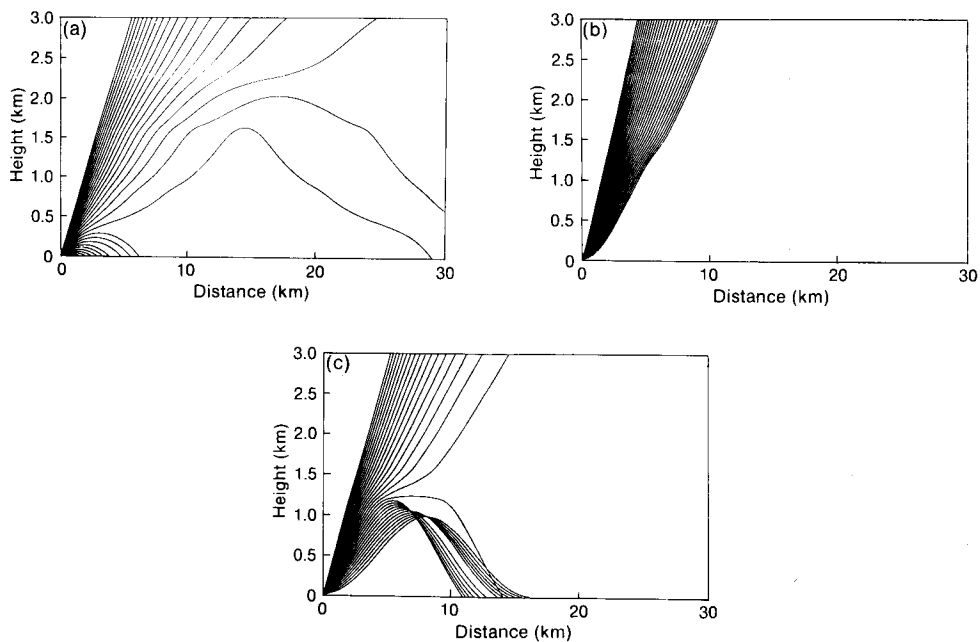


Figure 6. Predicted sound-ray trajectories for Larkhill at 1100 GMT on 20 August 1985 for (a) 035°, downwind, (b) 215°, upwind and (c) 150°. Rays are drawn at 1° intervals. Note the different scales from those in Fig. 3(a).

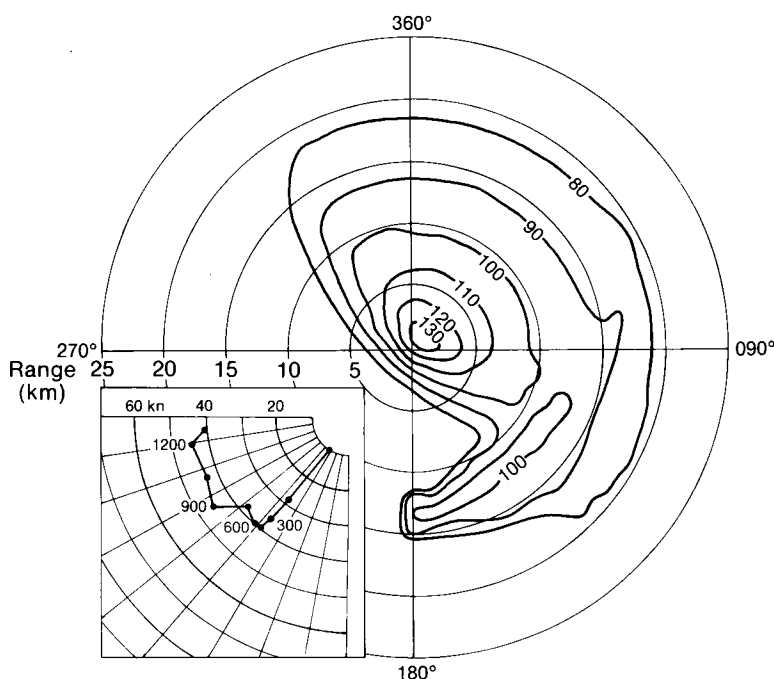


Figure 7. Polar diagram for Larkhill at 1100 GMT on 20 August 1985 showing model-predicted noise levels (for a 5 lb charge). Inset is a hodograph (with heights in metres) showing the winds on this occasion.

In the current model the predicted noise levels are related to the density of sound rays which return to the ground. The details of the method by which the noise levels are determined are described fully in the following section. However, the calculated noise levels for this example are shown in Fig. 7 to illustrate the three regions A, B and C mentioned above. To the north-east the downwind 'enhancement' of noise levels results (region A), whilst to the south-west, in the upwind direction, a sound 'shadow' with reduced noise levels occurs (region B). To the south-east, where many rays come down to ground away from the source, is a sound 'focus' where increased noise levels result (region C). Such foci tend to occur between 5 and 20 km away from the source and are often the cause of unexpectedly loud noise levels.

The relationship between these two enhanced regions of noise may be understood by considering the structure of the winds. These are shown by the hodograph inset in Fig. 7. The downwind enhancement is due to the difference in wind speed over the lowest few hundred metres, while the focus is caused by the changes in wind direction above 600 m, and lies in the direction of the wind shear vector. Basically, the downwind enhancement is mainly due to the differences in the wind speed whilst the focus primarily results from directional changes.

3. Determination of the noise levels

Although the above theory of the behaviour of sound within the atmosphere may appear fairly straightforward and account for many of the observed properties, it is inadequate as a predictive model when attempts are made to forecast the actual sound levels. There are a number of reasons for this, but the primary ones are the lack of any representation of the scattering of sound by turbulence, the difficulty in describing how sound rays combine when they come together, and the effects of the underlying surface. The first is a problem of defining the degree of turbulence on a particular day and

knowing how the turbulent motions interact with sound waves. The last two are more fundamental problems. These factors are discussed in more detail in Part II of the paper (Turton *et al.* 1988).

Thus, although a forecast model can be based on the above theory, there is a requirement for a number of empirical constants before forecasts of actual noise levels can be produced. The work of Kerry *et al.* (1987) provided these empirical constants, and the current 'noise assessment' model used at the range stations was developed from that work. For the purposes of defining noise levels from artillery, the loudness in decibels (dB) is related to the peak acoustic over-pressure; the units used to describe sound levels are discussed in the Appendix.

In the current model the actual noise levels are predicted using the equation

$$L = L_0 - 20 \log_{10} r - c_1 r + c_2 N (\Delta e / \Delta r) \log_{10} r + c_3 G_s r^{1/2} \quad \dots \quad (8)$$

where c_1 , c_2 and c_3 are empirical constants ($c_1 = 0.0015$, $c_2 = 500$ and $c_3 = 20$). L is the peak sound pressure level (in decibels) at a distance r (in metres) from the source, L_0 is the effective peak sound pressure level (at a distance of 1 m) from the (point) source. N is the number of sound rays returning to the surface within an incremental distance Δr (in metres), Δe is the increment of initial ray elevation which is used in the ray tracing procedure (in the current operational model $\Delta r = 1000$ m and $\Delta e = 1^\circ$). The final term is applied in regions where no sound rays return to the ground ($N=0$), then $G_s = \min(0, G_1)$, where G_1 is the gradient of the speed of sound from the surface (10 m) to 150 m (i.e. through the bottom layer in the model).

The various terms in the prediction equation describe some of the physical processes relevant to acoustic propagation.

- (a) $20 \log_{10} r$ describes the free-field (hemispheric) expansion of the wave front.
- (b) $c_1 r$, which gives a linear attenuation of the sound level, is an attempt to describe the effect of the terrain in dissipating sound energy. (Note that the constant c_1 was determined from measurements made over undulating terrain.)
- (c) $c_2 N (\Delta e / \Delta r) \log_{10} r$ accounts for the effect that returning rays have in enhancing the sound levels, e.g. it is this term that gives the enhanced sound levels which occur either downwind or within a focus.
- (d) $c_3 G_s r^{1/2}$ gives the reduction in sound levels which occurs in the sound shadow region.

The sound shadow region is predicted to be strongest in the direction in which the speed of sound gradient G_1 is most negative, i.e. at an angle α to the surface wind.

$$\tan \alpha = \frac{v_2 \sin \beta}{(v_2 \cos \beta - v_1)} \quad \dots \quad (9)$$

where β is the veer between the surface and 150 m winds. Usually the strongest sound shadow is predicted to be in a direction which veers some 10 – 30° from the surface wind. Because the region of enhancement results primarily from the bending of sound rays within the lowest 150 m layer the direction of maximum enhancement, i.e. where G_1 is most positive, is also given by equation (9), being in the opposite direction to that of the strongest shadow.

However, in order to predict actual noise levels resulting from particular guns or types of explosive the effective source level L_0 must be specified. L_0 is determined from an empirical relationship:

$$L_0 = K_1 + K_2 \log_{10} W \quad \dots \quad (10)$$

where W is the explosive charge weight (in pounds) and K_1 and K_2 are constants which depend upon the type of explosive being used (the model is set up for plastic explosive with $K_1 = 185.5$ and $K_2 = 11.0$).

As seen from equation (8) the noise levels are determined by considering the contributions of the various terms in the equation. The accuracy, sensitivity and limitations of the predicted noise levels are examined in Part II of the paper (Turton *et al.* 1988). The practical use of the model is also discussed, together with a simplified method of producing noise assessments using only synoptic data.

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Appendix — Units of sound intensity

The intensity (I) of a travelling sound wave is defined as the energy propagating through a unit area per unit time. The range of intensities that can be heard by the human ear is about 10^{-12} W m⁻² (the threshold of audibility) to 1 W m⁻² (the threshold of feeling), a dynamic range with a factor of 10^{12} in intensity. To cope with such a large range it is convenient to define a logarithmic scale.

$$L = 10 \log_{10}(I/I_0), \quad \dots \dots \dots (A1)$$

where L is the sound pressure level in decibels and $I_0 = 10^{-12}$ W m⁻². Thus the dynamic range of the human ear is about 120 dB; beyond this level the sound produces a tickling sensation which gives way to one of pain at about 140 dB (the threshold of pain). An increase in intensity by a factor of 10 is then given by an increase of 10 dB. A person with normal hearing can barely detect an increase in loudness of 1 dB. The over-pressures associated with even very loud noises are small compared to atmospheric pressure, e.g. for $L = 130$ dB the over-pressure is only ≈ 0.65 mb.

The following table shows the intensity levels of some familiar sounds.

Intensity dB	Source/effect
140	threshold of pain
120	roar of a jet engine, threshold of feeling
90	pneumatic drill
60	busy street with traffic
30	suburban street at night
20	faint whisper
0	threshold of audibility

Noise from gunfire or explosions is of short duration; it is called impulsive noise and is usually given by its peak level (which is usually in the range 80–140 dB), and is determined from the peak over-pressure P . The peak level L_p is then given by

$$L_p = 20 \log_{10}(P/P_0), \quad \dots \dots \dots (A2)$$

where P_0 is a reference pressure of 2×10^{-7} mb which corresponds to I_0 . Because of its short duration, impulsive noise does not usually sound as loud as continuous noise of the same level. Impulsive sound levels in excess of 130 dB tend to lead to complaints and may cause structural damage to buildings.

The subjective loudness of a sound is related to its intensity, although it also depends on its frequency. Sounds of a higher frequency tend to be more annoying than those with low frequencies. However, the absorption of sound by the atmosphere is frequency dependent with the higher frequencies being most strongly attenuated. Noise from artillery contains mostly low frequencies, whilst that from rifles and small arms contains mainly high frequencies.

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Turbulence measurements above rugged terrain: the Llanthony experiment

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Summary

The drag force transmitted to the atmosphere by boundary-layer turbulence is one of the physical processes that must be parametrized in large-scale numerical models. While a large amount of data has been collected over flat surfaces, experimental data on turbulent boundary-layer flow over rugged terrain are scarce and generally limited to wind, temperature and humidity profiles obtained with pilot balloons and/or radiosondes. Although such data has been used to suggest parametrizations for the surface drag in areas of rugged terrain, there is an urgent requirement for direct estimates of the surface drag based on turbulence data. In the spring of 1986 the Meteorological Research Unit, based at RAF Cardington, carried out a number of tethered-balloon flights in South Wales. Probes attached to the balloon's tether-cable were used to collect turbulence data up to heights of 1000 m above the tops of a series of ridges. Turbulence data from two of these flights are briefly presented and a value of the roughness length for the area derived.

1. Introduction

An important area of boundary-layer research is the parametrization of surface fluxes in terms of large-scale flow variables, for use in numerical weather prediction models. Over the past twenty years data have been collected over a variety of surfaces (the sea, homogeneous areas of land covered by crops, forests, etc.). However, one area which has received relatively little experimental attention is the parametrization of surface fluxes in areas of rugged terrain (i.e. areas where the topographic features are a few hundred metres high and have horizontal scales of a kilometre or two). This gap in our knowledge is a result of the difficulty in obtaining such data, in particular obtaining direct estimates of the turbulent fluxes. This paper will describe some measurements of surface drag obtained in an area of rugged terrain during a recent experiment.

A widely used parametrization for the surface stress is the drag coefficient, defined by:

$$\frac{\tau_0}{\rho} = C_d U^2(z) \quad \dots \dots \dots (1)$$

where τ_0 is the surface stress, $U(z)$ the wind speed at a height z , C_d the surface drag coefficient and ρ the density of air.

The drag coefficient depends on the nature of the surface, the height above the surface, atmospheric stability, etc. For most natural surfaces the physical mechanism for the transfer of momentum from the atmosphere, which is to be represented by equation (1), is drag due to pressure differences generated across the roughness elements (e.g. grass, trees, mountains, etc.). This type of drag is known as form drag and is generally much larger than the drag due to viscous stresses generated at the surfaces of the roughness elements.

For a simple surface, such as the sea or a flat homogeneous land surface, the structure of the cloud-free boundary layer is shown schematically in Fig. 1. Near the surface there is a region which is shallow compared to the total depth of the boundary layer but is far enough above the surface not to be directly affected by the flow around the roughness elements. Within this region, which is known as the surface layer, the turbulence length scales depend largely on height above the surface. When the effects of surface heating or cooling are negligible, the drag coefficient in the surface layer is

$$C_d = \frac{k^2}{(\ln(z/z_0))^2} \quad \dots \dots \dots (2)$$

where k is Von Kármán's constant (later taken to be equal to 0.4) and z_0 is the roughness length.

The roughness length characterizes the underlying surface and values have been estimated for a wide variety of surfaces. Equations (1) and (2) can be combined to give the well known logarithmic wind profile,

$$U(z) = \frac{(\tau_0/\rho)^{1/2}}{k} \ln(z/z_0) \quad \dots \dots \dots (3)$$

which describes the variation of the wind speed with height near the surface. It cannot be taken for granted that the above results, obtained for flat terrain, can be extended to rugged terrain since, in this case, the heights of the roughness elements (hills, ridges, etc.) may be an appreciable fraction of the boundary-layer depth so that the surface layer, as described above, will not exist. However, as a starting point it is reasonable to see whether the drag coefficient can be described by equation (2) and, if so, to estimate a value for z_0 . In order to be able to define such a roughness length the boundary layer must be in approximate equilibrium with the underlying terrain. Model results suggest that such an equilibrium will only be achieved if the terrain is statistically homogeneous over areas of 10^2 to 10^3 km².

In the spring of 1986 the Meteorological Research Unit, based at RAF Cardington, carried out series of measurements using instruments attached to the tether cable of a captive balloon above the Black Mountain region of South Wales. The balloon was flown from a site in the Llanthony valley, which is situated on the border between England and Wales and forms one of a series of approximately parallel ridges and valleys.

2. Instruments

The Llanthony experiment was the first major trial involving the newly developed Cardington turbulence probe system. The probes, which can measure wind, temperature, humidity and pressure, are clamped to the cable of a captive balloon and can be flown to heights of about 2000 m. Unlike the

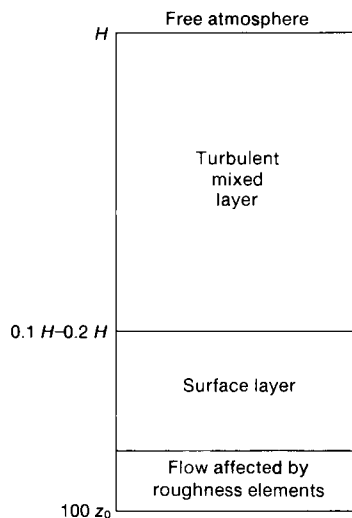


Figure 1. Schematic diagram showing the various regions in the cloud-free boundary layer, where H is the total depth of the boundary layer and z_0 the roughness length.

previous turbulence probes produced at Cardington, in which damped pendulums kept the wind-measuring instruments horizontal, the new probes use a combination of inclinometers and magnetometers to determine the probe orientation. The measurement of wind from tethered balloons is complicated by the motion of the balloon caused by turbulence and aerodynamic instabilities. These motions typically have amplitudes of about 1 m s^{-1} and periods of a few minutes, which are comparable with the amplitudes and periods of the energy containing turbulent eddies. With the new probe system it is possible to use the data from the inclinometers and magnetometers to derive an approximation to the catenary of the tether cable; from this the positions of the probes with respect to the tether point can be derived and the velocities of the probes calculated. Comparisons with probe velocities obtained directly by tracking a light source attached to the cable show that this procedure produces good results (Lapworth and Mason 1987).

The probe, which is free to turn around the cable, is kept pointing into the wind by a wind vane. Three Gill propeller-anemometers, mounted so that their axes lie on a cone, measure the wind vector relative to the probe. These data are combined with the probe orientation to provide the wind vector in a coordinate system fixed with respect to the ground. The wind data can then be corrected for the motion of the probe using the probe velocity determined by the procedure outlined above.

Temperature is measured using a fast-response platinum-resistance thermometer mounted between the Gill propellers. In addition there is also a more robust slow-response thermistor mounted in an aspirated radiation shield. Two wet-bulb thermistors, one a small fast-response bead thermistor and another which is slower but more robust, are used to measure humidity.

The outputs from all the sensors are sampled at 20 Hz. The data are digitized and then transmitted by radio link to a ground station which separates the data from different probes and passes it to a PDP 11/34 minicomputer where it can be stored on cartridge tape or disk. (A Micro Vax II computer has recently been acquired to replace the PDP 11/34 for logging turbulence-probe data.)

During the trial a total of twelve flights were carried out using up to six turbulence probes attached to the cable. The main limitations on flying during the experiment were winds in excess of 20 m s^{-1} and/or the occurrence of a significant lightning risk.

In addition to the tethered balloon a Doppler acoustic sounder was also operated from the valley and provided wind speed and direction up to 800 m above the valley floor. A sonic anemometer was used to provide turbulence data at about 20 m above the valley floor.

3. Results

The results from two flights will be presented here. The flights took place on 18 and 22 May 1986 in strong south-westerly winds (approximately perpendicular to the axis of the valley). The wind speed and direction remained constant throughout the flights which lasted nine and five hours respectively. The wind profiles from the two flights are shown in Fig. 2. The winds have been normalized by the wind speed at 150 m above the valley floor and heights (z) have been measured relative to the mean height of the valley system which has been taken to be 150 m above the valley floor. The profiles are very closely logarithmic up to 800 m. The line drawn through the data corresponds to a roughness length of 11 m. The surface stress has been obtained by extrapolating the stress values estimated from the turbulence data obtained at the different probe levels to the mean level of the topography. The drag coefficient estimated from the stress data, using equation (2), gives a value for z_0 of about 9 m. This is very close to the value derived from the wind profile alone and indicates that although there is no surface layer, such as found over smoother surfaces, the roughness length is still a useful basis for parametrizing the surface stress over rugged terrain.

Studies of turbulent flow over arrays of obstacles show that as long as the density of obstacles is not too large

$$\frac{z_0}{h} = c \frac{A}{S} \quad \dots \dots \dots (4)$$

where h is the height of the roughness elements, A is the total silhouette area of the obstacles in a horizontal area S , and c is a constant which will be a function of the shape of the obstacles. (Dimensional analysis would suggest that, for geometrically similar obstacles, $z_0 = hf(A/S)$, where $f(A/S)$ is some function of A/S .)

Fig. 3 is a plot of z_0/h against A/S for experimental data obtained in areas of rugged terrain (see Table I for sources). With the exception of the results of Mason (1987), which were calculated from stress data obtained with a prototype of the present Cardington turbulence probe, these estimates were obtained from wind profiles. The plot suggests that c is about 0.36 for the types of terrain that have been studied. This model of the roughness length assumes that all the drag is due to form drag on the large-scale topography. Mason (1986) has proposed the following formula to account for a contribution to the drag from the small-scale roughness elements covering the topography:

$$\ln \left(\frac{h}{2z_0} \right) = \frac{k}{\left(\frac{1}{2} D \frac{A}{S} + \frac{k^2}{(\ln(h/2z_{01}))^2} \right)^{1/2}} \quad \dots \dots \dots (5)$$

where D is the drag coefficient for the obstacles and depends on their shapes, z_{01} is the roughness length associated with the surface cover (e.g. trees, rocks, etc.) and k is von Kármán's constant.

The two terms in the denominator of the right-hand side of equation (5) represent the form drag on the large-scale topography and the drag due to small-scale roughness respectively. Comparison with numerical simulations of the flow over sinusoidal topography suggests a value of 0.3 for D . To apply equation (5) to the data in Table I a value for z_{01} is required. This can be estimated from a compilation of roughness lengths appropriate to various types of surface cover (e.g. Engineering Sciences Data Unit 1976). Unfortunately the descriptions of the topography and the surface cover, given in the references

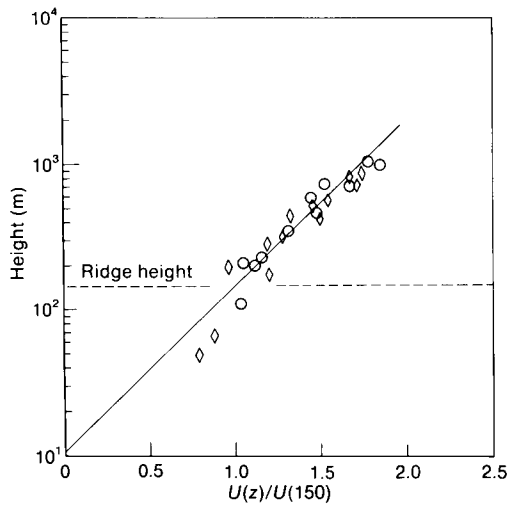


Figure 2. Wind profiles for two flights carried out at Llanthony on 18 May 1986 (\diamond) and 22 May 1986 (\circ). The height, z , is measured from the mean topography height of the surrounding area, taken as 150 m above the floor of the Llanthony valley. The wind speeds are normalized by the wind at $z=150$ m.

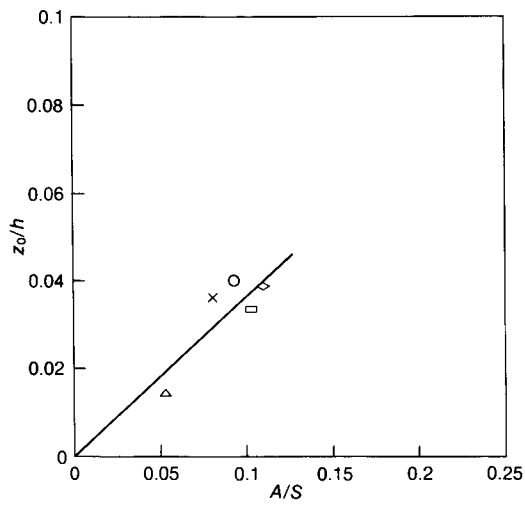


Figure 3. Plot of z_0/h against A/S for published values of the roughness length obtained for rugged terrain. Sources of the data are given in Table I.

Table I. Published values of roughness length obtained for rugged terrain. For explanation of symbols see text

Source	Symbol in Fig. 3	z (m)	h (m)	A/S
Thompson(1978)	\diamond	5.8*	150	0.110
Noilhan <i>et al.</i> (1982)	\triangle	2.0	140	0.053
Kustas and Brutsaert (1986)	\circ	3.8	95	0.093
Mason (1987)	\times	9.0	250	0.080
Present data	\square	10.0	300	0.103

* Recalculated from the data given in the paper using height measured relative to the mean topography height, taken to be 70 m.

listed in Table I, tend to be sketchy thus making it difficult to estimate z_{01} precisely, but a value in the range 0.1–0.5 m is probably reasonable in most cases. Fig. 4 shows a comparison between measured values of z_0 and values calculated from equation (5) for $z_{01} = 0.1$ and 0.5 m. Fortunately the value of z_0 is not very sensitive to the choice of z_{01} and the agreement between the measured and calculated values is very good.

Although both equations (4) and (5) give good results it is worth stressing the difference in their assumptions. Equation (4) assumes that all the drag is due to form drag on the large-scale topography, while for equation (5) the drag is partitioned between the large-scale topography and the small-scale roughness. For the data listed in Table I, equation (5) indicates that, for z_{01} between 0.1 and 0.5 m, around 20–30% of the total drag is due to small-scale roughness elements. A further feature of equation (5) is that as A/S and h become small $z_0 \approx z_{01}$, as would be expected.

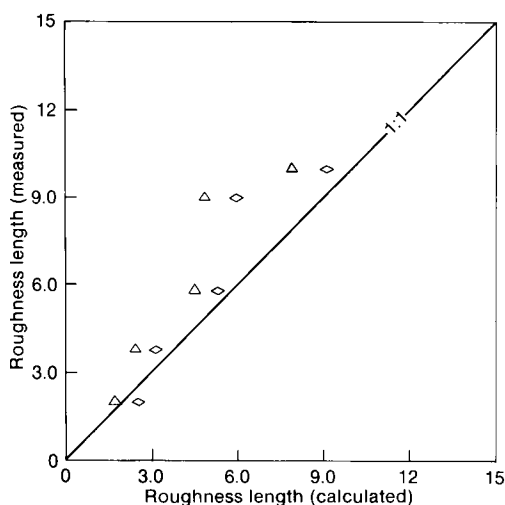


Figure 4. Comparison between the experimental values of z_0 listed in Table I and values calculated from equation (5) for $z_{01} = 0.1$ m (Δ) and $z_{01} = 0.5$ m (\Diamond).

The level of turbulence in windy conditions is related to the roughness of the underlying surface; so, for example, the wind is generally gustier over land ($z_0 \approx 1-10$ cm) than over the sea ($z_0 \approx 0.1$ mm). Fig. 5 shows the turbulence intensity (σ_u/U where σ_u is the standard deviation of the wind speed) and the standard deviation of the wind direction (σ_θ) measured at Llanthony as a function of height. For comparison the over-sea data of Nicholls and Readings (1979) have also been included. Consistent with the much larger roughness length the turbulence levels are considerably larger over Llanthony than over

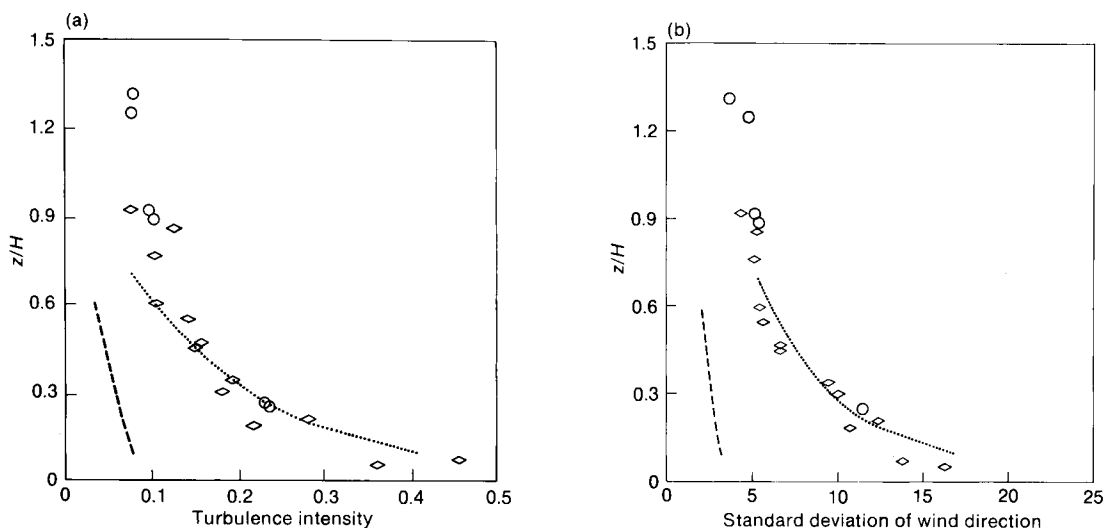


Figure 5. (a) Turbulence intensity and (b) standard deviation of the wind direction (σ_θ degrees) observed at Llanthony from two flights. The height (z) is normalized by the height (H) at which the momentum flux extrapolates to zero. The dashed curve shows the results of Nicholls and Readings (1979) obtained over the sea while the dotted curve shows turbulence levels calculated from the over-sea turbulence data for a roughness length of 10 m.

the sea. The dotted curve in Fig. 5 shows the turbulence intensity and σ_θ profiles calculated using the turbulence results in Nicholls and Readings (1979) and equation (3) with a roughness length of 10 m. The agreement between the measured values of σ_u/U and σ_θ and those deduced from the Nicholls and Readings data suggests that the presence of the large ridges and valleys does not lead to any dramatic change in the basic structure of the boundary-layer turbulence compared to that observed over smoother surfaces; that is, if the present data were to be non-dimensionalized using the appropriate velocity and length scales (see, for example, Holtstlag and Nieuwstadt (1986) for a discussion of boundary-layer scales) the results would be similar to those obtained over the sea.

4. Concluding remarks

The results presented here show that the concept of the roughness length is useful in parametrizing the surface stress over rugged terrain. The measured roughness length can be estimated from easily determined characteristics of the terrain with fairly simple formulae (see Mason (1986) for an outline of the use of such formulae). The present data go beyond most previous estimates of z_0 for rugged terrain by determining the drag coefficient using direct estimates of the surface stress obtained from turbulence measurements.

The Llanthony experiment concentrated on the drag exerted on the atmosphere via the turbulent boundary layer. However, a second mechanism which appears to be significant is the drag associated with the generation of gravity waves by topography. Brown (1983), using aircraft data, measured momentum fluxes of up to -0.35 N m^{-2} associated with gravity waves over the British Isles. For comparison the surface stresses observed on the two balloon flights described here were of the order of -2 N m^{-2} (note: the present measurements obtained at a point are unable to give the flux due to gravity waves which are stationary with respect to the surface, such as lee waves). Although the magnitude of the momentum flux associated with gravity waves appears to be only a relatively small fraction of the likely surface stress, these wave fluxes are significant since they can directly affect the atmosphere remote from the surface.

The Llanthony experiment was the first major field trial involving the new Cardington turbulence probe system and illustrates its potential in atmospheric boundary-layer studies.

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The summer of 1987 in the United Kingdom

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Summary

The summer of 1987 was rather cool, dull and wet in many areas; in particular June was very wet nearly everywhere. July and August were mainly settled months in southern coastal areas and were particularly so in the south-western peninsula.

1. The summer as a whole

Rainfall amounts during the summer (June–August) of 1987 were above normal over all parts of the United Kingdom except the south-western peninsula, north-west Scotland and Shetland. In parts of the south-west, and in parts of Devon in particular, there was less than 60% of normal rainfall, despite the heavy rain there in early June. In parts of East Anglia, however, there was as much as twice the normal rainfall during the summer. Sunshine amounts were near normal over south-west England and South Wales, but elsewhere it was generally dull. The mean temperatures were below normal everywhere, apart from one or two places in the far south of England. The greatest difference was around the Tyneside area, where the mean was about 1 °C below normal for the season.

Information about the temperature, rainfall and sunshine during June–August 1987 is given in Table I and Fig. 1.

Table I. District values for the summer months, June–August 1987, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	−0.4	+2	88	79
Eastern Scotland	−0.5	+3	113	82
Eastern and north-east England	−0.4	+4	130	74
East Anglia	−0.3	+5	162	75
Midland counties	−0.4	+4	119	81
South-east and central southern England	−0.1	+2	120	89
Western Scotland	−0.5	+1	115	89
North-west England and North Wales	−0.4	+3	163	84
South-west England and South Wales	−0.2	0	86	93
Northern Ireland	−0.2	+2	115	78
Scotland	−0.4	+2	105	83
England and Wales	−0.3	+3	117	82

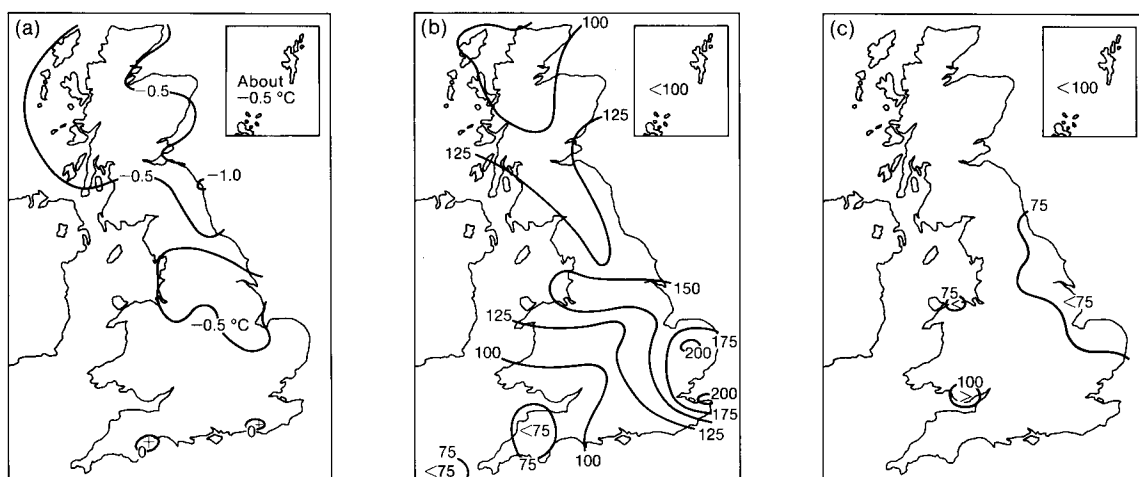


Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for summer 1987 (June–Aug.), relative to 1951–80 averages.

2. The individual months

2.1 June. Mean monthly temperatures were below normal throughout the United Kingdom, ranging from 2.3 °C below normal in north-east England to less than 1 °C below normal in the London area. Monthly rainfall totals were above normal in all areas except northern Scotland and the Western Isles, ranging from 289% of average at Ringway, Greater Manchester to 52% at Benbecula, Western Isles. Sunshine amounts were below normal everywhere except for parts of northern Scotland and the Western Isles and ranged from 117% at Tiree, Strathclyde to less than 40% in Cambridgeshire.

2.2 July. Mean monthly temperatures were near normal generally, ranging from about 0.8 °C above normal in the south-west to 0.3 °C below normal in places in eastern England. Rainfall totals were above normal in most parts of the British Isles except south-west England, central and southern Wales and parts of the Midlands where it was rather dry; amounts ranged from less than 50% of average in parts of south-west England and Northern Ireland to 232% at Manston, Kent. Sunshine amounts were about normal nearly everywhere in the United Kingdom, apart from northern Scotland where it was a rather dull month, ranging from 42% at Cape Wrath and Poolewe, both in Highland Region, to 120% in the Isles of Scilly.

2.3 August. Mean monthly temperatures were near normal in most parts of the United Kingdom, ranging from 0.6 °C above normal in south-west England to 0.9 °C below normal in eastern Kent. Monthly rainfall totals were above normal in southern Scotland, Northern Ireland, northern and eastern England, parts of the Midlands and North Wales, but below normal elsewhere. Rainfall amounts ranged from as little as 13% at Plymouth, Devon to 273% in Norfolk. Sunshine amounts were above normal generally in South Wales, south-west England and eastern Scotland, and below normal elsewhere, ranging from 70% in the Western Isles to 118% in Shetland.

3. The weather month by month

3.1 June. The first half of June was cool and showery, with many places on the eastern side of the United Kingdom having twice as much rain as could normally be expected. It remained unsettled for the

rest of the month; there was only a little improvement during the third week, with the best of the weather being in the north. During the last week there was a further deterioration and, for the first time since 1969, there was no play on the first day of the tennis championships at Wimbledon. However, the weather improved in the last few days of the month.

3.2 July. Most of England and Wales was dry throughout the first half of July with no measurable rain reported in many areas south of a line from South Wales to The Wash up to the 13th, while it remained unsettled in Scotland and Northern Ireland. By about mid month outbreaks of rain, with isolated thunderstorms, had spread from the south-west into Wales and southern England, becoming persistent and at times heavier in eastern areas of England on the 16th. For the next week it remained generally unsettled, with the worst of the weather in south-east England. Central and eastern areas of England had heavy showers or longer spells of rain with thunder in places but Wales and western areas of England were mainly dry with sunny spells. From the 27th to 31st rain belts crossed all areas from the west followed by showery outbreaks but also some sunny spells.

3.3 August. The month of August was cool everywhere for the first 10 days, but became warm for a while in the middle of the month and then ended cool in the east but warm in the west. It was dry and warm over most parts on the 29th and 30th, but cooler and more cloudy on the 31st. Thunderstorms brought heavy rainfall to parts of South and West Yorkshire on the 9th, causing flooding and disrupting traffic. Over England and Wales during the weekend of the 21st and 22nd, widespread and at times violent thunderstorms gave very heavy rain in many places, especially from North Wales to East Anglia, causing floods in some parts of eastern and northern England and the Midlands. On the 22nd Suffolk and Essex suffered havoc and destruction caused by the worst storm in living memory, particularly affecting the area from Chelmsford to Ipswich. East Anglia had the wettest August for over 30 years, while south-west England had the driest August since 1981. North Wyke, Devon reported the driest August since records began there in 1959. While southern areas enjoyed a hot spell on the 16th, Scotland, Northern Ireland and some northern parts of England and Wales had heavy rain and storms; some minor roads in the Highlands were almost impassable because of flooding. Heavy falls included 87 mm at Creebridge and 86 mm at Bargrennan, both in Dumfries and Galloway, on the 16th, 73 mm at Birmingham Airport, West Midlands on the 22nd, and 56 mm at Hemsby, Norfolk on the 25th.

Reviews

The physics of atmospheres, second edition, by J.T. Houghton. 176 mm × 252 mm, pp. xi + 271, *illus.* Cambridge University Press, 1986. Price £27.50, US \$54.50 (hardback), £9.95, US \$16.95 (paperback).

For a well-prepared physicist who wants a compact introduction to the physical and dynamical processes that determine the structure and motion of (neutral) planetary atmospheres this is an excellent book.

The first edition (1977), given a cautious welcome by a *Meteorological Magazine* reviewer, proved a valuable addition to the literature — the author has not found it necessary to make much change to his account of the basic processes. The major modification is to the chapter on radiative transfer; this was given a relatively detailed treatment in the first edition and is now restructured. Here, and in other chapters, there are additions to the extensive sets of problems which are designed not only to check comprehension but also to extend the succinct text (one, for example, derives and illustrates Ertel

vorticity). It may be regretted that the opportunity was not taken to revise other chapters — that on turbulence remains rather dated (though it is good to see that the spelling of Ekman's name has been corrected) and that on clouds could do with more dynamics, even though it does manage to give a serious account of condensation and coalescence mechanisms together with an indication of the radiative properties of clouds, all in five pages.

The new material is mainly in the chapters concerned with application of the basic physics to studies of the general circulation and to climate, especially by computer modelling. These chapters give a concise indication of the problems and possibilities of this important and rapidly developing field, not neglecting advances in observational technique.

The new edition is slightly bigger than the old one, an increased page size and larger fount making it more legible, though I feel the equations now stand out less clearly from the text; the opportunity has also been taken to include some satellite images and photographs. A physicist who gets seriously involved in meteorology will necessarily go to specialized texts (the bibliography has been updated) but this relatively small introductory volume will suit good students admirably.

H. Charnock

Acidic precipitation, edited by H.C. Martin. 2 Vols 170 mm × 246 mm, pp. Part 1 xvi + 1053, Part 2 xvi + 1118, *illus.* Dordrecht, D. Reidel Publishing Company, 1987. Price £196.00, US \$240.00, Dfl.560.00.

These two massive tomes include roughly half the 400 papers presented at the Muskoka Symposium held in central Ontario in September 1985. Apparently these papers have already been published in issues of the journal *Water, Air and Soil Pollution*, volumes 30 and 31, in 1986, which makes it even more surprising that anyone would have the energy and zeal to bring them together in book form. Of course the standard of papers inevitably varies quite a lot, but some at least seem very good, and so the editor, Hans Martin, is to be congratulated on finishing such a mammoth task with such a comparatively short time delay, and Reidels on producing two books which are aesthetically presentable.

It does raise the impish question as to whether the forests of the world are at greater risk from air pollution or from the paper requirements of books like these. However I cannot imagine that the sales will be very large — only the larger scientific libraries will, I imagine, contemplate acquisition.

Very briefly, the books cover the following topics: the transport and deposition of acidifying species, and the influences of these depositions on soils, forests and aquatic biological communities. The largest number of papers are concerned with this last aspect, the influence on freshwater life.

To review each of the papers properly, or even a fair selection of them, would be an almost impossible task for any reviewer. Alternatively it seemed fair to see how well the books could be used to answer or comment on a few relevant questions within the scope of the subject matter. The questions were chosen after a very quick survey of the books and before I knew whether or not answers would be forthcoming. Four questions were chosen:

- (1) How important are episodes of acidic occult deposition? (Occult deposition arises from the direct impaction of contaminated fog or cloud droplets blown by the wind onto vegetation.)
- (2) Have techniques been developed to measure dry deposition by direct methods?
- (3) What is the influence of emissions of ammonia on the deposition fields of acidity?
- (4) How bad is the effect of acid rain (in its popular general sense) on forests in Ontario?

I was able to find some comment or answer to all these questions using the index and the titles as a guide to where to look. The process was quite quick although I cannot be sure other answers were not missed.

In summary, one paper by Barrie and Schemenaur discussed question (1). For clouds at ground level, the rate of deposition of cloud water apparently depends almost linearly on wind speed, being typically 1.1 mm h^{-1} for a wind speed of 10 m s^{-1} . This rate is comparable to the rate of light rain. The associated acidity in wind-blown fog droplets is, however, often much higher than in rain (pH values below 3 are not uncommon) and this could lead to a high accumulated deposition.

Question (2) was the subject of an excellent paper by B.B. Hicks which reviews the various possible techniques, none of which seem suitable for general operational use outside research conditions. Two other papers, one by Dasch and the other by Edwards and Ogram, discuss specific techniques of considerable promise. The method discussed by Dasch is essentially a simple one — that of washing off particulate depositions from tree branches.

Question (3) is discussed only in a single paper (Schuurkes *et al.*) in which it is concluded that emissions of ammonia in the Netherlands lead to higher depositions of ammonium sulphate and this in turn leads to increased acidification through nitrification in the soil. It is interesting that this question, which is now very topical and the basis for many research studies, had barely surfaced just two years ago.

The final question, chosen because it was somewhat parochial to the venue for the Symposium, attracted comment from only two papers, one by Linzon and the other by Crocker and Forster. According to Linzon there is some evidence that acid rain is contributing to the extensive decline in maple trees in Ontario, which are commercially grown for maple syrup. The second paper attempts to assess the economic consequences of acid rain on timber yields in Ontario. It estimates that roughly 5% is lost from a gross annual value of just over \$1 billion. If this is true it is a very sizeable loss, although to verify it must be well-nigh impossible.

Overall then, the books provided some useful comments on these randomly chosen questions. To anyone in the field of acid rain, the implication is that access to these books could prove very useful on occasions, although the price must surely preclude individual scientists buying them for their own bookshelves.

F.B. Smith

Monsoons, edited by J.S. Fein and P.L. Stephens. 167 mm × 240 mm, pp. xix + 632, *illus.* New York, Chichester, Brisbane, Toronto and Singapore, John Wiley and sons, 1987. Price £71.75.

This is an interesting and wide-ranging book covering almost every conceivable aspect of monsoons: meteorological, oceanographical, historical, sociological and political.

The editors have done a good job in bringing together such diverse material and organizing it in such a way as to present a fairly coherent and balanced account of the monsoon. The material is well presented and generally very readable, and a 12-page index provides very useful cross referencing. The book is primarily aimed at the non-specialist; indeed, the editors suggest that it should be useful to administrators, policy makers and interested lay people. With the exception of a few chapters, any reasonably intelligent reader should experience little difficulty in following the text; in parts, however, a scientific background would be an advantage. Many useful and up-to-date references are provided throughout; those so inclined should have no difficulty in using these to pursue their interests further. For the specialist, the book offers an interesting and painless account of the broader aspect of monsoons.

Although other monsoons are mentioned, the emphasis is on the Asian monsoon and, in particular, the Indian summer monsoon. The material is fairly up to date and, by its nature, much of the material is unlikely to date very quickly. In some areas, notably numerical modelling, current work is still very much at an experimental stage and our understanding is increasing more rapidly.

The material is divided into six sections: an elementary account of the physics of monsoons; a review of the monsoon in literature and folklore; economic impact and political response; historical and current understanding of the physics of the monsoon; monsoon variability and interactions; prediction and government response. This material is covered by 16 authors, each an expert in his own field. With so many authors some overlap is inevitable; this, however, is kept to a generally acceptable level. The 30–60 day oscillation, for example, is covered a number of times. Many of the authors tend to exhibit their own biases which provide the reader, in some cases, with alternative explanations of certain phenomena.

I found little to fault. However, some of the mathematical definitions in the chapter on *Physics of Monsoons* are a little loose. Also the chapter on *Interannual Variability of Monsoons* is heavy going for the non-lover of statistics with 22 pages of tables! At one point there is a confusion between the text and figure legend (Fig. 15.1) as to precisely whose model is being depicted. It was surprising to find no use of satellite pictures by any of the authors. Also, whilst photographs are used to advantage on the dust cover, there are none within the book itself.

The authors and editors deserve congratulation on providing such a modern and readable account of the monsoons. The book is a natural choice for libraries, and provides good coffee-table reading, but at £71.75 an individual would require more than a casual interest to buy it. Whilst it serves to provide a very useful introduction and good references, mathematics is kept to a bare minimum, which may widen the book's appeal, but it limits its utility as a student text. As to its suitability for administrators and policy makers, at 632 pages, such people might prefer a more concise account.

W.A. Heckley

Statistical analysis of spherical data, by N.I. Fisher, T. Lewis and B.J.J. Embleton. 155 mm × 234 mm, pp. xiv + 329, *illus.* Cambridge University Press, 1987. Price £35.00.

I found this book a stimulating introduction to a body of statistical knowledge of which I knew nothing, but which I enjoyed encountering for the first time.

The spherical data of the title are measurements of the orientation of straight lines in space, where the lines may be directed (and called vectors) or undirected (and called axes). The theoretical starting point for the book is the question 'What is the analogue on the sphere of the normal distribution on the line or plane?' The problems for which this question is important range from archaeology to geomagnetism. Examples discussed in the text include measurements of pole position from palaeomagnetic data, arrival directions of cosmic ray showers, measurements of facing directions of conically folded bedding planes and serial correlation of wind directions.

The text develops the theory of statistical analysis of directional data of this kind in a coherent step-wise fashion that is a pleasure to read. The main emphasis is on practical applications. The mathematics is clearly presented, the examples are well chosen and lucidly expounded, and the illustrations are crisp and uncluttered.

The statistical topics appropriate for spherical data that are discussed in the book have been mainly developed since the 1950s. They roughly parallel the range of topics one expects to find in a good beginning graduate textbook on conventional statistical methods: exploratory analysis, statistical

models, analysis of unimodal and multimodal distributions, tests of uniformity and symmetry, analysis of several samples of vectorial or axial data, correlation, regression, and temporal/spatial analysis. The mathematical prerequisites are final-year calculus and matrix algebra.

For someone having to work for the first time with data of this kind, I can warmly recommend the book.

By the way, an elegant analogue of the normal distribution on the sphere is the function $\exp(k \cos \theta)$ which has the usual Gaussian behaviour for small angular separation θ .

A. Hollingsworth

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Gravity currents in the environment and the laboratory, by J.E. Simpson (Chichester, Ellis Horwood Ltd, 1987. £35.00) explains the nature of gravity currents (buoyancy-driven flow in fluids) and their manifestation in the atmosphere, the oceans and the earth sciences. Factors influencing the behaviour of gravity waves are reviewed and descriptions of numerous laboratory experiments are included.

Satellite remote sensing, by R. Harris (London, New York, Routledge and Kegan Paul Ltd, 1987. £10.95 (paperback), £22.50 (hardback)) is designed to give students a sound basis and introduction to this fast-changing and exciting field. The physical principles, methods of processing, applications and the way forward are examined.

Weather patterns of East Anglia, by A. Glenn (Lavenham, Suffolk, Terence Dalton Ltd, 1987. £14.95) sets out to show that, however apparently freakish, the weather conforms to certain recurring patterns. Simple rules for predicting weather changes and advice on setting up a weather station are given.

Award

Congratulations to Brian Hoskins, Professor in Meteorology at the University of Reading, who has been elected to the Fellowship of the Royal Society in recognition of his analysis of the physical processes that control weather systems and his development of mathematical methods that have led to the understanding of weather fronts and to major improvements in weather forecasting. Brian Hoskins has many connections with the Meteorological Office and is a member of the Research Subcommittee which advises the Meteorological Committee on the general scientific lines along which meteorology and geophysical research should be developed within the Office.

Correction

Meteorological Magazine, April 1988, pp. 121/122. The charts shown as Figs 3(a), 3(b), 3(c) should have been respectively Figs 4(a), 4(b), 4(c), and vice versa in the article 'Numerical forecast studies of the October 1987 storm over southern England'.

Satellite photograph — 30 January 1988 at 1721 GMT

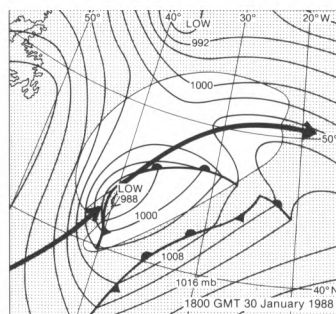
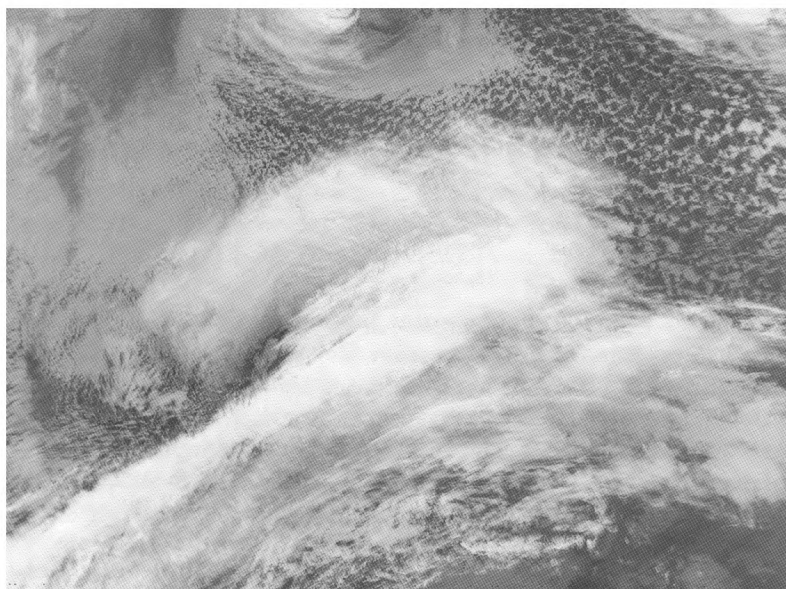
The central feature of this infra-red image is an outstanding example of a 'cloud head', a pattern that often precedes rapid cyclogenesis and very strong surface winds (Böttger *et al.* 1975, Monk and Bader 1988)*.

Cloud heads such as shown here are regions of cold-topped cloud that are more extensive than those associated with most developing frontal waves. Their distinguishing features are

- an unusually broad extension of cloud into the cold-air mass (poleward of the upper tropospheric jet stream — see surface chart, with envelope of cloud unshaded),
- a pronounced convex poleward edge,
- a wedge of dry air aloft, shown by the presence of only lower cloud through the middle of the head,
- curved bands of convective cloud immediately poleward of the dry wedge.

When significant cyclonic development occurs, considerable convection which partially moves beneath the head is normally present within the cold air mass, and sustained cloud-top warming occurs within the frontal zone upwind of the system.

The head shown in the picture had existed for 12 hours — a characteristic lifetime for heads — and a surface low was beginning to deepen rapidly (see chart). Following its deepening to 946 mb in the next 24 hours, ship reports indicated mean winds as high as 70 kn, and a gust of 90 kn was recorded at Land's End (Cornwall).



Photograph by courtesy of University of Dundee

* Böttger, H., Eckardt, M. and Katergiannakis, U.; Forecasting extratropical storms with hurricane intensity using satellite information. *J Appl Meteorol*, 14, 1975, 1259–1265.

Monk, G.A. and Bader, M.J.; Satellite images showing the development of the storm of 15–16 October 1987. *Weather*, 43, 1988, 130–135.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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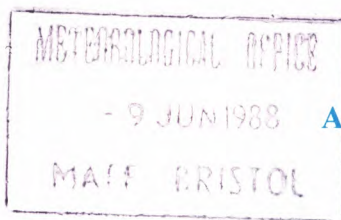
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THE METEOROLOGICAL MAGAZINE

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Noise assessment model
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The Larkhill noise assessment model. Part II: Assessment and use

J.D. Turton and D.A. Bennetts

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Meteorological Office, Larkhill

Summary

Noise forecasting is a routine task performed operationally for a number of Ministry of Defence ranges in support of artillery training exercises and explosives testing. The forecasts are produced using a numerical model which is run on a desk-top computer. Part I of this paper published in the previous issue of the *Meteorological Magazine* described the current operational model and discussed the theoretical background. Part II assesses the model and describes its use. A simplified technique for providing noise assessments for remote sites using synoptic data is also presented.

1. Introduction

Over the last 30 years or so it has become well established that the noise generated by gunfire and explosions can travel long distances in the atmosphere. During the last 10 years there has been a growing demand for some assessment of when such noise is likely to be sufficiently loud so as to cause structural damage or lead to complaints. In response to this demand a numerical model to assess the likely noise levels around the ranges has been developed.

Part I of this paper (Turton *et al.* 1988) discussed the theoretical background to the problem and presented the current operational model. The results from the model suggested that the downwind enhancement is mainly due to differences in the wind speed over the lowest few hundred metres, whilst focusing is mainly due to the directional changes in the wind profile.

In Part II the accuracy, sensitivity and limitations of the model are assessed and some empirical results that allow noise assessments to be prepared using synoptic data are presented. For ease of reference, equations given in Part I are referred to with the prefix I (e.g. the equation used to predict the noise levels is referred to as equation (I8)).

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2. Assessment of the model

Since 1981 a number of trials have been conducted at various ranges to investigate the noise levels from artillery fire and explosives. Most of these trials were conducted on Porton Down (about 12 km south-east of Larkhill), although other investigations have been carried out at Sennybridge (Cowley 1983) and more recently at Lulworth (Lord *et al.* 1986).

The model-predicted noise levels have been compared to actual field measurements made during the Lulworth trials in order to assess the accuracy of the predictions. Fig. 1 shows the model-predicted noise field on 10 October 1985. On this occasion the surface wind was 7.2 m s^{-1} (14 kn) from 245° and the 150 m wind was 8.8 m s^{-1} (17 kn) from 247° . The sound enhancement region lies between 50 and 160° and is centred on a direction close to the 110° given by equation (19), with a shadow region in the opposite direction. A slight focus occurred to the south-east at about 10 km distance. As can be seen from the inset in Fig. 1, the direction of the focus was fairly well predicted by the wind shear vector determined from the 10 and 900 m winds. Also shown in the figure are the mean observed noise levels at various measurement sites; the measured values have been normalized to an equivalent 5 lb charge of plastic explosive, as used in the model prediction. In this example the largest difference is at 1575 m , 074° where the measured level was 123 decibels (dB) and the predicted value was 128 dB. Further away from the source the model-predicted 120 dB contour lies about 800 m too far out — the model is overpredicting the noise levels in the enhancement region.

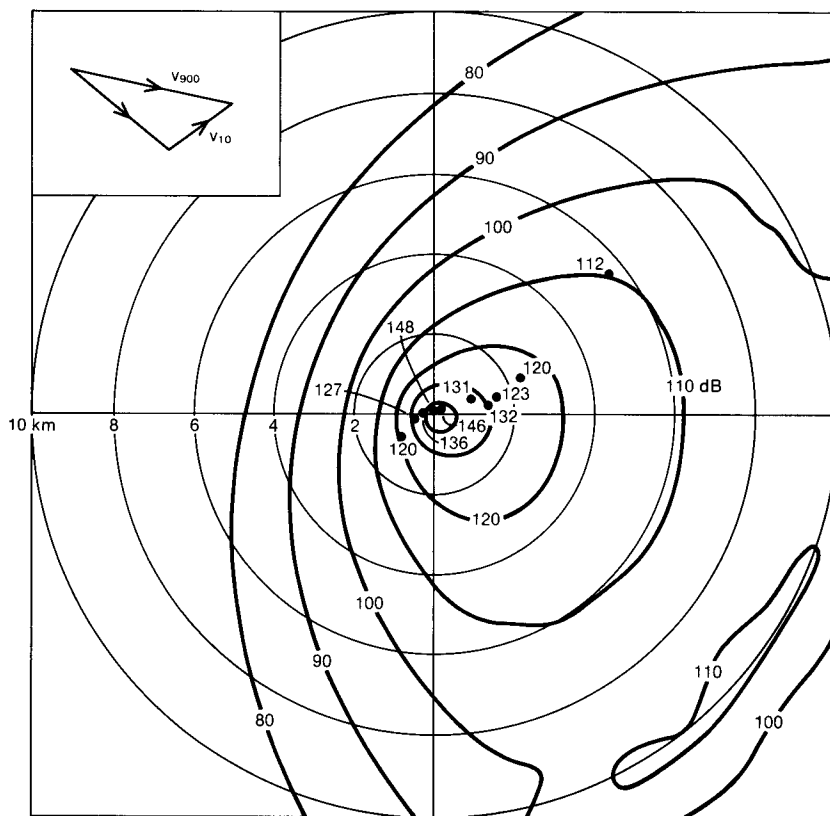


Figure 1. Polar diagram for Lulworth at 1010 GMT on 10 October 1985 showing model-predicted noise levels (dB) for a 5 lb charge. Mean measured noise levels at various locations are also shown. The inset shows how the surface (10 m) and upper (900 m) winds give an indication of the direction of the focus.

Fig. 2 shows the mean prediction errors at various distances from the source for the six Lulworth trial days, using the data of Lord *et al.* (1986). In the downwind direction (defined here as within 45° of the surface wind) the results given in Fig. 2(a) show considerable variation from day to day, although the prediction errors show no obvious dependence on distance. The root-mean-square (r.m.s.) error (of the plotted points) is 4 dB. Fig. 2(b) shows similar data, but upwind of the source; here the results suggest that the model has a tendency to underestimate the noise levels. In particular, on one day (9 November 1985) the model underestimates become exceptionally large with increasing distance from the source. On this occasion the weather was cloudy with heavy showers, and the surface wind was variable between 8 and 15 m s^{-1} . In the model forecast a surface wind of 9.8 m s^{-1} (19 kn) was specified; if this is increased to 12.9 m s^{-1} (25 kn) then the upwind predicted noise levels are significantly higher (e.g. at 2000 m the predicted levels are increased by about 20 dB) and the error is substantially reduced. However, this change has a detrimental effect on the downwind predictions (e.g. at 1625 m the levels are decreased by 5 dB and the error is increased). This illustrates an important aspect of the model in that the predicted noise levels can be very sensitive to the low-level winds specified; this is discussed more fully later. The r.m.s. error of the upwind plotted points is 14 dB, but is reduced to 7 dB if the data for 9 November are omitted.

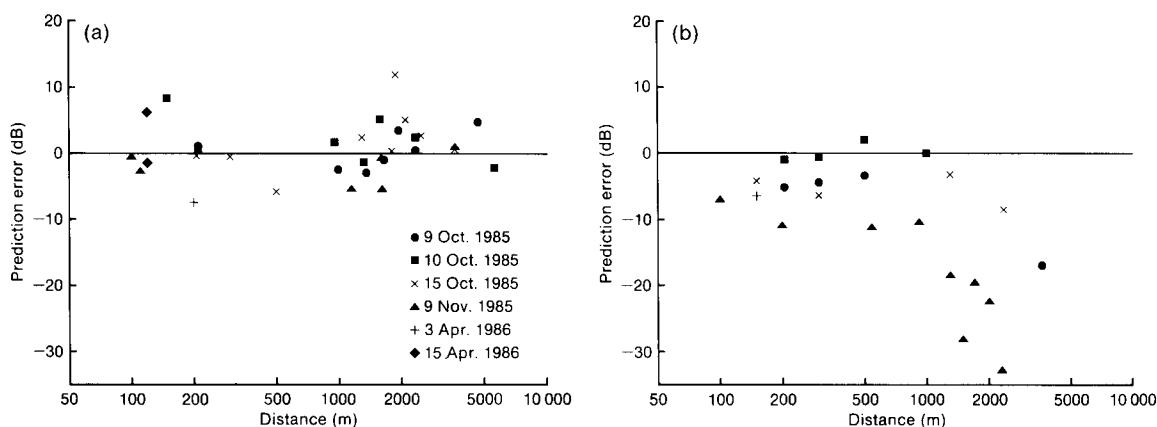


Figure 2. Comparison of model predictions with measurements made during the Lulworth trials for (a) downwind and (b) upwind directions.

All the measurements made to date have been in enhancement and shadow regions; no measurements have been made in a focus region. The main reason for this is that foci are caused by the shears aloft, often associated with frontal systems, which change with time as the front passes through. Consequently, identifying where a focus might occur at a particular time, so as to deploy instrumentation, is a problem.

The results suggest that on average (in the enhancement and shadow regions) the model predictions have a typical error of about ± 6 dB, although there are wide variations from day to day. Whilst this might seem reasonably accurate, it should be noted that this is equivalent to an error in predicting the actual intensity of the sound wave by a factor of 4. Nonetheless, a prediction error of about 6 dB should be viewed against the effects of meteorology, which can lead to variations in noise level of about 30 dB, thus demonstrating that the model does have some skill. It should be emphasized that a 6 dB error in the noise levels in the enhancement region is more significant than a similar error in the shadow region because the levels are much higher. The predicted noise levels in the focus region would be expected to be much less accurate than this, as discussed in the following section.

There are a number of reasons why the model predictions are different from those measured:

- (a) Errors introduced by the sensitivity of the model predictions to internal parameters (i.e. terms in the prediction equation (I8)) and external parameters (i.e. the quality and details of the input meteorological data).
- (b) Deficiencies in the model formulation (i.e. the neglect of the effects of turbulence, interference and of the surface).
- (c) Inaccuracies in the determination of the source level, L_0 (equation I10).

These factors are discussed in sections 3 and 4.

3. Sensitivity of the model

The sensitivity of the model-predicted noise levels has been investigated by examining:

- (a) the effect of internal parameters which specify the incremental distance (Δr) and the incremental ray elevation (Δe), and
- (b) the effect of changes in the atmospheric profiles.

3.1 Sensitivity to internal parameters

The choice of internal parameters Δr and Δe can affect the predicted noise levels in situations where sound rays are brought down to ground, i.e. in enhancement and focus regions. The term Δr introduces a degree of spatial averaging on the predicted noise levels; the computed values are only independent when their (radial) spacing exceeds $2\Delta r$. The example of 20 August 1985, described in Part I (Turton *et al.* 1988), was recomputed using differing values for these parameters, and the results are summarized in Table I.

Table I. Predicted noise levels (dB) in enhancement and focus regions for different values of internal parameters Δr and Δe

Parameters		Enhancement		Focus
Δr km	Δe degrees	2.5 km, 40°	5.0 km, 40°	11 km, 140°
1.00	1.00	128.3	115.4	106.0
1.00	0.10	128.6	116.3	104.3
0.10	0.10	128.3	115.4	114.0
0.10	0.01	128.8	116.5	113.8
0.01	0.01	130.0	115.4	114.0

The results show that adjusting the internal parameters changes the computed noise levels only slightly in the enhancement region, but quite markedly in the focus region. The largest differences arise by reducing Δr , which effectively reduces the averaging implicit in the computed values. Since the characteristic wavelength of artillery noise is a few tens of metres, this imposes a physical limit on the degree of spatial averaging that is sensible. However, in practice the choice of these parameters is constrained by the need to collect a significant number of ray returns, N , within the specified incremental distance, Δr . The resolution with which the computations are performed in the current operational model ($\Delta r = 1$ km, $\Delta e = 1^\circ$) is limited by the computing power available at the range stations. Whilst the model does show an unhealthy sensitivity to these parameters in the focus region, it should be recognized that the empirical constant c_2 (see equation (I8)) was determined by comparing predictions from the model with measurements in enhancement regions. The model predictions have not been validated, however, in focus regions. The level of the increase in noise in the focus region in the model with $\Delta r = 1$ km is some 8–10 dB in the above examples; this increase is nearly doubled when Δr is reduced to

0.1 km. The predicted noise levels are also, obviously, dependent upon the values of the other empirical constants c_1 and c_3 .

3.2 Sensitivity to external parameters

The results from the model are particularly dependent upon the specified low-level winds; these influence the results in several ways, as discussed below.

Examination of equations (18) and (19) shows that the low-level winds directly determine the extent and direction of the sound shadow region (this was illustrated by the Lulworth predictions for 9 November 1985). More importantly, they affect the extent and direction of the sound enhancement region. To illustrate this the case of 20 August 1985 was recomputed, but with adjusted surface and 150 m winds; the changes made were comparable with the likely errors in the winds. The results are summarized in Table II.

Table II. *Maximum noise levels (dB) at 2.5 km and 5.0 km in enhancement region with adjusted low-level winds*

Surface wind		150 m wind		Maximum noise level	
degrees	kn	degrees	kn	2.5 km	5.0 km
215	20	217	29	128.8	115.4
210	17	217	29	131.7	115.4
220	23	217	29	126.6	121.0
215	20	212	24	124.9	126.5
215	20	222	34	131.7	113.6

The table shows that relatively small adjustments in the specified low-level winds can give rise to significant changes in the computed noise levels because they lead to changes in the vertical gradient of the speed of sound. In situations with light winds, comparable changes would be expected to have an even larger effect. This suggests that the accuracy of the low-level data will limit the reliability of the model predictions in the enhancement region. However, these changes do not make a significant difference to the predicted focus region.

In the model the low-level winds are only defined at two levels (10 m and 150 m); clearly this is insufficient to resolve any detail in the boundary-layer wind profile. An important question is whether the lack of detail near the surface has much effect on the predicted noise levels. To examine this, hypothetical wind profiles for neutral conditions were determined from a simple model (Smith 1977). The profiles were derived by specifying a geostrophic wind of 20 kn, a roughness length of 10 cm (appropriate to open countryside) and a Coriolis parameter of $1.1 \times 10^{-4} \text{ s}^{-1}$. The temperature profile specified was dry adiabatic with a surface temperature of 10 °C. Two predictions were made, one with winds and temperatures at the standard model levels 10, 150 ... 3000 m, and one with values at 10 m intervals up to 150 m. Whilst the wind speed shows a considerable difference in structure up to 150 m, the wind direction profile is virtually unchanged. Increasing the resolution of the low-level data has a marked effect on the sound enhancement region; at 2.5 km the maximum noise level is reduced by 3.4 dB, whilst at 5 km it is reduced by 1.8 dB, and the 120 dB contour lies about 900 m closer in. The changes in the predicted noise levels result because the trajectories of the sound rays are different.

It is also probable that the strong wind shears found below 10 m have some effect on the propagation of sound. However, uncertainties in the definition of the noise source (as discussed later), and the degree of spatial averaging implicit in the current model, make such detail superfluous at present.

These results suggest that the current operational model predictions would be changed (but not necessarily improved) if more detailed low-level data were available. However, a more sophisticated

model would almost certainly require better data, particularly near the surface where the shears are greatest. Wessels and Velds (1983) have shown that similarity theory can be applied to the problem of sound propagation in the surface layer and such an approach could be used to supplement the available data.

4. Deficiencies in the model formulation

The main deficiencies in the model are the neglect of the effects of turbulent diffusion, wave-form interference, and the underlying surface.

4.1 Effects of turbulence

Turbulence has an important role in the propagation of sound. Turbulent fluctuations in wind, temperature and humidity, which can occur on scales from a few millimetres to several hundred metres, are associated with variations in acoustic refractive index. If the scale of these fluctuations is larger than, or comparable to, the wavelengths of interest then they cause scattering of the sound waves. The main consequence of this is that the noise levels at a particular point can be variable, another effect is that sound can be spread into shadow regions. Because there is relatively little back-scatter, any attenuation of the sound energy is small, and is generally much less than that due to atmospheric absorption. For low-frequency impulsive noise both the attenuation due to absorption and turbulence are negligible.

4.2 Interference effects

Within a shock wave there are both over- and under-pressures, as illustrated in Fig. 3(a) which shows the type of wave-form which results from artillery fire. If two sound rays come together as shown in Fig. 3(b) then the two waves combine and there is a considerable increase in the noise level. However, if the two waves are out of phase then the resulting wave-form shape changes; in the example shown in Fig. 3(c) the duration of the shock wave is increased. The noise at a particular point, near the surface, is related to the resultant pressure change due to the direct wave, the ground reflected wave(s) and (in the enhancement and focus regions) the refracted wave(s). Depending on the phase of each of these, either constructive or destructive interference effects may be possible, as illustrated in Fig. 3. The details of the interference process are not considered in the present model.

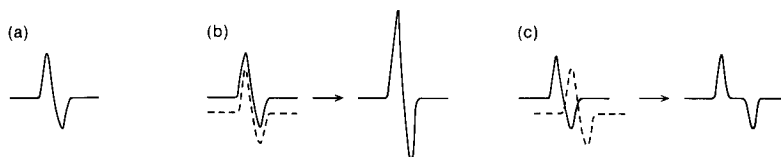


Figure 3. Schematic of (a) typical wave-form shape and possible interference effects that occur when two combining waves are (b) in phase and (c) out of phase.

4.3 Effects of surface and terrain

In Part I (Turton *et al.* 1988) the propagation of sound in the atmosphere was described by geometric optics methods. Such techniques can also be used to describe the reflection of sound waves at ground/sea surfaces provided the wavelengths of the sound waves are large compared with the scale of undulations in the surface. If this is so then the angles of the incident and reflected sound rays are equal. For artillery noise the basic wavelengths are a few tens of metres, thus water surfaces are usually acoustically flat and so geometric methods apply. However, land surfaces may be sufficiently rough for diffraction effects, rather than reflection, to occur. Also, the character of the surface is important; acoustically 'hard' surfaces (such as a water surface, which has a reflection coefficient close to unity) are

good reflectors, whilst 'soft' surfaces (which may result from vegetation) can absorb much of the incident sound energy and so reflect much less of it. However, for the low-frequency noise resulting from explosions or gunfire, it is suspected (but not established) that the reflection coefficient over land surfaces may still be significant, perhaps even as large as 0.8.

Furthermore, the situation is not quite so simple as suggested above because the wave-front is spherical rather than plane. The consequence of this is the so-called 'ground wave', which is required mathematically to match the boundary conditions as the spherical wave-front is distorted by the (plane) boundary; see, for example, Chessell (1977) and Piercy *et al.* (1977). Although the physical interpretation of the ground wave is not well understood, it is believed that it has an important role in propagating energy away from the source at low levels.

In addition to the effects of the actual surface, topography can also have a significant effect. If sound rays are reflected off sloping surfaces then the reflected and incident rays have different angles to the horizontal and this will affect where the rays next come down to ground. Complex terrain also has an important effect on the propagation of sound because the boundary-layer wind and temperature gradients are significantly modified from those found over flat surfaces (e.g. by cold air drainage and lee eddies over hills).

The effect of sea surfaces in reflecting sound waves is one of some importance, and is believed to be a particular problem at the Proof and Experimental Establishment range at Shoeburyness. Complaints of noise, evidently originating from Shoeburyness (suggesting levels in excess of 120 dB), have been made at Margate, some 50 km away across the Thames estuary. The explanation for these anomalously high noise levels is believed to be the 'bouncing' of sound waves across the estuary. At present any assessment of bounce is made subjectively by a forecaster since there is no explicit inclusion of surface reflections in the current model; this is an important aspect in which the present operational model is deficient.

4.4 *Determination of noise levels in focus regions*

It can be seen from equation (18) that the predicted increase in noise levels, for a particular density of returning sound rays, is greater further away from the source. In reality the opposite is true. Because the wave-front diverges, the intensity of sound rays returning to ground further away from the source is reduced. This is not reflected in equation (18), which clearly does not conserve energy. As the empirical constant c_2 has been determined from measurements made in the enhancement region closer to the source, the predicted noise levels in the focus region are likely to be much less certain than those for the enhancement region.

4.5 *Determination of the source level*

The peak over-pressure of the shock wave resulting from gunfire or explosions, which initially propagates supersonically, decreases rapidly as the wave diverges. By the time the shock wave has travelled about 100 m from the source, the peak over-pressure is small, and the wave propagates at nearly the speed of sound, i.e. it effectively becomes a sound wave.

As noted in Part I, L_0 is determined by equation (110), which has been determined from, and validated for, a limited range of explosive charge weights (0.2–37 lb). In the model the noise source is assumed to be omnidirectional, but for artillery guns this is not so. The measurements made at Lulworth (Lord *et al.* 1986) showed that the noise levels, to the rear and side of the guns at 100 m distance, were on average up to 6 dB different; for obvious reasons no measurements were made in front of the guns. These differences result partly because the effective noise source is somewhere in front of the gun, and partly because wind effects can still occur within 100 m of the source. No account of this difference is made in the model when predicting the noise levels.

5. Meteorological data as used in the model

In order to compute the sound-ray trajectories, the model considers the atmosphere as a series of layers of 150 m thickness. These data are currently provided from the Mark 3 radiosonde, details of which are given by Pettifer (1979). At the range stations radiosonde flights are made every 2 hours, and the data may be supplemented by radiowind flights between radiosonde ascents. The radiosonde measures temperature (every 2 seconds), humidity (every 4 seconds) and pressure (every 8 seconds), i.e. with an approximate vertical resolution of 12, 24 and 48 m respectively.

Values of (virtual) temperature are determined (by interpolation) at the designated model levels 150, 300 ... 3000 m. The surface temperature in the model is based on the hourly screen measurements. If the screen temperature changes between flights then the forecaster adjusts the upper temperatures to maintain an appropriate lapse rate.

Winds are determined by radar tracking of a target suspended from a balloon. Mean winds are evaluated for 150 m thick layers centred on the designated levels. However, since reliable winds from the radar cannot be obtained below about 200 m, the wind at 150 m is usually estimated by the forecaster from comparison of the surface (10 m) wind and the mean wind around 300 m.

As discussed earlier, the model-predicted noise levels are particularly sensitive to the low-level winds. Unfortunately this is the area in which the data are least reliable. Also the surface wind at the anemometer may well differ from that at the point of firing/detonation; at Larkhill the two locations can be up to 13 km apart, so the influence of local terrain and surface obstacles may lead to significant differences in the winds.

The winds aloft, which are layer means, are probably adequate since the model assumes horizontal homogeneity and sound waves traversing these layers will be (as their height increases) further away from the source.

Since the model results are less sensitive to temperature, the temperature data should, in general, be adequate. However, changes in the thermal structure of the boundary layer need to be taken into account (together with any accompanying changes in wind shear).

6. A simplified method for noise assessments

Whilst the noise assessment model described in this paper has been found to be a valuable tool for predicting noise levels at the range stations, there is on occasions a need for noise forecasts at remote sites where few data are available. A simplified method of producing assessments using synoptic data has been developed, which may be applicable for use at such sites.

The results from the model have shown that the low-level wind shear and wind direction are the main factors that determine the extent and direction of the sound enhancement region. This suggests that, with some knowledge of the winds, it should be possible to provide guidance towards the likely direction and degree of enhancement. For remote sites the only available information is the geostrophic wind (which may be determined from a synoptic chart). Using this, and a surface (10 m) wind (either forecast from the geostrophic value or estimated from the nearest observation), it is possible to make an assessment of the likely noise enhancement. In practice the ranges usually require to know to what distance are the noise levels likely to be sufficiently loud so as to cause complaints or nuisance, i.e. the distances from the source of the 130 dB and 120 dB levels.

The vector wind difference (i.e. the thermal wind speed) can be related to the predicted noise enhancement. Fig. 4 shows the model-predicted maximum distances from the source of the 130 and 120 dB noise levels, from operational predictions made at Larkhill over a 6-month period. The curves are simple exponential least square fits to the data and enable the forecaster to estimate the maximum distance from the source of the 130 and 120 dB noise levels. The regression equations for the curves are

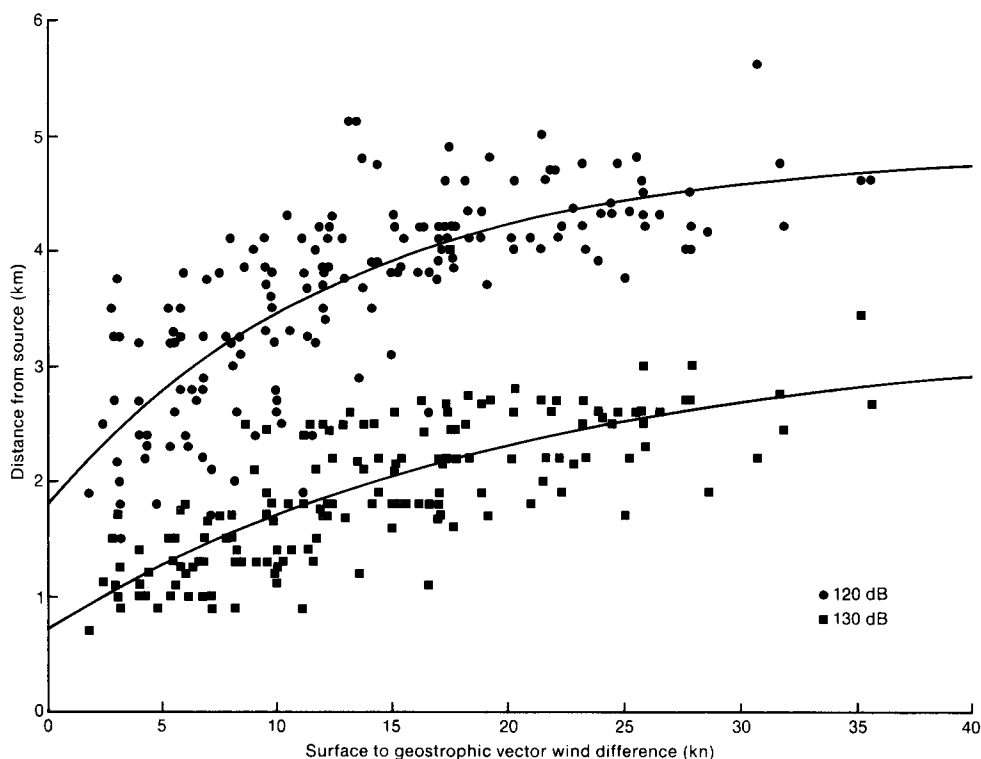


Figure 4. Model-predicted maximum distances from the source of the 130 and 120 dB noise levels for various surface to geostrophic vector wind differences. The curves are exponential least square fits.

$$d_{130} = 3.240 - 2.536 \exp \{-0.050 (v_G - v_{10})\}, \quad \dots \dots \dots (1)$$

$$d_{120} = 4.860 - 3.075 \exp \{-0.078 (v_G - v_{10})\}, \quad \dots \dots \dots (2)$$

where v_G and v_{10} are the geostrophic and 10 m winds given in knots, as is practised at the range stations. As an example, for a velocity difference of 20 kn the 130 and 120 dB levels would be expected to occur at approximately 2.3 and 4.2 km from the source. Fig. 4 shows that the distances determined from equations (1) and (2) are generally within 1 km of those predicted by the model; the standard errors of the fits are 390 m (d_{130}) and 540 m (d_{120}). The figure is valid only for an effective charge weight of 5 lb; however, a correction to the distances obtained, based on the noise-level decay rate, can be made for different charge weights. The corrected distances are obtained by multiplying d_{130} and d_{120} by a factor, F , which is given by

$$\log_{10} F = 1.1 \log_{10} (W/5) \log_{10} (d_{120}/d_{130}), \quad \dots \dots \dots (3)$$

where W is the equivalent charge weight (in pounds).

Forecasters should also be aware that, in conditions when there is a low-level inversion (perhaps a nocturnal inversion, or an inversion capping a cloud layer), the noise levels are likely to be higher and so the relevant distances will be increased.

The direction in which the noise enhancement is greatest usually veers some $10\text{--}30^\circ$ from the surface wind direction, and depends on the turning of the low-level wind, which would usually be expected to be less than that between v_{10} and v_G . As a rough guide the enhancement region might be expected to occur within a sector centred on the average wind direction and extending by about 50° to the side of the surface and geostrophic wind directions.

Because there is no detailed information about the wind profile, the method can give only a very rough indication of focusing. However, the model suggests that focusing is most likely when the directional shear is large, and is again related to the thermal wind speed. Fig. 5 shows the percentage occurrence of focusing for various wind speed classes. The figure shows that when the thermal wind speed is less than 10 kn the likelihood of focusing is low. For thermal winds greater than this, the likelihood of focusing increases with increasing speed. It should be noted that any focusing indicated by this method is caused by the turning of the wind within the boundary layer; such focusing tends to occur 5–10 km from the source. Overall, the model suggests that boundary-layer focusing would occur on about 45% of all occasions.

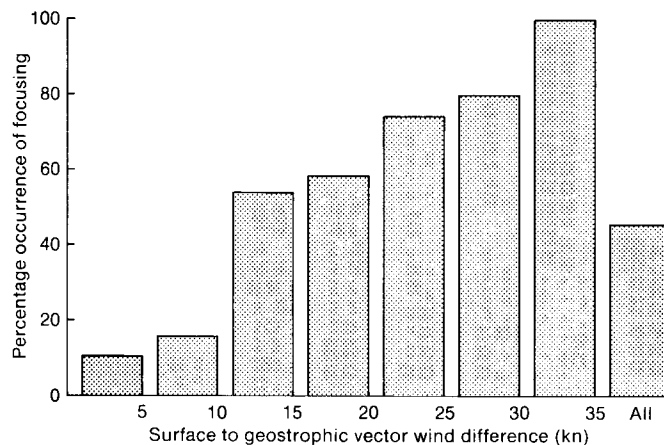


Figure 5. Percentage occurrence of focusing for various surface to geostrophic vector wind differences.

In the example for 20 August 1985 (see Part I, Fig. 7) the direction of the focus region is related to the directional shear in the wind profile. The wind shear in the layer, between the surface and the geostrophic wind is given by the thermal wind, which can be used as an indicator of the focus direction as illustrated in Fig. 1. In the model the predicted foci generally extend over a range of azimuth, typically 60° . When the boundary-layer foci were forecast to occur within 60° of the thermal wind direction, then this agreed with the model predictions on about 80% of occasions.

Focusing can also occur as a result of directional shears above the boundary layer. Obviously the method cannot give any guidance to this type of focusing. Forecasters should assess the likelihood of such focusing from the directional changes in the winds shown by an upper-air ascent. Foci due to shears above the boundary layer tend to occur further away from the source, at 10–20 km distance.

7. Concluding remarks

This paper has reviewed the current noise assessment model used operationally at a number of Ministry of Defence ranges. Use of the model has proved valuable to the ranges in identifying, and avoiding, occasions when noise levels are likely to be high, so producing a decrease in the number of complaints received by the Ministry of Defence for nuisance and damage. Complaints do still arise,

however, and indicate both a reluctance by the ranges to curtail activities in marginal conditions and the limitations in the accuracy of the current model, in particular the neglect of surface reflection effects. Trials have suggested that the mean r.m.s. accuracy of the model is about 6 dB, but there are very wide variations from this value day to day. However, this figure should be viewed against the overall effects of meteorology which can cause differences of about 30 dB in the noise levels.

The results from the model are also somewhat dependent upon the resolution at which the calculations are performed, especially in regions where focusing is predicted. The results also suggest that low-level winds have a major influence on the propagation of sound and on the resulting noise levels, particularly in the enhancement region. Limitations on the quality and representivity of the data used in the model can lead to significant errors in the forecast.

The demand for noise forecasts for various activities, in addition to artillery training and explosives testing, is increasing (e.g. demolition, quarrying, and wind turbine noise). The Meteorological Office is in a unique position to provide such forecasts which, in the future, might also form the basis of a commercial service using data from the observational network and/or products from the mesoscale model. However, before such a service could be established, more confidence is needed in the predictions.

Further modelling work needs to be done to include important effects (e.g. surface reflections) not presently considered. However, any potential improvements in the current model will probably be limited because of its empirical nature. A more sophisticated model based on firm theoretical principles, which takes account of the most important effects, would be necessary to produce more reliable forecasts. In addition, such a model would benefit from better quality data on winds and temperatures in the lowest few hundred metres of the atmosphere.

Noise forecasts are increasingly needed at sites remote from the observational network. To provide guidance for such sites, a simple method for making noise assessments has been developed. This method is now being used for several ranges where on-site meteorological support is not available.

Acknowledgements

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The identification of rainfall type from weather radar data

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Summary

A method of identifying rainfall type (frontal or convective) using data from a weather radar is described. The basis of the method is the use of pattern-recognition information, derived from space-time correlation surfaces, as local rainfall type indicators. The potential of this method for real-time implementation is discussed.

1. Introduction

Estimates of rainfall may be made by using radar. Precipitation particles back-scatter a proportion of the radar energy which can be quantified as a radar reflectivity, Z . Use is normally made of an empirical relationship between Z and the rainfall rate, R , of the form $Z=AR^B$, the values of A and B being dependent upon the distribution of precipitation particle sizes and hence rainfall type. In the UK radar system (Collier and James 1986) the values are $A=200$ and $B=1.6$, although many values of A and B are possible (see Battan 1973). The value of B does not vary as much as that of A , and therefore the factor A is modified in real time using data from a few telemetering rain-gauges.

The real-time adjustment procedure involves the fully automatic recognition of rainfall type (frontal rain, rain shadow, convective rain and bright band‡), and the modification of the factor A is made in different ways for different topographic areas dependent upon the rainfall type (see Collier *et al.* 1983). This technique has been shown to significantly improve the accuracy, relative to gauge-only measurements of areal rainfall, of the radar estimates of rainfall (Collier 1986). Nevertheless, the technique of objectively recognizing rainfall type was shown to be unreliable in particular circumstances.

The procedure of using different $R:Z$ relationships for different rainfall types has been investigated in several countries (see, for example, Attmannspacher 1976, Wilson and Brandes 1979, Calheiros and Zawadzki 1987). In principle, a reliable method of identifying rainfall types could produce useful improvements in rainfall measurement accuracy. More recently, it has become evident that estimates of wet deposition, either of radioactivity (reference Chernobyl) or of pollutants such as acid rain, depend upon knowledge of wash-out efficiency which is related to rainfall type (Monk and Jonas 1986). Hence, there are good reasons for considering whether it is possible to objectively estimate rainfall type. Collier *et al.* (1983) proposed a technique based upon a time series analysis of ratios of radar estimate to rain-gauge estimate. However, if a procedure could be found that was independent of rain-gauge data, then it would be possible to analyse in real time the spatial variations of rainfall type in much finer detail.

This paper outlines a rainfall-type analysis procedure that uses radar data alone, and is capable of real-time operation. Limited case-studies are presented to demonstrate the success of the procedure and highlight areas of difficulty.

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‡ When the radar beam intersects the region where snow melts to form rain, the radar reflectivity is enhanced and a 'bright band' is observed.

2. The possible technique

Sharon (1974) describes the application of space-time correlation analysis to rain-gauge data (see also Huff and Shipp 1969). A similar procedure may be applied to radar data. Consider the correlation coefficient, C_{ij} , which is defined as a function of pairs of points in the radar reflectivity field, Z . For any two points, (x_i, y_i) and (x_j, y_j) , the correlation coefficient is given by

$$C_{ij} = \frac{\overline{Z'_i Z'_j}}{\sigma_i \sigma_j}$$

where Z'_i and Z'_j are deviations of the measurements of Z at the points specified from their respective long-term average, and σ_i, σ_j are the standard deviations in time of the measurements of Z at the same points (the overbar indicates a time mean). Assuming the field of radar reflectivity to be homogeneous and isotropic with respect to the correlation coefficient, then C_{ij} becomes a function of the distance d_{ij} between the respective points where

$$d_{ij} = \{(x_i - x_j)^2 + (y_i - y_j)^2\}^{1/2}.$$

For a given type of precipitation and a given area, the sample correlation function, $r(d_{ij})$, is derived from estimates of r_{ij} obtained from the reflectivity data using

$$r_{ij} = \frac{\overline{Z'_i Z'_j}}{S_i S_j}$$

where S_i, S_j are estimates of σ_i, σ_j respectively. This expression for r_{ij} may be written as

$$r_{ij} = \frac{\sum_{t=1}^n (Z_{it} - \overline{Z_i})(Z_{jt} - \overline{Z_j})}{\left\{ \sum_{t=1}^n (Z_{it} - \overline{Z_i})^2 \sum_{t=1}^n (Z_{jt} - \overline{Z_j})^2 \right\}^{1/2}} \quad \dots \quad (1)$$

where t takes values from 1 to n with n the number of sets of data acquired over the period considered (1 hour or 12 sets in the present work).

Once the r_{ij} have been computed a set of correlation fields can be constructed by considering each data point in turn as being the 'key point' relative to which the correlations are plotted. Thus if there are N data points there would be N fields each consisting of $(N-1)$ plotted correlations. If the reflectivity field is regarded as homogeneous, the correlation function depends only on the distance d_{ij} between points and not on the specific locations. In this case the N fields can be combined with each key point being at the centre of the composite. The result is a field with $N(N-1)$ plotted correlations, each at an appropriate distance and direction relative to the original key point. Each computed correlation is included twice at diametrically opposed points relative to the centre. The correlation surface is constructed by plotting contours of equal correlation on the composite surface. It should be noted that the spatial distribution of values on this surface does not map onto the topography underlying the area under consideration; vector distances from the centre of the field simply indicate the relative positions of points whose correlations have been calculated.

The approach outlined is only valid if the variance is constant throughout the field (Gandin 1965). This is an appropriate assumption for convective systems, but may not be appropriate for rainfall in which orographic effects vary significantly. In such circumstances the correlation surfaces may become

very variable in space, although this variation will be closely linked to orographic features. For situations in which orographic effects are small, and rainfall patterns are dominated by mesoscale frontal dynamics, one might expect characteristic correlation surfaces, provided that areas over which the analysis is carried out are small compared to the synoptic scale (hundreds of kilometres). It is evident that the correlation surfaces can perhaps be used to describe objectively the spatial structure of the storm rainfalls. In what follows this possibility is investigated.

3. Analysis of rainfall patterns

Examples of radar data associated with events which produced local river flooding have been studied. The effects of the automatic calibration procedure applied in real time were removed before the data were analysed. All the data considered were recorded with the Hameldon Hill radar in north-west England as part of the North West Weather Radar Project (Collier *et al.* 1980).

Four areas each containing 100 data elements in a 10×10 array with a 2 km grid were selected around the locations of the existing telemetered rain-gauges. Only three of these locations are considered in this paper and these are shown in Fig. 1.

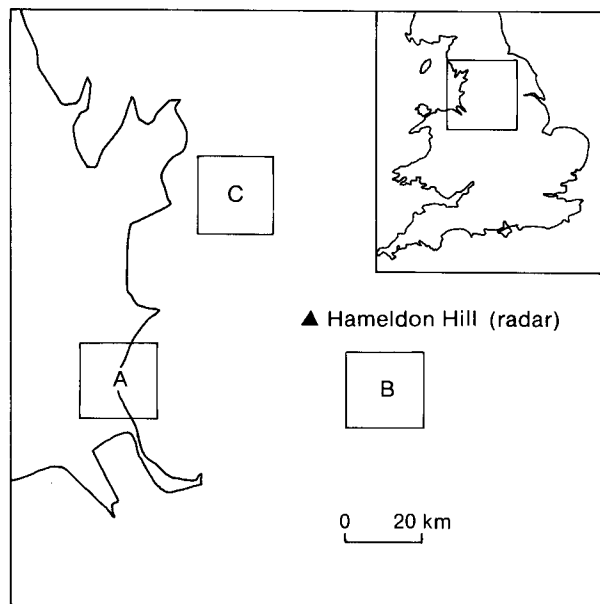


Figure 1. Locations of the space-time correlation windows A, B and C.

The space-time correlation surface technique was applied to each set of radar elements, one hour's data (12 scans at 5-minute intervals) being used for the time series. After the sets of data had been analysed, a contour-plotting routine was used to display the surfaces. The results of this analysis agreed with the findings of Sharon (1974) for convective rainfall and of Marshall (1980), in that definite forms of pattern were produced by different weather conditions detected by the weather radar. Samples of these contours during the passage of a convective trough are shown in Fig. 2. In general terms, the shapes of these surfaces confirm that under showery conditions the data elements have very poor correlation with their immediate neighbours, the contours enclosing almost circular areas (Fig. 2(a)). In the region of the convective trough there is much higher correlation between data elements lying along

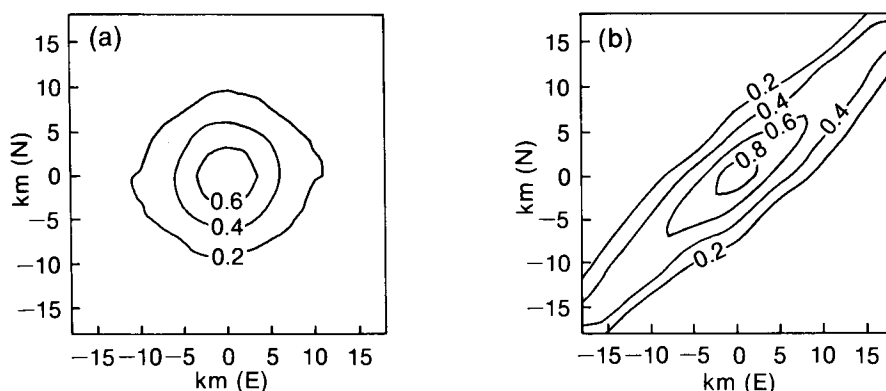


Figure 2. Correlation surfaces for (a) box A (see Fig. 1) for 0847 to 0947 GMT on 19 October 1984 (showery conditions) and (b) box B (see Fig. 1) for 0802 to 0902 GMT on 19 October 1984 (frontal conditions).

the axis of the trough (Fig. 2(b)). This supports the idea of using such a pattern-recognition algorithm to discriminate between various rainfall types.

Although visual discrimination between patterns is automatic, some more basic property was sought that would enable numerical values to be computed which described the pattern characteristics of the space-time correlation surface. An initial attempt was made in which the values of the correlation surface were summated in the expectation that the elliptical patterns, indicative of frontal rainfall, would produce a different order of value than would a circular pattern. However, it became evident that this solution would not produce a unique numeric property possessing high discrimination between rainfall types.

In an attempt to define the shape of the contours making up the space-time correlation surface, the ratio of the summated value of the data lying on the major axis of the shape to that of the data on the minor axis was extracted. This ratio is referred to as the 'rectangular ratio' for the correlation surface (see Fig. 3).

The space-time correlation surface is symmetrical about its diagonal. This symmetry enables the ratio of the two data axes to be extracted very simply since it is only necessary to operate on half of the data. A series of ratios was produced by successively discarding the oldest data scan and including an extra one

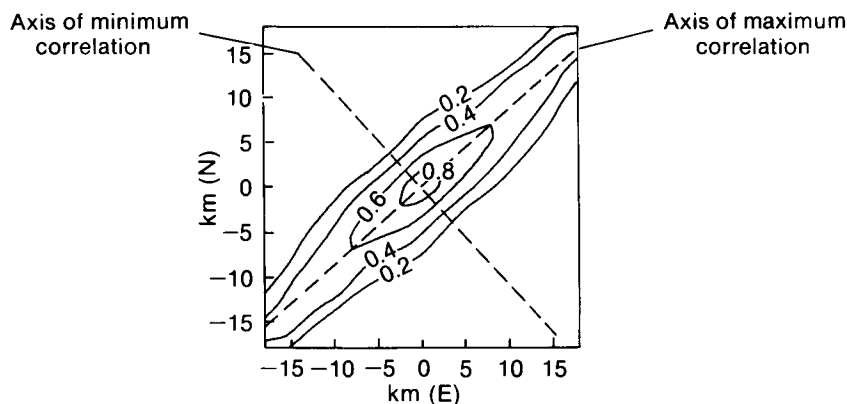


Figure 3. Illustration of the axes of maximum and minimum correlation used in the calculation of the 'rectangular ratio'.

from the data file. The continuous analysis of one day's data produces 288 values for this parameter; however, the structure of the available data meant that the first hour of the day was used to establish the first ratio. In real-time application, data for the previous day would be included in the analysis of the first 11 scans in any day. Examples of the values of this ratio are shown in Fig. 4 together with corresponding synoptic maps showing the analysed weather type.

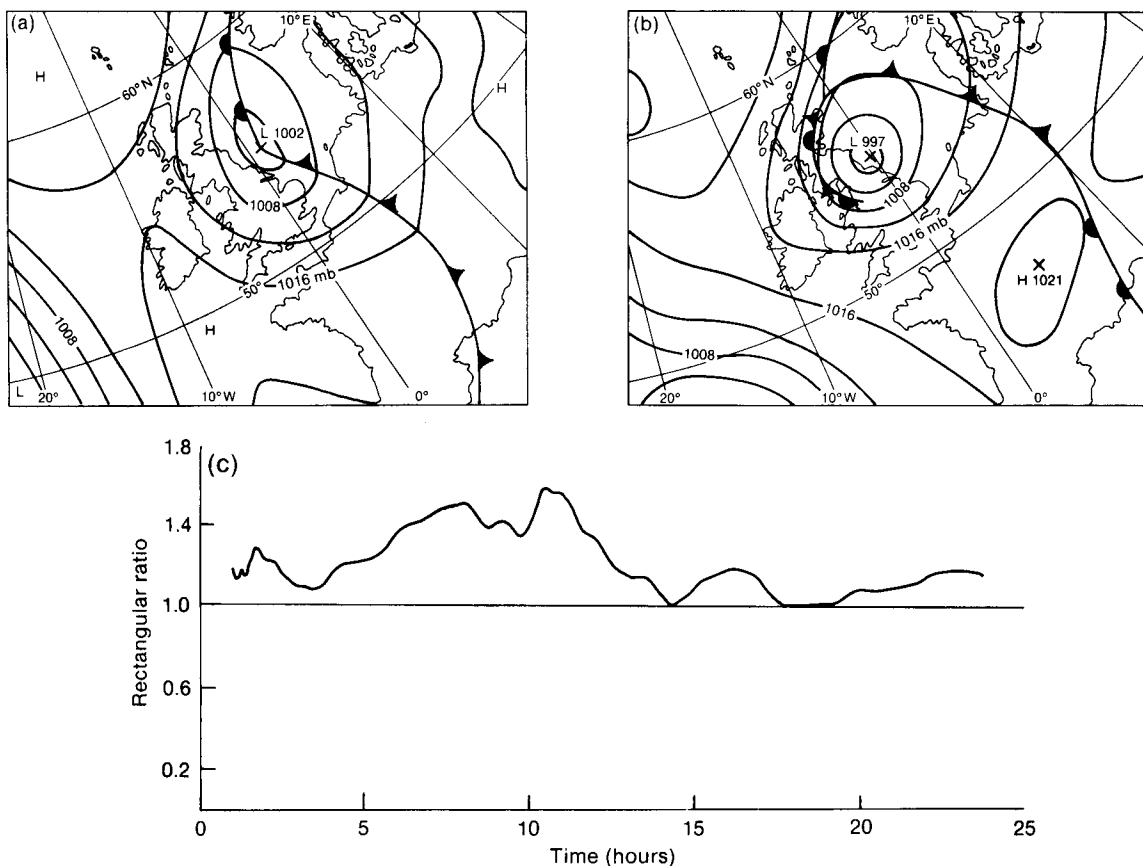


Figure 4. Illustration of (a) the synoptic situation over the United Kingdom at 0600 GMT on 3 November 1984, (b) the synoptic situation at 1800 GMT on 3 November 1984, and (c) the variation of rectangular ratio calculated for box C (see Fig. 1) during the period 0100 to 2400 GMT on 3 November 1984.

4. Discussion and conclusions

The magnitude of the rectangular ratio, which is always greater than 1, is typically less than 2. However, this value may be exceeded when, for example, very narrow bands of rain, such as line convection, are observed (James and Browning 1979). Large values may also be produced by orographic rainfall associated with extensive upland areas. Negative values of the ratio occur when the data element value Z_{it} used in equation (1) is less than the mean value \bar{Z}_i for the series. Such negative values causing these excursions could be indicative of bright band or large gradients of rainfall since under these conditions the rainfall within the area of the data elements can vary by an order of magnitude. However, it is unlikely that this technique would provide a method of identifying bright band which was more reliable than that described by Smith (1986).

Fig. 4 shows examples of showery and frontal rainfall with the corresponding rectangular ratios. The movement of an occlusion across northern England is marked by changes in the value of the rectangular ratio. The choice of window size is very important. If the window is too small a front may not be recognized, as the convective elements in the front dominate the calculation of the value of the rectangular ratio. Insufficient data have been analysed to make reliable identification of the relationship between the rectangular ratio of correlation and the rainfall type. Nevertheless, the examples shown in Figs 2 and 4 give the authors sufficient confidence that the procedure may be reliable enough for operational use. Work has begun to investigate further the operational performance that can be expected. The following conclusions may be made, albeit tentatively at this stage.

- (a) The use of space-time correlation surfaces may be applied to radar data in the same way as proposed for rain-gauge networks.
- (b) The use of space-time correlation surfaces to identify the statistical structure of storm rainfall is a practical method and deserves further detailed investigation. More detailed consideration should be given to the most appropriate size for the windows used.
- (c) The rectangular ratio of space-time correlation surfaces shows variations that are a function of the shape of the data contours and therefore provide a means of identifying storm type for the data window analysed. This procedure is inherently related to pattern-recognition techniques, and would therefore benefit from developments in this field.
- (d) The use of the rectangular ratio may provide a method of identifying local storm type within small areas of a data field, thereby reducing the temporal errors and also allowing the individual analysis of topographic features.

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The achievements of COST-43*

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Summary

The history of the COST-43 Agreement — a project to set up an experimental European network of ocean stations — is described from its origins in the late 1960s, through to the two formal phases which occurred from 1979 to the present day. It is shown that many of the aims and objectives of the project have been achieved.

1. Introduction

In the Report of the Political Working Group for Scientific and Technical Research established by resolution of the Council of the European Communities on 31 October 1967 the birth certificate of 'Action 43' is registered in the descriptive notice 'Oceanography, Action 43: Setting up of a network for oceanographic and meteorological measuring stations in European waters'. One of the initial aims was 'the common development of a complete network of automatic measuring stations allowing the collection and transmission of oceanographic and meteorological observations both along the coast and in the open sea' — a bold and far-seeing objective.

However, it was rapidly realized that the technology was not at that time sufficiently developed, and that the most likely way of making progress was by a policy of short steps via *action concertée* by the interested parties.

In 1970 the creation of the COST (Co-operation in Science and Technology) framework resulted in a number of Consultants Groups, amongst which was the Oceanography/Meteorology Technical Committee. Initially chaired by Dr A. Nyberg of Sweden, this group was charged in April 1970 with defining in one year the technical content of a concerted project between the governments which were

* Based on a paper presented to the COST-43 Seminar on Operational Ocean Station Networks — COST Project 43, Institut Français de Recherche pour l'Exploitation des Mers, Brest, France, 16–18 June 1987.

interested. It took a little longer than that, but by autumn 1972 the Senior Officials Committee of COST had received the required report. One of the aims of COST is to promote co-operation between industrial companies in the field of research and development projects, and so the Senior Officials discussed the report with various commercial and industrial companies only to find that the proposals for organization and finance were not sufficiently well defined, and the technical specifications insufficiently detailed for the manufacturers to be confident that progress could be made within a reasonable budgeting framework.

By June 1973 it was clear that there was a need for a consultant to define the detailed specification of the project and to estimate the amounts of money that would be required to implement it. To that end Professor J.P.G. Martinais of the Centre Océanologique de Bretagne was appointed to produce a report.

Professor Martinais' (1976) report is still well worth reading today. First he addressed the requirement in terms that recognized the interdependence of the global atmospheric and oceanographic circulations, which he called 'Marine meteorology' and 'Global oceanography', tempering this requirement by the perspective and constraints of the economic context.

Second he considered the state of the art in marine meteorological measurements, making an inventory of the technical problems which he could see would be posed in implementing an established network of ocean stations. He found a mismatch between the parameters that needed to be measured and those sensors that existed at that time, and came up with the idea of 'pilot networks' in which 'new instruments could be tried, tested and evolved as technical progress is made and scientific knowledge increased'. His basic concepts involved:

- (a) sensors,
- (b) buoy transmit terminals,
- (c) the transmission unit,
- (d) the structure, and
- (e) one or several onshore stations,

and he gives us the excellent advice that 'some day, every piece of equipment at sea will either be damaged or lost; therefore, it must be simple, robust, uncomplicated and cheap.' I am sure that today we all recognize all these concepts and we have learnt the truth of the advice one way or another.

Third, and most important, Professor Martinais made some proposals as to the way ahead as he saw it in 1975. These involved:

- (a) Pilot networks — these would require Ocean Data Acquisition Stations and onshore data reception to be organized for limited areas or regions at a reasonably low cost. Comparisons of a number of such networks would allow technical and financial solutions to be tested.
- (b) Concrete proposals for data transmission systems via polar-orbiting and geostationary satellites, and via high frequency.
- (c) Concrete proposals for structures and various types of buoy ranging from fixed platforms through moored buoys to drifting buoys.
- (d) A plea for some standardization both in the area of structures and with regard to sensors as soon as the developing technologies allowed.

Lastly he made a plea for European nations to pool some of their technical and scientific efforts for the greater good of the whole, since he saw that it was only in this way that the efforts of the COST countries could come together to complement each other and to provide the European/Atlantic-wide network that was required. To quote from the final words in his report — dated January 1976 — 'The efforts to co-ordinate the investigations are difficult, the long-term programme is ambitious, but today a realistic and constructive stage is possible.'

2. COST-43 — the First Agreement

By mid-1975, therefore, the Technical Committee on COST-43 had seen its early ideas for an intergovernmental Agreement drift back in time by several years. The hopes of some that a European industrial consortium could be set up to run the whole network had foundered because of a downturn in the economic situation and it was becoming clearer that *action concertée* via co-ordinated national programmes was the only way ahead. During 1975 it became clear that the ideas for pilot networks of Ocean Data Acquisition Systems (ODAS) in five regions were feasible, based on national contributions, and it was agreed that a Project Co-ordinator would be required to help the work. In January 1976 Dr T. Kvinge was first named as the Project Co-ordinator.

It was now necessary for the Memorandum of Understanding (MOU) and Technical Annexes of the Agreement to be prepared. This took some time, but by October 1976 Dr K. Holberg (Norway), who was then the Chairman of the Technical Committee, was able to put the document describing COST-43 to the Committee of Senior Officials.

There was then an 'interim' period while the lawyers got to work, but I am glad to say that this did not stop buoy instrumentation development and installation work continuing on a national basis. The final document was dated 29 July 1977 (COST/60/1/77) and was entitled 'COST-43 — a project to set up an experimental European Network of Ocean Stations (ENOS) for the purpose of providing meteorological and oceanographic data on a real time basis.'

The project was to be implemented in two phases:

- (a) Evaluation, testing and further development of existing and/or new systems (sensors, structures, transmission systems) provided in national programmes.
- (b) Setting up of pilot networks in selected test sea areas, i.e. the Azores, Bay of Biscay, Faeroes/Shetland, North Sea/Baltic and Mediterranean.

The project was intended to form an opinion on whether an integrated European regional network would be feasible and politically practical, and was to take 4 years by *action concertée*. The initial signatories to the Instrument included Denmark, France, Ireland, Norway, Portugal, Finland, Sweden and the United Kingdom. (Other countries now participating such as Belgium, Iceland, Italy, The Netherlands and Spain signed later, and the Federal Republic of Germany has been a regular Observer.)

It was now necessary to await ratification before the Agreement could come into force, and in the meantime an Interim Management Committee was set up (Chairman, P.M. Vitureau of Centre National pour l'Exploitation des Océans, France). This Committee dealt with the administrative problems whilst continuing to make some progress towards the objectives of the project. From 4 to 6 December 1978 the first Technical Seminar under the auspices of COST-43 was held at the Instituto Dofesu Nacional in Lisbon. During the seminar, attended by 42 participants, 23 papers were presented covering a wide range of ODAS-related topics.

The Agreement entered into force on 29 June 1979 when ratifications had been obtained from the necessary seven countries, and the first meeting of the Management Committee was held in Brussels on 6 July 1979 under the chairmanship of the author. The budget for the first 4 years was some 12.5 million Belgian francs. The majority of this sum was required to cover the meetings and to support the Head of Project and a small Technical Secretariat located in the Christian Michelsen Institute (CMI) of Bergen, Norway.

In September 1980 a second COST-43 Seminar was held at the CMI, which was devoted to the practical problems of ODAS development and applications that were then uppermost — in particular ODAS sensors, their calibration and stability, the reliability of data retrieved from ODAS, and of the ODAS structures and moorings, and the future of the COST-43 project. By that time it was becoming clear that COST-43 was moving steadily towards an operational phase and the need for planning

beyond 1983 was already being considered. The words of T. Hovberg and U. Karstrom (Sweden) at this time are noteworthy:

It will not be possible to cover future needs for meteorological and oceanographical data from European waters by ships and satellite observations only. Buoy and platform stations will also be needed.

An ocean station network in European waters must — to a large extent — be designed and run in common. Otherwise it will be inefficient and expensive!

Different national projects get a little extra push from the existence of a formal international agreement.

These remarks are still true today.

At the end of 1980 Dr R.E.W. Pettifer (United Kingdom) became the new Chairman, and during 1981 and 1982 Belgium, France, Iceland, The Netherlands and Spain acceded to the Agreement, bringing the total number of countries in COST-43 to 12. The COST-43 ODAS network as at 30 June 1980 is shown in Fig. 1 (COST-43 1981). Further progress was made as more ODAS were brought into operational status. For the first time joint multilateral projects became part of the plan (e.g. Iceland, Norway and the United Kingdom in the south-west of Iceland; France and Portugal in the Azores; Finland and Sweden in the Baltic). At the same time drifting buoys and wave riders (Portugal) were being considered. A highlight of 1982 was the COST-43 Project Review and Proposals for the Future (COST-43 1982a) which was put forward to the COST Senior Officials by the Management Committee. This document proposed a further 4 years' extension to the existing Agreement with organization and funding broadly staying the same so that the co-operative development of the European ODAS network within the individual programmes of participating countries could be continued via the encouragement and guidance of the COST framework. Member states supported these proposals and, following a questionnaire, a diagram showing the areas of national interest was produced (Fig. 2, COST-43 1982b). On the technical side a third COST-43 Seminar was held at the European Centre for Medium-range Weather Forecasts (ECMWF) in Reading, England from 14 to 16 June 1983. There were 86 participants

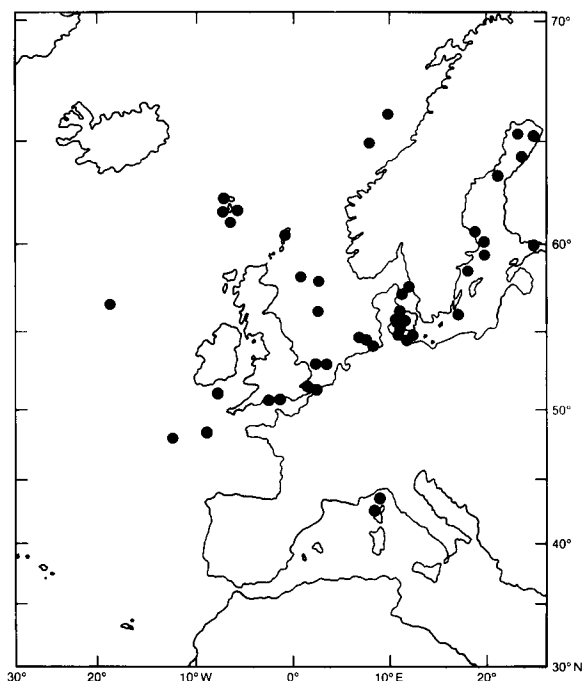


Figure 1. COST-43 ODAS network on 30 June 1980 (from COST-43 1981).

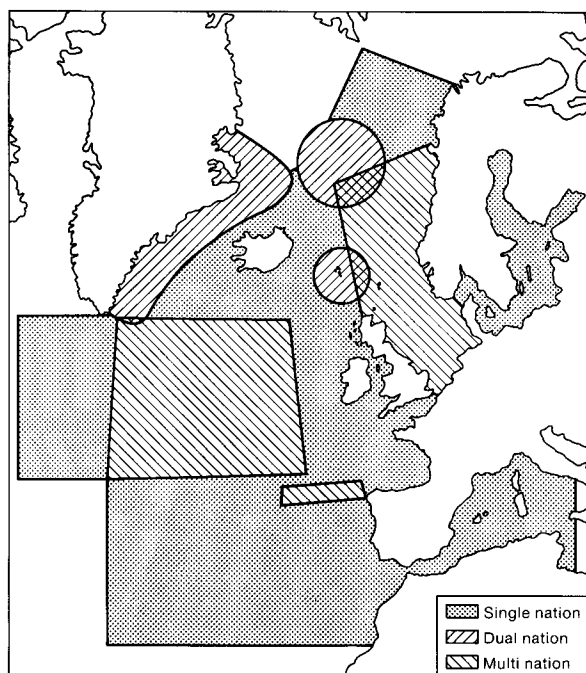


Figure 2. Areas of national interest for ODAS location (from COST-43 1982b).

from 8 countries and 27 papers were presented. ODAS manufacturers from Finland, Norway and the United Kingdom made an appearance at this seminar giving a scientific and industrial session.

3. COST-43 — the second phase 1984–88

The aims for the second 4-year period were clear. Firstly there was a continuing need to complete experimental development in respect to buoy technology and sensor technology, particularly in the area of drifting buoys. Secondly there was a need to define and agree an achievable programme of specific ODAS in a suitable network over the European/ North Atlantic area. Fig. 3 (Pettifer 1983) identified the areas and sites of common interest and it also showed the existing ODAS sites in early 1983. Other aims included the maintenance of close co-operation with the World Meteorological Organization (WMO) and Intergovernmental Oceanographic Commission (IOC) programmes, and the desire to encourage and if possible implement a programme of drifting buoys in the North Atlantic.

The new second phase of the COST-43 Agreement was signed on 21 November 1983 and came into force a year later on 1 December 1984. It is therefore valid for a period of 4 years until 1 December 1988. During the period from June 1983 until December 1984 an Interim Management Committee was formed to carry on the good work. The project continued to make progress. In particular, and perhaps most importantly, an *ad hoc* Working Group was set up to plan the implementation of a major co-operative drifting buoy programme in the northern part of the North Atlantic. At the same time the Project Leader was specifically instructed to start investigating the possibilities for the development of another drifting buoy programme in the southern part of the North Atlantic.

It was during this period that the first Joint Venture Programme — System of Operational (drifting) Buoys in the Atlantic (SOBA) was planned and started operation. Six nations — France, Iceland, Ireland, The Netherlands, Norway and the United Kingdom participated.

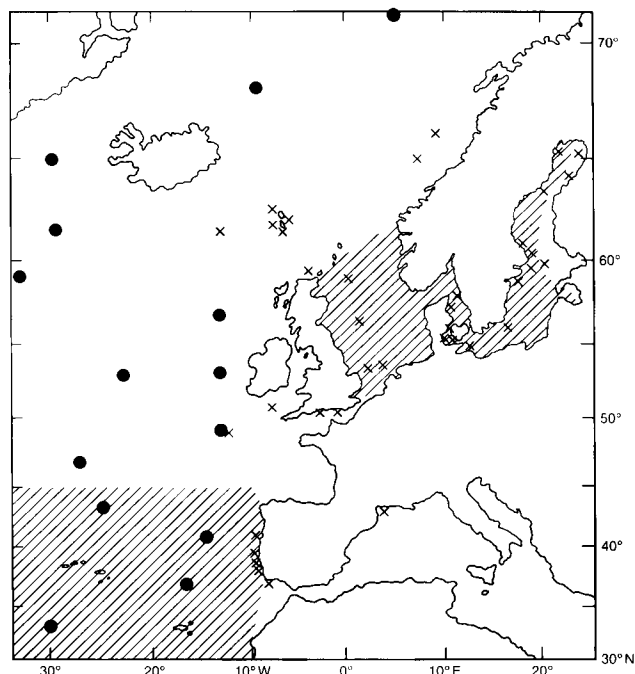


Figure 3. Areas (hatched) and sites of common interest for the establishment of new ODAS stations (solid circles) compared with those in place on 30 June 1983 (crosses) (from Pettifer 1983).

The basic elements of the SOBA programme are as follows:

- (a) A minimum of two drifting buoys are kept operating in a specified area 55–63° N, 25–45° W at all times over a period of 3 years.
- (b) The data are transmitted via the Argos system and received by local user terminals, from where they are disseminated in near real-time in DRIBU code via the Global Telecommunication System (GTS).

It was also during this period that COST-43 was able to send a representative to the Informal Meeting on Observing Systems with particular emphasis on the North Atlantic which was held at ECMWF in October 1984. This led on to COST-43 participating in the Operational World Weather Watch Systems Evaluation for the North Atlantic (OWSE-NA) which is currently under way.

On 5 December 1984 the new Management Committee held its first meeting under the new Agreement and continued, at first under the continuing leadership of Dr R.E.W. Pettifer and later with Dr W.A. Oost (The Netherlands) as Chairman.

While the co-ordinated programmes for measurements from moored buoys and marine platforms have continued to be important elements of the COST-43 programme in its second phase, perhaps the most important (and exciting) new venture has been the genesis and implementation of the co-operation between European nations to establish the SOBA and the SCOS (Southern COST-43 Operational System) operational drifting buoy programmes.

As stated above it was possible to implement the SOBA programme from October 1984. The SOBA programme has now been operational for 2½ years. The statistics show that during the first 14 months of operations a total of 7 buoys were deployed giving some 60 'buoy months' of accumulated buoy deployment time with an average buoy coverage in the SOBA area of 1.3 buoys. Early in 1986 it was

decided to increase the target number of buoys in the SOBA area from two to three, and to make greater efforts to ensure that the data from the buoys were being recovered and received into the GTS.

In general the SCOS programme for drifting buoys in the southern area of the North Atlantic has followed the operational procedures of the SOBA programme. In this case two deployment areas, 40–45°N, 30–35°W and 35–40°N, 20–30°W, were chosen to be used alternately with fixed time intervals. Due to the southerly position, the number of useful passes of the TIROS polar-orbiting satellites are significantly lower for this area than for the SOBA area, and the idea of using buoys with a Meteosat transmitter as well as the Argos system (used for position location) has been developed. For the SCOS programme France, Ireland, The Netherlands, Portugal, Spain and the United Kingdom have participated. The SCOS programme began in July 1986.

4. Achievements of COST-43

4.1 ODAS and drifting buoys

So far the emphasis has been on the activities of the COST-43 project, and this is natural since it is through the activities that the achievements can be demonstrated. The initial aim was the establishment of an experimental network of ODAS providing oceanographic and meteorological data in real time. Back in 1979 there were very few established ODAS within the COST-43 area, apart from the highly expensive ocean weather ships. During the ensuing years over 60 ODAS stations have been established under the aegis of COST-43. Some have only been deployed for a short period, but many are maintained to be fully operational (see Fig. 4, COST-43 1986). Further, we now have two programmes in which drifting buoys are routinely seeded into chosen weather-sensitive areas of the North Atlantic.

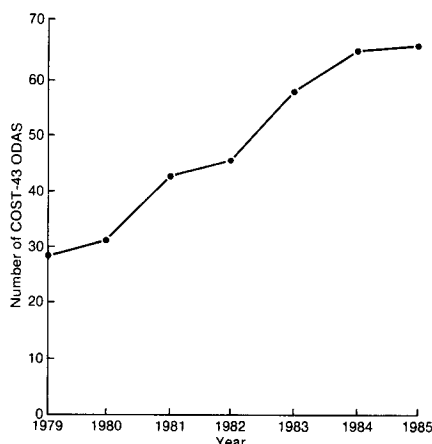


Figure 4. Operational COST-43 ODAS from 1979 to 1985 (from COST-43 1986).

4.2 Technology development and transfer

Through the proceedings of the four major Technical Seminars run by the project, and via many (approximately 150) further Technical Documents as well as personal contacts brought about by the existence of the project, there has been extensive European-wide exchange of technical ideas and information concerning the difficult problems of the engineering and technology of ODAS deployment and routine operation. Inter-calibrations between the different national systems and sensors have been carried out under the project to ensure the consistency and value of the data provided by the ODAS. Successful long-term deployment of ODAS in European North Atlantic waters is now a part of the operational data-gathering scene.

At the same time the development of marine buoy/ODAS industries has been aided through the various COST-43 national programmes, particularly in Norway, France and the United Kingdom.

4.3 *North Atlantic Ocean data*

International liaison between the Technical Secretariat of COST and international bodies such as WMO and IOC has ensured that the data generated under the auspices of COST-43 have contributed to the wider requirement for real-time and archival data. Ocean data are now available which were not there before, and they have only become available through the encouragement of COST-43 ventures and the guidance of the COST-43 Management Committee.

4.4 *European co-operative structures*

As has been said before, one of the most important achievements of the COST-43 project has been to discover new ways in which nations (National Meteorological and Oceanographic Services and Institutes) can come together in joint projects in their common interest with the minimum of legal and bureaucratic procedures. COST-43 has acted as an 'umbrella' under which new precedents and simple procedures have been created for co-operative ventures. The use of simple Letters of Intent between Directors of National Meteorological Services is now an agreed method of procedure. Joining the COST-43 Agreement has not bound the signatories to specific (perhaps expensive) joint actions, it has instead created a favourable climate for co-operation through which individual national institutions have been able to take part in the establishment of an ODAS network which would have been outside their financial reach acting alone.

5. Conclusion

It is clear that this project has already been a major influence in drawing the European nations together to establish a network of over 60 ODAS and that the amount of data has increased by over 1500 reports a day. The essential nature of the Technical Secretariat and Project Leader has been demonstrated both in giving guidance and encouragement and also in forming a focal point for technical co-ordination of programmes. Simple procedures for multilateral international co-operation in establishing joint ODAS programmes have now been established, and it is my view that the way is now clear to obtain general agreement to extend the networks into a more fully operational and long-lasting context within a continuing regional umbrella organization.

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The refurbishment of the Central Forecasting Office, Bracknell

R.M. Morris

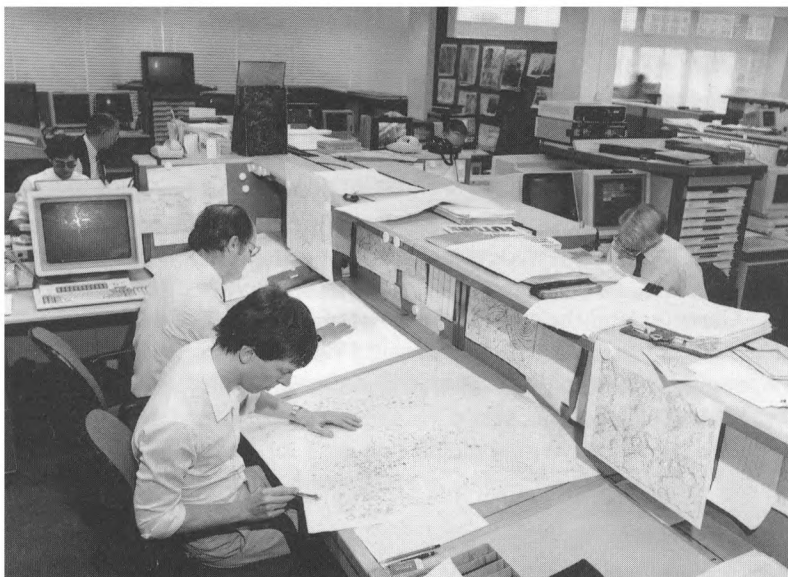
Assistant Director (Central Forecasting), Meteorological Office, Bracknell

Following a decision taken in the summer of 1986 to transfer the civil aviation Principal Forecasting Office from Heathrow to the Central Forecasting Office (CFO) at Bracknell, a major refurbishment programme for CFO was set in motion to culminate with the transfer of the Heathrow team at the end of March 1988. The transfer in fact occurred on 23 March and, although there were some difficulties with the communications, the aviation unit was operational at 1200 GMT.

The refurbishment was planned with the 1990s in mind. Working positions were designed as single movable units with greater use of VDUs envisaged than ever before, although it is recognized that persuading forecasters to use screens rather than paper will be a slow process. (This slowness is not necessarily due to forecasters' conservatism; the versatility of the software and the speed of keyboard response have to reach acceptable standards before it becomes more efficient and effective to use the VDUs rather than paper.) The increased use of VDUs meant that a false floor had to be inserted in CFO to take the cables and the ceiling had also to be lowered in order to accommodate a more efficient air-conditioning system to cope with the extra staff and machines! It was necessary therefore to evacuate CFO for about 6 months.

By dispersing staff in adjacent offices, it was possible to relocate CFO temporarily in accommodation that was just adequate if rather cramped and lacking in air-conditioning. (Visitors would have noticed numerous electric fans during the summer and numerous radiators during the winter although fortuitously the summer was not hot and neither was the winter very cold!) The temporary accommodation was occupied from July 1987 till early February 1988 and as we all know this period





contained some exceptional weather events. On a positive note the return to the refurbished accommodation was marked in style by the prediction of the deepest February depression ever recorded to affect the United Kingdom. This proved to be a good forecast.

The new CFO includes the Storm Tide Warning Service unit for the first time, and the Metroute and Prestel units are also firmly established as integral parts.

The fact that the refurbished CFO is functioning smoothly and that the integration of the Heathrow team into the system also occurred fairly smoothly — and on schedule too — was due to the combined efforts of several Branches in the Office, Property Services Agency and the private contractors, and also to the whole-hearted, unselfish and positive attitude of the staff directly concerned.

There is still much work to be done; the display and storage of paper has to be accomplished in the most efficient manner and the lines of communication (human as well as data) have to be thoroughly effective. It is a huge organization and it will take time and resources to meet these objectives.

Notes and news

European Geophysical Society

The European Geophysical Society (EGS), for active research workers of all ages, is run entirely by its members, with no official backing from governments. Its 13th Assembly was held from 21 to 25 March 1988 in Bologna, Italy, as part of the celebrations of the 900th anniversary of the foundation of the university in that city. The three sections of the Society (Solid Earth Geophysics; Atmospheric Sciences, Oceanography and Hydrology; and External Geophysics) organized a variety of symposia, workshops, general sessions and review lectures, including meetings and lectures on general meteorology, the physics and dynamics of the ocean circulation, climatic variations during the historical and instrumental periods, variational methods in meteorology and oceanography, the physics of low-frequency internal atmospheric variability, interaction of scales in weather systems, moisture and water in the soil and

atmosphere, space oceanography, air-sea-ice interaction, large-scale general circulation modelling, results from ALPEX (Alpine Experiment), oceanography in WOCE (World Ocean Circulation Experiment) and POEM (Physical Oceanography of the Eastern Mediterranean) and numerical weather prediction and predictability. Amongst the 1000 participants was Dr Raymond Hide, FRS, head of the Geophysical Fluid Dynamics Laboratory in the Meteorological Office and sixth president (1982–84) of EGS, who was awarded honorary membership in recognition of 'his excellence in original and stimulating contributions to the field of geophysical hydrodynamics and his valuable efforts in the promotion and growth of the Society'. Dr Axel Wiin-Nielsen of Denmark, formerly Director of ECMWF and Secretary-General of WMO, was elected as ninth president of EGS (to serve from 1988 to 1990) and Dr W. Ian Axford, FRS, Director of the *Max-Planck-Institut für Aeronomie* at Lindau, Federal Republic of Germany and the current president of COSPAR (Committee on Space Research), was elected as the tenth EGS president (to serve from 1990 to 1992).

The 14th EGS Assembly will be held next year in Barcelona, Spain during the now 'traditional' week before Easter, 13–17 March 1989.

Retirement of Mr D. Forsdyke

Donald Forsdyke was educated at Dunstable Grammar School and followed his father's footsteps in joining the Meteorological Office. He entered in 1949 as a Scientific Assistant, the forerunner of the present ASO grade. His first appointment was to the CRDF or Sferics unit at Dunstable but that did not last long because he was called up for national service in January 1950 and posted first to Changi (Singapore) with the Far East Air Force and later to Upavon which he left on release from the Royal Air Force in 1951. As other successful members of the Office have done, he then obtained special leave without pay to further his education, taking an honours physics course at Imperial College. He rejoined the Office as a Scientific Officer in the Instrument Development Branch at Harrow, his first paper there being written on the digitalization of meteorological information, a pretty avant-garde topic at that time. In the late 1950s he saw the new cloud-base recorder through its trial phase before turning his hand in 1960, as a Senior Scientific Officer, to forecasting at Prestwick, directly joining the Senior Forecasters' roster at a time when Prestwick was an independent forecasting office for the transatlantic air routes.

In 1964 Don progressed to the Principal Forecasting Office at Heathrow, still forecasting for civil aviation. In 1966 he returned to instrument work for a time, running the operational radiation equipment at Easthampstead Park, near Bracknell, and working on the development of an instrument designed to measure the distribution of solar radiation in fifteen different spectral bands. He had made good progress with a task that others had found very troublesome when he was transferred back to forecasting in 1968, on promotion to Principal Scientific Officer, this time as Senior Forecaster in the Central Forecasting Office. Less than two years later he was posted overseas to Bahrain to be Chief Meteorological Officer with the Royal Air Force in the Arabian Gulf. It was in Bahrain that a flair for military staff work and planning began to be evident and he was involved, as a UK delegate, in the negotiations with the Government of Bahrain for the withdrawal of the permanent British military presence from the Arabian Gulf.

Another sharp change of career direction came with a posting on repatriation in 1971 into the field of agrometeorology. This took him to Bristol where he was Principal Meteorological Officer with the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food. During five years at Bristol he thrived on the applied side of this work and gained a high reputation with his agricultural colleagues as their specialist adviser. In 1968 Don returned to work with the Royal Air

Force, this time as Chief Meteorological Officer at the Headquarters of the Royal Air Force in Rheindahlen. In Germany, he showed himself again to be very effective in the administration of meteorological services and he was highly regarded within the Headquarters for his appreciation of the military need and his ability to organize the resources under his control to meet it. Few were surprised when he was promoted as Senior Principal Scientific Officer to the post of Chief Meteorological Officer, Headquarters Strike Command (HQSTC) in 1979 on completion of his tour in Germany. At HQSTC his ability to work within the framework of the Royal Air Force system continued to stand him in good stead and he did particularly well during the Falklands crisis. He represented his Commander-in-Chief on relevant NATO Committees at this time.

For his final appointment Don returned in 1985 to Heathrow and civil aviation. As Chief Meteorological Officer there he has seen through the transfer of Heathrow's major forecasting responsibilities to Bracknell and retired on 31 March 1988 as the last of an illustrious line, extending back to the Second World War, of characterful officers-in-charge at the Heathrow forecasting office.

Don met his wife, Sheila, whilst studying at Imperial College and they have a daughter and a son, both now launched on their independent paths. Don and Sheila plan to retire to Dorset where the very best climate is to be found and we wish them many years of happiness there.

D.H. Johnson

Reviews

Geophysical fluid dynamics, second edition, by J. Pedlosky. 155 mm × 234 mm, pp. xiv + 710, *illus.* New York, Heidelberg, Berlin, London, Paris, Tokyo, Springer-Verlag, 1987. Price DM 89.00.

Since the first edition of this book appeared in 1979 it has become established as one of the foremost texts in its field. In the 1980s (so far!) perhaps only the late Adrian Gill's *Atmosphere–Ocean Dynamics* has had as great an impact on theoretical meteorology and oceanography. This is not to say that Professor Pedlosky's book suits all tastes, even amongst theoreticians, for its detailed treatment of fundamentals (as perceived by the author) co-exists with some surprising omissions. For example, there is no discussion of the hydrostatic primitive equations which, of course, form the basis of most modern weather forecasting and climate simulation models. The meteorologist working with such models finds in the book much useful geostrophic theory to aid his understanding of their behaviour, but gains no insight into the justification for, or the properties of, the hydrostatic primitive equations themselves. This restriction of interest — which, sadly, is sometimes considered to define the scope of geophysical fluid dynamics — becomes increasingly uncomfortable as meteorological theory progresses. Within its own confines, however, the book is a recognized authority which has proved invaluable to both students and research workers. It gives clear, vigorous and detailed accounts of wave motions in rotating fluids, wave kinematics, geostrophic flow models, instability theory, boundary-layer techniques, conceptual models of ocean circulations and many other basic aspects of geophysical fluid dynamics.

What changes does the second edition show? At a superficial level, its red, white and blue livery presents a striking contrast to the rather dull green shades of the original; one can imagine mathematically innocent browsers being attracted to it in university bookshops (with results best not contemplated). As for content, the eight chapter headings are unchanged, but the text is 80 or so pages longer than before and revisions are evident as well as additions. The first two chapters, on the general

dynamics of rotating fluids, are virtually unchanged, as is the chapter on 'Ageostrophic motion'. The chapters on 'Inviscid shallow water theory' and 'Friction and viscous flow' contain new sections on the theory of geostrophic turbulence, whilst the treatment of the effects of bottom topography (in the chapter on 'Homogeneous models of the wind-driven oceanic circulation') has been revised and expanded. The two chapters on quasi-geostrophic models and instability theory contain the most extensive changes. Sections on wave-mean flow interactions and thermocline models have been extended (or multiplied) to take account of recent developments, and a new multi-scale derivation of the quasi-geostrophic formulation is offered. The section on Charney's baroclinic instability problem has been redrafted, and there is a new section dealing with the instability of non-parallel flows. Weakly non-linear baroclinic instability theory is illustrated by a more fruitful example than before.

Of the new or revised sections, those on geostrophic turbulence are particularly helpful, and the new treatment of non-linear baroclinic instability is a great improvement. The section on Charney's problem is also improved, a conceptual framework now being more clearly discernible; it is a pity, however, that J.S.A. Green's elegant approximate treatment of short-wave instabilities is not included. The section on non-parallel flow instability sets out the fundamentals well, but leaves a misleading impression by failing to note the tendency of finite domains to promote the stability of Rossby waves.

The second edition of this book adheres to the structure and philosophy of the first, its new sections all conforming to the standards of clear and detailed exposition set by the author in 1979. Text, equations and diagrams are well presented (although the new sections, perhaps inevitably, bring their own crop of misprints). It will be of interest to all those meteorologists who recognize the value of conceptual models and thought-experiments in developing physical understanding of large-scale motions in the atmosphere.

A.A. White

Weather radar and flood forecasting, edited by V.K. Collinge and C. Kirby. 154 mm × 235 mm, pp. x + 296, *illus.* Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons Ltd, 1987. Price £39.00.

This book is based on the proceedings of a symposium that marked the completion of the North West Radar Project in 1985. More than 20 research workers reviewed the results of the project and other related work on flood forecasting and on the use of radar in meteorological forecasting.

A continuous programme of research and development on weather radar commenced in the 1950s and has now led to the commissioning and operation of a national radar network providing real-time precipitation data. This is an achievement of which the Meteorological Office can be proud, since it is a world leader in this field. Although many of the authors of this volume have contributed papers to learned journals and conference symposia, this is the first book which details what has been achieved and charts how weather radar technology might be further developed in the future.

The contents are divided into four parts, the first two of which consider the technical development and operational experience of weather radar. Hydrologists then consider how runoff can be modelled using radar data, and finally future developments in the technology are assessed. Each paper is well illustrated with clear maps and diagrams, and the book greatly benefits from a series of full coloured plates of specific radar images which are considered in detail in the text.

Although nearly three years old, the volume brings together a lot of material previously scattered through meeting reports and technical memoranda, and should provide hydrologists and other radar users with a useful overview of how the present network has been achieved and how it will develop. The recent announcement that there is now a fair prospect of at least three radar stations in Scotland brings overall coverage of the British Isles significantly closer, and it is interesting to note that it is the winter maintenance of highways rather than flood forecasting which looks likely to derive the greatest benefit north of the Border. One issue that the authors, and meteorologists concerned with radar, have not fully addressed is how this exciting, visually stimulating real-time data can best be marketed and brought to a wide section of the community that could benefit from it.

A. Perry

Satellite remote sensing, by R. Harris. 155 mm × 235 mm, pp. xi + 220, *illus.* Chichester, Ellis Horwood Ltd, 1987. Price £35.00.

This book should carry a government health warning: 'Reading chapter 2 could seriously damage your understanding of electromagnetic radiation.' To be fair, the rest of the book is much better and makes no reference to the radiation fundamentals which are so confusingly described in the second chapter. Some examples from this chapter include a diagram to define wavelength, phase and amplitude, only one of which is correctly defined, a table with inconsistent wavelength and frequency values, a careful definition of micrometer and nanometer followed by a version of the Planck function using ångströms as the wavelength unit, and the statement 'The earth and the sun are black bodies.' Enough of chapter 2, what of the rest of the book? It is intended as an introduction to remote sensing for undergraduates in environmental science. The first half covers basics: radiation, sensors, satellite systems, image processing and, unusually, ground data collection. The second half describes the applications of remote sensing in different areas of environmental science — agriculture, geology, the atmosphere and hydrosphere. The book concludes with a summary of developments planned for the next decade.

The author is particularly good at collating information from a number of sources and presenting it concisely. The sections on sensors, satellite systems and applications are examples of this. The more technical sections on radiation and image processing are weaker, and in the latter the lack of criticism or comparison between techniques leads to a very simplistic view of the problems involved. Each of the sections on applications of remote sensing is quite detailed and draws on a large number of references. There is, however, an imbalance introduced by the lack of criticism as in, for example, citing a paper which derived wind speeds from cloud tracking which differ from rawinsonde winds by about 4 m s^{-1} but were then used to calculate low-level divergence and convergence.

The book is well produced with clear diagrams, readable text and a very extensive reference list (over 200 items). There is a useful two-page list of acronyms, but the index is poor. It contains many geographical entries such as Wales or Bangladesh but few like 'sea temperature', 'snow', 'water quality', 'soil water content', and 'agriculture', all of which are section headings within the book.

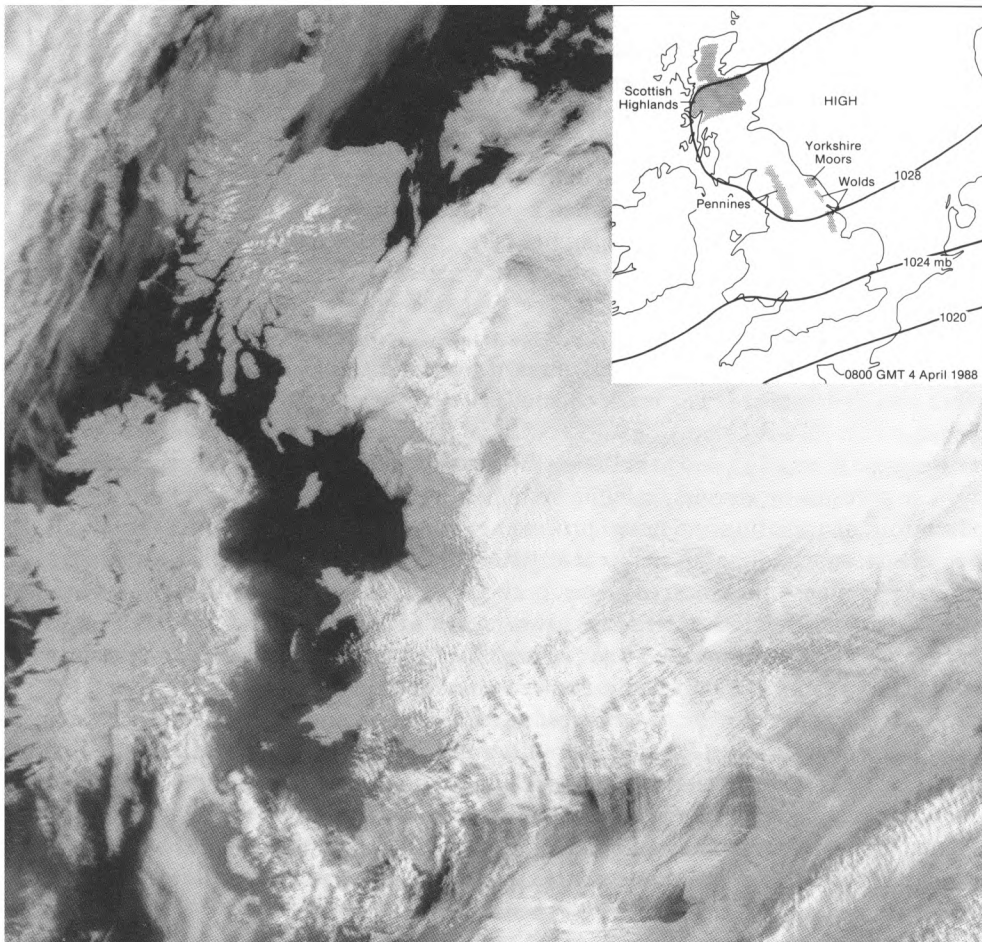
With these criticisms in mind, it would be difficult to recommend this book. It is certainly not suitable as the main text for an undergraduate course, but it does contain useful information and could be interesting to a newcomer to remote sensing if considered as a sort of 'Observer's book of remote sensing' — omitting chapter 2.

C. Duncan

Satellite photograph — 4 April 1988 at 0805 GMT

This visible image from NOAA-10 shows considerable detail within a sheet of low cloud in an east-north-easterly airstream beneath a subsidence inversion at about 500 m above sea level. Over the North Sea most of the cloud has a cellular structure, although near The Netherlands it is composed of a series of narrow, parallel bands. Over the land of eastern and central England, lee waves predominate. They appear to be triggered by relatively low hills such as the Yorkshire and Lincoln Wolds (100–200 m). The cloud dissipated on descent from hills of comparable height to that of the inversion (e.g. Pennines and Yorkshire Moors). The amorphous areas over Northern Ireland and parts of central Scotland are the remnants of overnight radiation fog.

During the day, much of western Britain enjoyed unbroken sunshine with temperatures reaching around 13 °C, whilst in the sunless eastern England, maxima were only 6 °C near coasts and 9 °C well inland where the cloud broke during the afternoon. Highest temperatures of the day were 15 °C in the Scottish Highlands — despite the mountain snow cover seen in the photograph.



Meteorological Magazine

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July 1988

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No. 1392, July 1988, Vol. 117

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The nature of climatic variability

D.E. Parker and C.K. Folland

Meteorological Office, Bracknell

Summary

Climatic variability results not only from the complex dynamics of the atmosphere but also from feedbacks involving the atmosphere, the oceans, the biosphere, and ice and snow. External influences such as solar changes, volcanic eruptions, and man-made pollution may also influence climate. Observed variations range in time-scale from daily weather fluctuations to pronounced interdecadal changes of temperature, rainfall and atmospheric circulation. The longer-term changes may involve changes in variability as well as in average conditions. Except for the very shortest time-scales, local and regional variations of weather and climate cannot be understood without considering the whole globe.

Examples of observed climatic variations are used to amplify the above remarks. The possibility of climatic prediction is discussed. Improved understanding of the earth's complex climatic system is a prerequisite for useful climatic prediction, and the need for much further observational and modelling research is clear.

1. Introduction

The subject of climatic variability is a difficult one to outline. There is no precise boundary between short-term variability consisting of spells, months or seasons of differing character, which can be regarded as a natural part of a fixed climate, and long-term variability, which involves changes in the frequencies and mean values of climatic quantities (e.g. values of temperature, rainfall, patterns of atmospheric pressure) over periods of several decades or longer. The complexity of the subject is increased by the fact that long-term variability can show itself not only as a change in the average value of a climatic variable (e.g. a warming or a drying trend) but also as a modulation of the short-term variability that is inherent in the climate (e.g. a changed likelihood of extremes). This paper illustrates several different types of climatic variability in an attempt to clarify some of these issues.

Climatic variability is predominantly irregular. Apart from the annual and diurnal cycles, there are few proven regular periodicities in the atmosphere, and most of these are in the stratosphere or above. The characteristic irregularity of climatic variability results from the large number of physical processes that contribute to the earth's climatic system which includes the oceans, biosphere and cryosphere (snow and ice) as well as the atmosphere. Climate may also be affected by additional influences such as solar changes, volcanic eruptions and man-made pollution. A consequence of this complexity is that it is at present especially difficult or impossible to predict details of future local or regional climate. Statistical

extrapolation of trends or recurrent tendencies in the climate is scientifically unsound to the extent that it fails to take account of the competing physical processes involved, though occasional limited successes have been achieved. The use of numerical models encapsulating the physical processes occurring world-wide should provide the firmest foundation for progress. Such models are extremely complex and their present state of development, while allowing generalized predictions on a global scale (e.g. of globally averaged surface warming resulting from increased atmospheric carbon dioxide), is still inadequate for confident prediction of future changes in local and regional climate. This limitation is underlined by the inability of the models to reproduce precisely the present climate — including its inherent short-term variability, though some progress is now being made (see section 4).

2. Short-term variability

Weather fluctuations, and short and long spells of differing or unusual character, are illustrated by the sequence of daily 'Central England Temperature' for 1986 in Fig. 1. Central England Temperature (see, for example, Manley 1974, Jones 1987) is computed by averaging daily maximum and minimum temperatures for several stations in an area stretching from the south Midlands to south Lancashire. Fig. 1 includes the climatological averages for 1951–80, so that daily deviations from normal can be seen clearly. For individual stations in England, the daily deviations are similar to those in the Central England Temperature sequence, but are not identical; individual locations tend to show slightly more variability, which is smoothed out by the averaging, and there are variations across country according to weather type.

Marked irregular fluctuations ranging from a few days to over a month's duration are evident in Fig. 1. The existence of a number of coherent atmospheric patterns, whose scale is of the order of several thousand kilometres and which repeat in approximately the same form with lifetimes of the order of

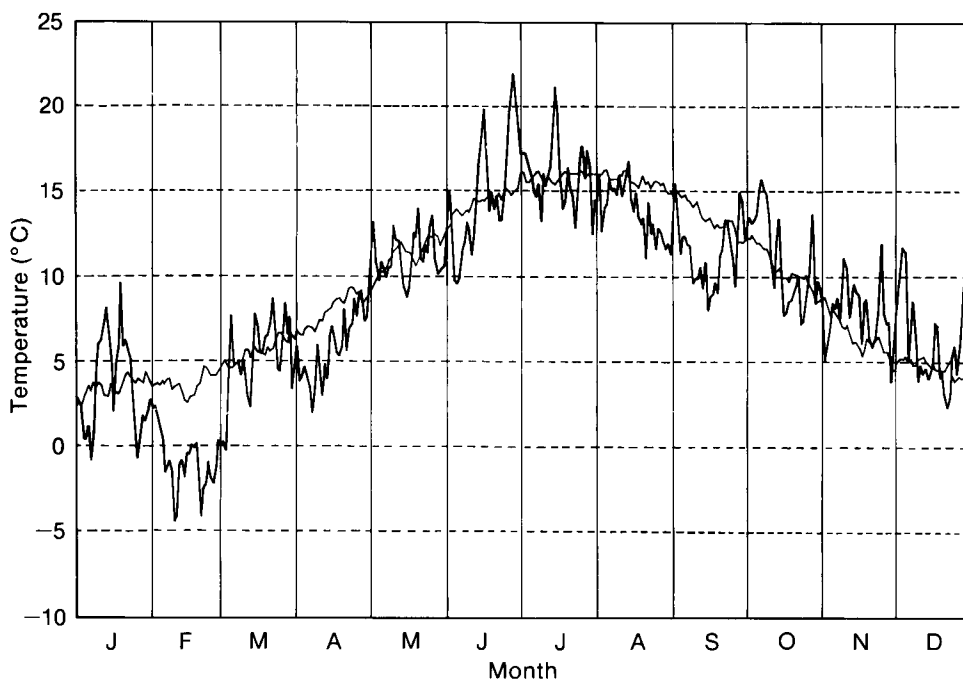


Figure 1. Daily Central England Temperature for 1986, and the 1951–80 normals.

weeks, is increasingly recognized (e.g. Barnston and Livezey 1987). Although the shortest-term fluctuations can be predicted a few days in advance by using atmospheric general circulation models provided with timely data well distributed over the globe, prediction of the variations on time-scales of weeks and months requires a better understanding and representation of the physics of the world's climate system, including ocean-atmosphere interaction. Statistical techniques can also be used with some limited success to make forecasts for the United Kingdom for a month ahead if the methods used take account of conditions world-wide (Folland, Woodcock and Varah 1986).

Fig. 2 (from Folland and Woodcock 1986) contrasts the atmospheric circulation in the two very different summers of 1983 and 1985. The maps show the tracks of the strongest westerlies at 500 mb for 5-day periods. These tracks are closely linked with the tracks of depressions giving wet and windy weather. In 1983 the tracks bypassed Britain to the north, and the country experienced a very warm and dry summer; in 1985 the tracks crossed the country and the summer was cool and wet. Scotland was especially wet because the wettest conditions are generally slightly north of the axis of the strongest upper westerlies. The summer of 1985 had more day-to-day variability than that of 1983, in association with passing troughs and ridges; 1983 was settled and anticyclonic. This, and the previous illustration,

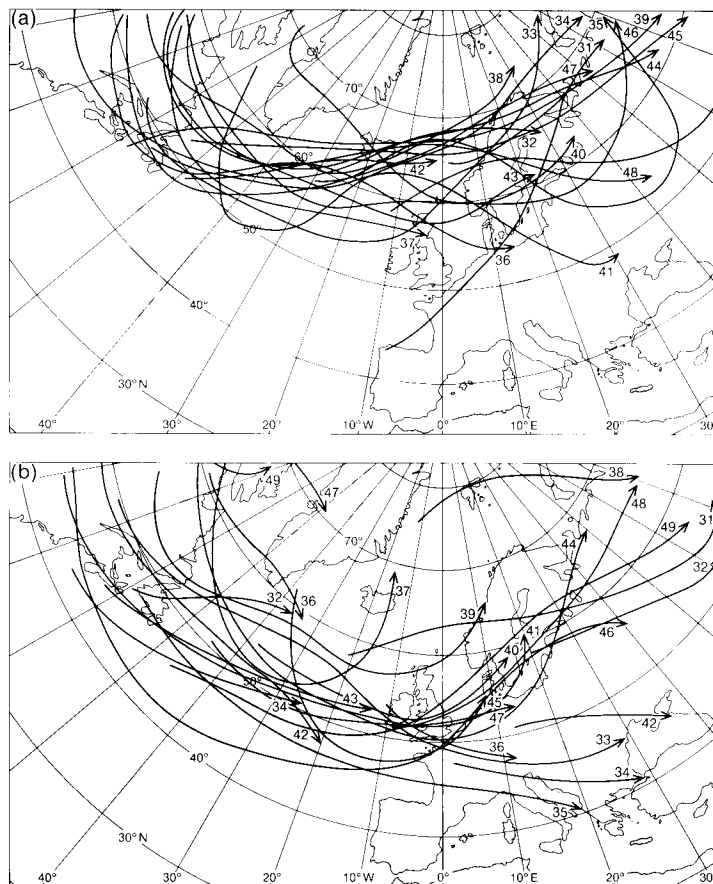


Figure 2. Position of 5-day (pentad) mean maximum wind speed (> 50 kn) at 500 mb during June, July and August for (a) 1983 and (b) 1985. The arrows indicate the direction of the mean flow and the figures give the pentad number (e.g. 41 refers to the 41st 5-day period into the year). (From Folland and Woodcock 1986.)

shows that local or regional short-term climatic variability includes an erratic tendency to longer spells of more or less persistently abnormal atmospheric conditions of similar character. Research needs to be directed at understanding these longer spells, because a persistent tendency for a given type of long spell to repeat at a given season more frequently than before for an extended period would constitute one prominent type of regional climatic change.

3. Long-term variability

If short-term variations need to be studied with a world-wide perspective, then the same is clearly true of longer-term variability because of the greater involvement of the slowly varying parts of the world's climatic system, especially the oceans. The long-term variations manifest themselves as changes in mean values and changes in variability.

3.1 Changes in mean temperature, precipitation and circulation

The reality of long-term temperature variations during the past 150 years on a scale as large as the globe itself has now been established beyond doubt. Figs 3(a) and 3(b) show smoothed changes of northern and southern hemisphere sea surface temperatures and land surface air temperatures (relative to a 1951–80 standard) since the mid-nineteenth century (see also Folland *et al.* 1984, Jones *et al.* 1986, Jones, Raper and Wigley 1986). Details in the nineteenth century are still disputed, but the warming for both land and ocean between about 1910 and the 1940s is well established and really was world-wide in that it occurred to a greater or lesser extent everywhere. A subsequent temporary cooling affected the northern hemisphere from about 1945 to 1970 over land and from about 1955 to 1975 over the ocean.

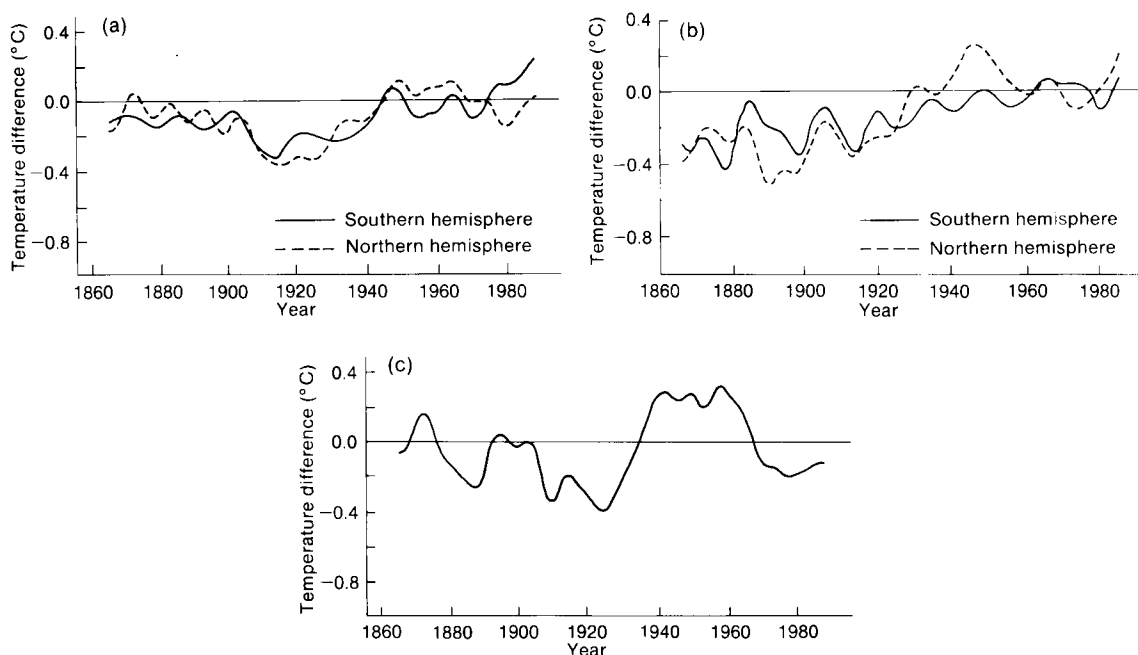


Figure 3. (a) Hemispheric sea surface temperature difference for 1856–1987 relative to 1951–80. (b) Hemispheric land surface air temperature difference for 1856–1984 relative to 1951–80. (From data supplied by P.D. Jones, University of East Anglia.) (c) Sea surface temperature difference for 1856–1987 relative to 1951–80 for the Atlantic Ocean north of 35°N. All were plotted at the end date of a 10-year smoothing filter.

The very recent global warming has been most noticeable in the southern hemisphere and parts of the tropics. Instrumental corrections (which reduce the amplitude of the measured variations) have been applied to sea surface temperatures observed up to the Second World War to compensate for the predominant use of uninsulated buckets to measure sea temperature up to that time. The long-term changes in sea surface temperature averaged over the extratropical North Atlantic have also been marked (Fig. 3(c)). These changes should be sufficient, according to energy-budget considerations, to give rise to significant changes in atmospheric circulation whose character cannot, however, thereby be deduced at present from a knowledge of the sea surface temperature changes alone. Nevertheless, changes in atmospheric circulation on these longer time-scales have indeed been observed. Fig. 4 shows that, in winter, the period 1901–30 had much stronger westerlies over the North Atlantic than did the period 1951–70. As a result, there were few cold winters in the United Kingdom between 1901 and 1930 and, at least in the west, Britain was windier then (Palutikof *et al.* 1987). What is not yet clear is the extent to which the atmospheric circulation changes caused, or were caused by, the oceanic temperature changes. The question needs to be investigated with the aid of numerical models with realistic representation of the physics of ocean–atmosphere interaction.

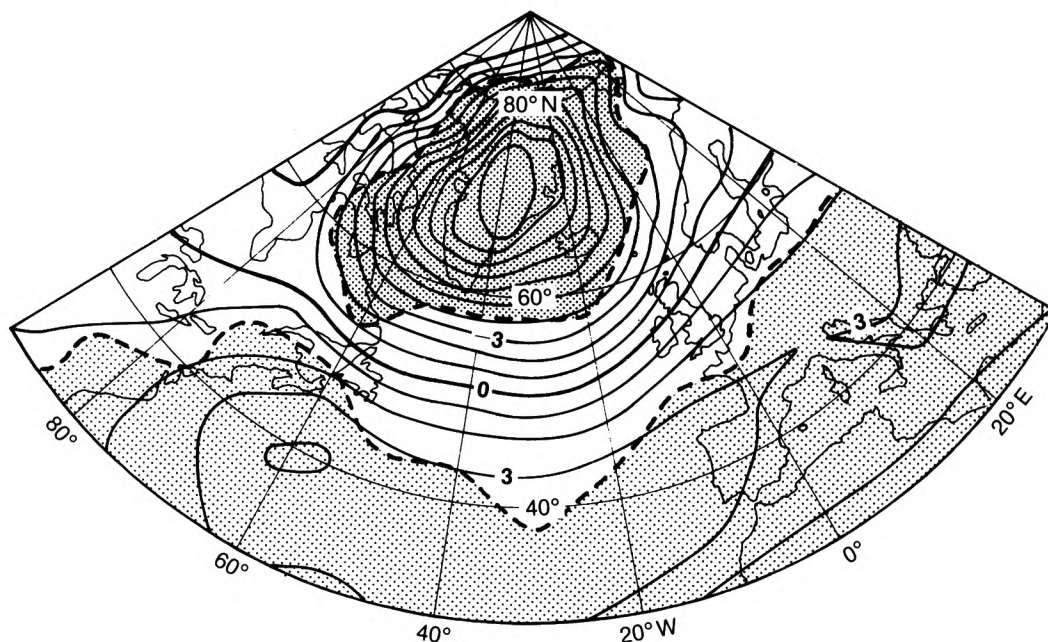


Figure 4. Mean-sea-level pressure difference (mb) for January 1901–30 relative to January 1951–70. Areas of 5% significant difference obtained using a Student's *t*-test (approximate assessment) are shaded: heavy shading, 1901–30 lower; light shading, 1901–30 higher.

A cooling has been observed in north-western Britain since about 1960, especially in northern Scotland (Fig. 5). A reason for this change appears to be the simultaneous decline in sea surface temperatures in the middle-latitude North Atlantic (Fig. 3(c) and Fig. 6) over which the air has often passed to reach the above regions. The linear trend-regression in Fig. 5 is included to illustrate the cooling. The trend correlation of -0.35 is just statistically different from zero at the 95% level of confidence but, in the absence of a full understanding of the physical mechanisms involved, it is not possible to estimate future trends.

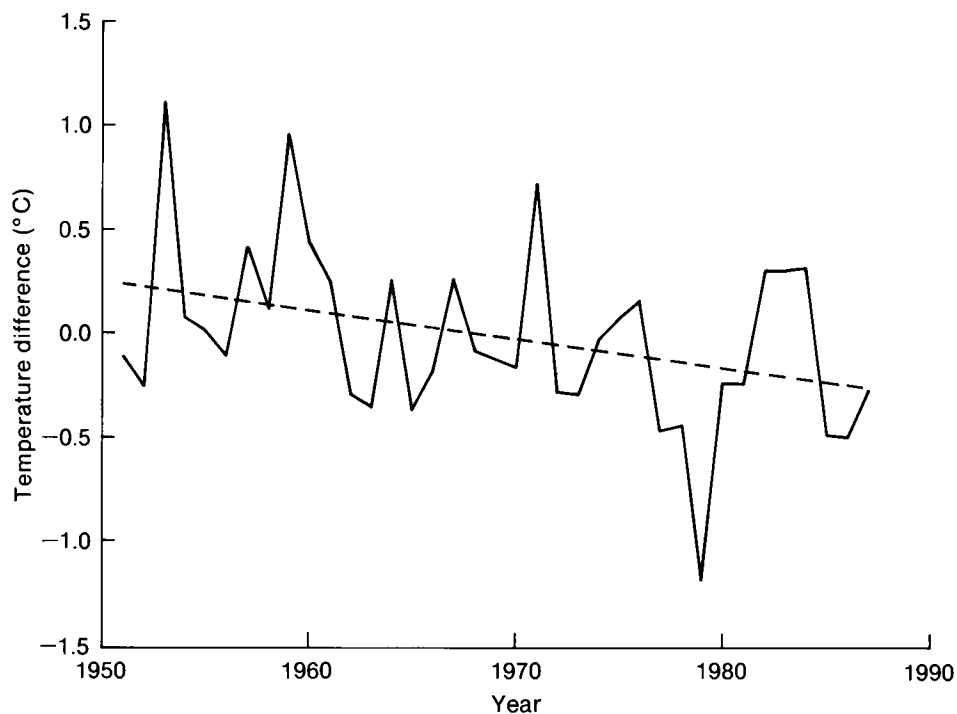


Figure 5. Annual mean temperature difference for northern Scotland, 1951-87 relative to 1951-80. The dashed line is a linear trend-regression.

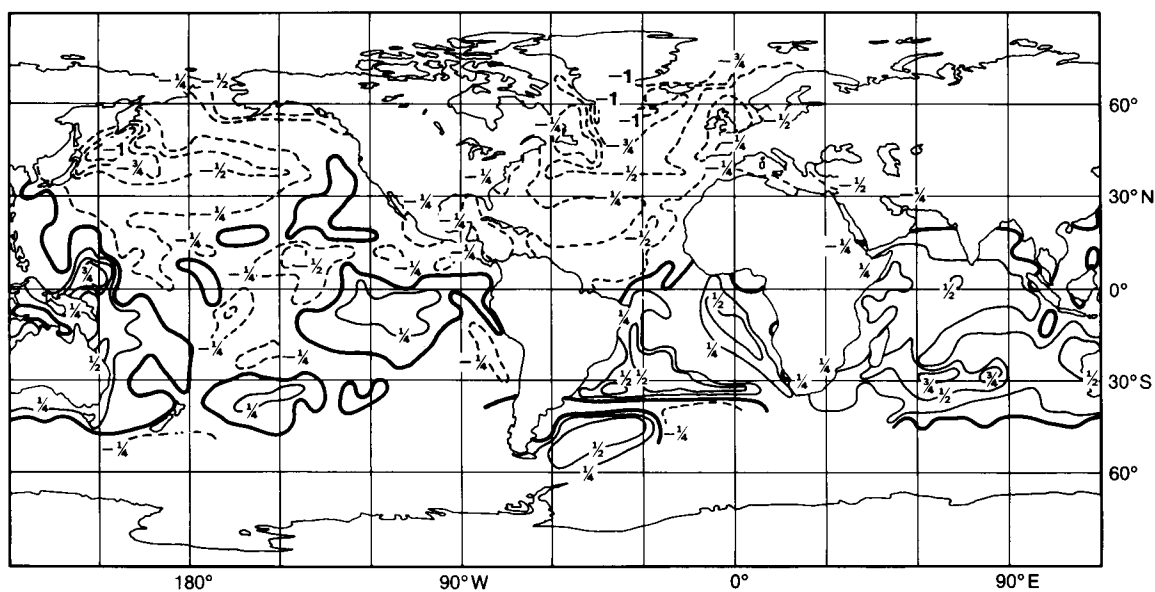


Figure 6. Mean sea surface temperature difference (°C) for 1971-1987 relative to 1951-60.

The warming of the southern hemisphere oceans, relative to those in the northern hemisphere in recent decades (evident in Fig. 3(a) and Fig. 6), appears to be associated with the recent droughts in sub-Saharan Africa (Folland, Palmer and Parker 1986). Effects of this pattern on weather in the United Kingdom are less certain, but the changes have coincided with a recent longer-term tendency to dry summers (Fig. 7). The summers of 1985–87 did not reverse these indications of generally drier summer conditions. The extreme summer drought of 1976 and the very dry summer of 1983 were two of the three driest summers in the record of over 200 years; 1984 was also very dry and gave rise to a brief drought emergency in England and Wales. It must be stressed that there is no indication of any regular variation in the summer rainfall series. The same remark applies to Fig. 8 which shows the great warmth of October in central England in recent decades, in comparison with the whole period from 1659 to about 1940. Before predictions of long-term variations can be attempted, their physical causes need to be investigated using a combination of observational and numerical modelling techniques.

3.2 Changes in variability

The examples of long-term variability presented so far have only been discussed in terms of shifts in the average. However, long-term climatic fluctuations may also involve changes in variability about the average. Fig. 9 illustrates changes in the interannual variability of monthly Central England Temperature for selected months of the year. In the early twentieth century, when winter westerlies predominated (Fig. 4) and cold winters were rarer, the standard deviation (scatter) of January Central England Temperature was low. At the same time the skewness of the January values was near zero, i.e. the January mean temperatures were almost normally distributed about the mean. Recently, the standard deviation has increased and the skewness has become rather negative, indicating more very cold Januaries than very mild ones. December and February show similar changes to a lesser extent. A recent increase in positive skewness in July reflects an increased tendency to occasional very hot months (e.g. 1976, 1983); a similar feature is shown by August but not by June. The recently increased likelihood of warm summers is consistent with the tendency to drier summers shown in Fig. 7.

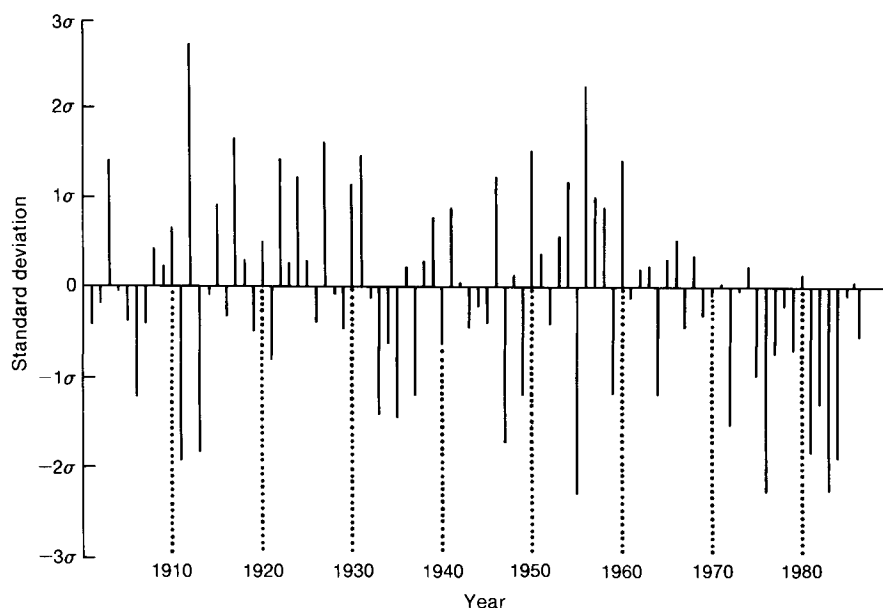


Figure 7. Standardized July and August total rainfall for England and Wales, 1901–87, based on the period 1901–80.

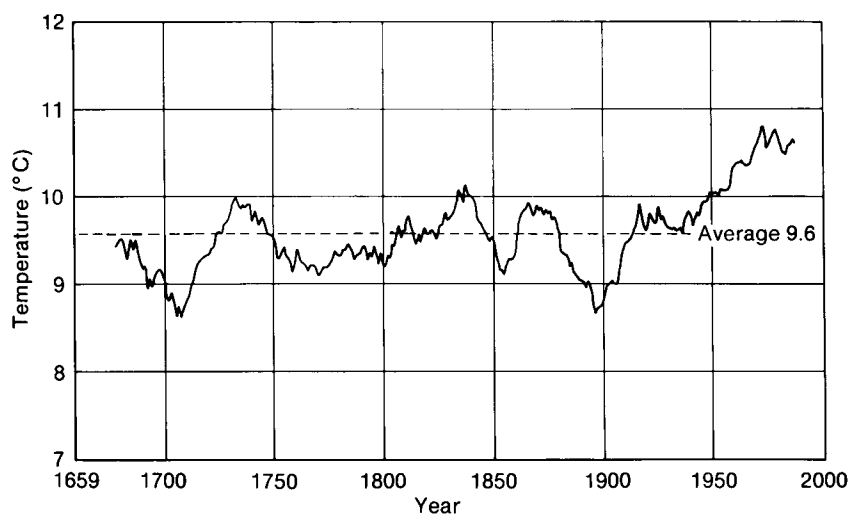


Figure 8. 20-year running mean monthly Central England Temperature for October, 1659–1987.

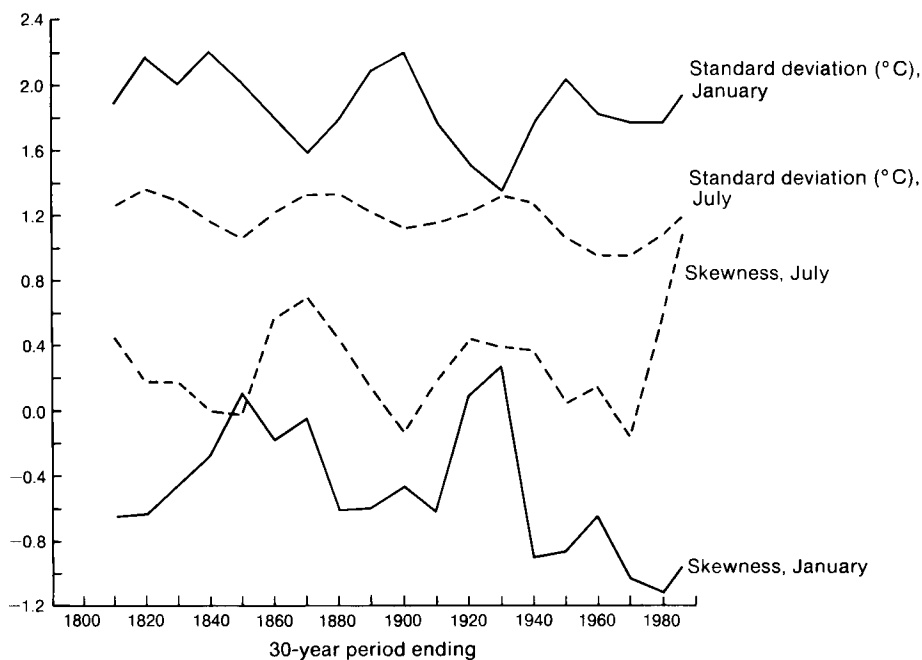


Figure 9. Variability of January and July monthly Central England Temperature from 1781–1810 to 1956–85.

A change in the incidence of perceived 'extremes' need not of course imply a change in short-term variability, because a change in the average of a given sign is likely to increase the frequency of extremes of that sign, and vice versa. Thus the general warming of October in the United Kingdom during this century, and especially since 1940 (Fig. 8), has been associated with an increased number of very mild Octobers and a reduced number of very cold ones.

4. Prediction

For periods of up to a month into the future, statistically based prediction for the United Kingdom has shown limited but definite skill (Folland, Woodcock and Varah 1986). For the tropics, rather longer time-scale predictions of Sahel seasonal (June to October) mean rainfall based on developments of the work of Folland, Palmer and Parker (1986) have been somewhat more successful (Parker *et al.* 1988), though the methods used have not yet had to stand the test of time. Hastenrath *et al.* (1984) have also provided good evidence for potential predictability, months in advance, of rainfall in the wet season in north-eastern Brazil; and evidence of potential skill of the same order has recently been demonstrated for the Indian monsoon by Hastenrath (1987). All these predictions have been strongly guided by an understanding of the physical processes at work, and recently by the use of numerical models to make detailed studies of those processes. Numerical models forced with observed sea surface temperatures have now been used to simulate Sahel monthly and seasonal rainfall in specific past years, with encouraging preliminary results (Owen and Folland 1988).

A different approach to estimating future climate is the use of the 'actuarial' method; that is the use of statistics of the past and present climate to estimate the probabilities of future events, often expressed in terms of 'return period' or the average time interval between events of magnitude on or beyond some threshold. Strictly speaking, however, this is not prediction, and it does not require in-depth physical understanding of the climate system.

The remaining approach to the estimation of future longer-term climatic conditions is via numerical modelling of the physical processes underlying climatic change and variability. Estimation of long-term climatic variations by this means therefore demands the simulation of the oceans and cryosphere as well as the atmosphere. Also, assessments are required of uncertain future man-made inputs such as increasing atmospheric carbon dioxide and other greenhouse gases. Other possible future influences, such as changes in solar radiation, the occurrence of major volcanic eruptions or changes of the frequency and intensity of El Niño type warmings, which eventually influence much of the world (Pan and Oort 1983), are further sources of uncertainty. At present the use of numerical modelling in longer-term climate studies is mainly limited to determining the equilibrium response of the atmosphere to an a priori specification of a physical change in the climate system, e.g. a doubling of atmospheric carbon dioxide or a change of the solar constant by a few per cent. Results are very sensitive to the design features of the models themselves; the globally averaged warming for a doubling of carbon dioxide deduced for various models ranges between 2 and 5 °C. The models differ to an even greater extent in some of their indications of the regional and local climatic responses to a carbon dioxide increase, partly because they do not agree in their simulation of the present regional climate or on how regional atmospheric circulation patterns will change. However, there are some qualitative agreements such as the enhancement of warming near the poles in winter, earlier spring snowmelt, and increased annual mean run-off in high latitudes. Much further research and development is required, therefore, before the models realize anything like their full potential (Wilson and Mitchell 1987).

5. Conclusion

The increasing evidence of man's influence on the global climate indicates a clear need to intensify research into climatic variability, using a combination of observational and numerical modelling studies. Local or regional climatic variability cannot be understood in isolation; a global context is essential, and it is essential to take the oceans into account when studying atmospheric changes on time-scales longer than a few weeks. Understanding the world's climatic system, with its many complex interactions and feedbacks, is the *sine qua non* of climatic prediction, and is one of the most complex tasks in current scientific endeavour.

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Cloud-top temperature/height: A high-resolution imagery product from AVHRR data

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Summary

A scheme for deriving accurate cloud-top temperatures and cloud-top heights from NOAA Advanced Very High Resolution Radiometer (AVHRR) data is described. To illustrate the products derived using this scheme three case-studies were chosen, one with deep convective cloud along the east coast of England on 14 April 1985, one with a marked cold front across the British Isles on 3 September 1986 and one with patchy fog over southern England on 23 October 1983.

1. Introduction

One of the principal meteorological variables of interest to aviation forecasters is the height and/or temperature of the cloud/fog tops within their area of responsibility. This quantity is not easy to determine accurately from surface observations and can only be inferred at a few points, twice a day, from radiosonde temperature and humidity profiles.

Satellite images, however, offer the possibility of obtaining reasonably accurate estimates of cloud-top height over a large area. Meteosat imagery is currently used operationally for determining cloud-top heights by computing a cloud-top height image product which is then disseminated to users three times a day using the WEFAX transmissions (Bowen 1982). This has proved to be a useful product for civil airline pilots who use it to help them plan their routes. The advantage that Meteosat has, is that the data are available every half hour and so the development of a rapidly changing cloud system can be monitored. The disadvantage of the Meteosat product is the relatively low horizontal resolution of individual radiance measurements over north-western Europe ($\approx 9 \text{ km} \times 6 \text{ km}$). In contrast, data from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar-orbiting satellites can give a cloud-top height product with a horizontal resolution as high as 1.1 km, four times a day (assuming a two-satellite system which is normally the case). One way of making use of the advantages of both sampling systems would be to 'calibrate' the Meteosat cloud-top heights using the AVHRR product.

A cloud-top temperature/height product has a number of applications. For aviation forecasts the current location and accurate cloud-top height of significant convective and frontal cloud systems over the area of interest would be valuable information to take into account while preparing the local area and route forecasts. The temperature of fog tops is also a useful parameter for estimating how quickly fog might clear at an airfield or along a stretch of motorway.

This paper describes a scheme for deriving accurate cloud-top temperatures and heights from AVHRR data and some examples of cloud-top products produced by such a scheme are presented. Where possible the product is validated with coincident radiosonde profiles. Work is now in progress at the Meteorological Office to make possible the dissemination of such products to forecast offices in the United Kingdom within an hour of receipt of the data.

2. Determination of cloud-top temperature and height from AVHRR data

This section explains the various steps required to retrieve a cloud-top temperature and height product from the raw AVHRR data received from the spacecraft. Fig. 1 shows the principal operations in the processing scheme which are described in more detail below.

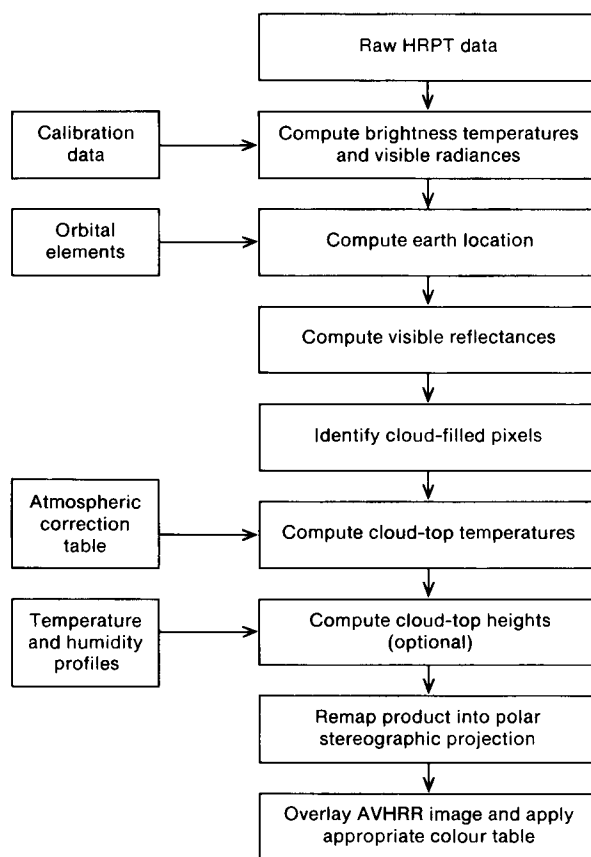


Figure 1. Flow diagram showing how the raw HRPT data received from the spacecraft are processed to give a cloud-top temperature or height image.

2.1 Preprocessing of AVHRR data

Data from the NOAA satellites are collected by the ground station at Lasham, in Hampshire, which provides the Meteorological Office with most of the satellite data which are used operationally. The digital AVHRR data are received from the NOAA spacecraft as part of the High Resolution Picture Transmission (HRPT) data stream. The basic processing scheme for determining cloud-top height from the raw HRPT data is shown in Fig. 1 and is part of a more general AVHRR processing software package called APOLLO (AVHRR processing over land cloud and ocean) developed for research purposes in the Meteorological Office (Saunders and Pescod 1988).

The initial processing of the AVHRR data follows the same steps as those outlined in Pescod *et al.* (1986) to derive a sea surface temperature product and so the interested reader is referred to section 2 of that paper for more details. However, one major difference is in the use made of the results from the cloud analysis. This cloud analysis step actually classifies a pixel as cloud-free, partly cloudy or cloud-filled in one operation. The details of this analysis have been described by Saunders and Kriebel (1988) who give some examples of cloud-free and cloud-filled pixels that were identified by the analysis for the scheme described here. Instead of using the pixels identified as cloud-free (for determining surface parameters), only cloud-filled pixels are used here for determining cloud-top temperature.

2.2 Determination of cloud-top temperature

The next step is to compute a representative cloud-top temperature from the pixels identified as cloud-filled. To explain the basis of this method the various contributions to the measured satellite radiance, shown in Fig. 2, are considered. The radiance, I_{11} , measured by a satellite radiometer above the atmosphere at a wavelength of $11\ \mu\text{m}$ (corresponding to channel 4 of the AVHRR) where aerosol and cloud scattering effects and reflection of solar and downwelling atmospheric radiation by the cloud top are neglected, is given by

$$I_{11}(\theta, \phi, \Psi) = \epsilon_c(\theta, \phi) B(T_c) \tau_{h_c}^H(\Psi, \theta) + \int_{h_c}^H B(T(h)) \frac{\partial \tau_h^H(\Psi, \theta)}{\partial h} dh + \\ + (1 - \epsilon_c(\theta, \phi)) I_s(\Psi, \theta, \phi) \tau_{h_c}^H(\Psi, \theta) \quad \dots \quad (1)$$

where ϵ_c is the emissivity of the cloud, T_c is the cloud-top temperature, $\tau_{h_1}^{h_2}$ is the atmospheric transmission from height h_1 to h_2 (H is the top of the atmosphere and h_c is the height of the top of the cloud), $B(T)$ is the Planck function for a temperature, T , at a wavelength of $11\ \mu\text{m}$ and I_s is the upwelling radiance entering the cloud base; θ and ϕ represent satellite zenith and azimuth angles from the cloud top and Ψ the atmospheric state (e.g. water vapour amount, pressure, temperature, etc.).

The first term normally represents the radiation emitted by the cloud top, as shown in Fig. 2, and will generally be the dominant contribution to the measured radiance at a wavelength of $11\ \mu\text{m}$ where the atmospheric absorption is small. The second term represents the upwelling radiation emitted by the atmosphere between the cloud top and the top of the atmosphere. This term will be small except over low

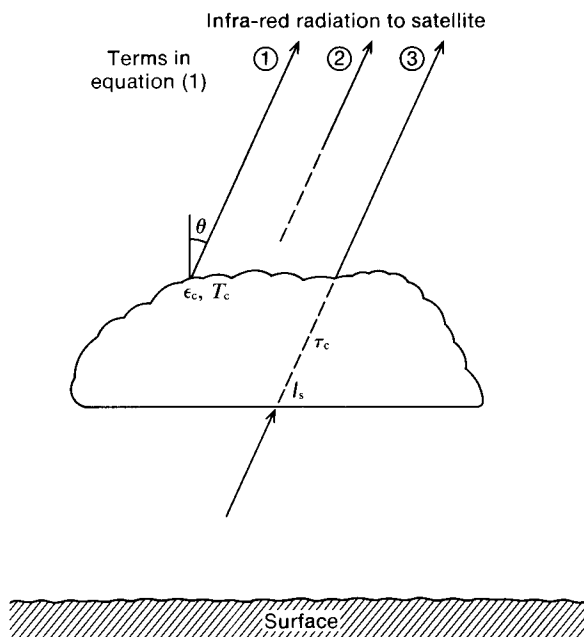


Figure 2. Schematic diagram showing the three different components of infra-red radiation over a cloud top which are detected by a satellite sensor. See text for explanation of symbols.

cloud in warm, moist, tropical atmospheres. The third term represents the upwelling surface radiation after attenuation by the cloud and atmosphere. For thick stratus or cumuliform cloud nearly all the surface radiation is absorbed by the cloud and this term becomes negligible. However, for thin cirrus cloud, typically 50% of the upwelling radiation from below will be transmitted and contribute to the overall measured radiance I_{11} . This effect complicates the measurement of cloud-top temperature from a single infra-red radiance measurement in one channel.

For this study, to simplify matters, a test was devised to identify thin cirrus cloud by the temperature difference obtained between channels 4 and 5 when semi-transparent cloud is in the field of view. The basis for this test is described in Saunders and Kriebel (1988). Cloud-top temperatures were not computed from pixels which were identified as containing semi-transparent cloud; hence term 3 of equation (1) can be neglected for this study. The assumption that the radiation measured by the satellite emanates from the cloud top (i.e. $\epsilon_c = 1$) was checked by Kriebel *et al.* (1983) by making coincident satellite and airborne lidar measurements of cloud-top heights. For optically thick high cloud they reported a mean difference of 0.4 km (equivalent to ≈ 3 K). Over fog some comparisons of aircraft, radiosonde and satellite measurements made by Findlater *et al.* (1988) indicated a mean difference of about 1 K in fog-top temperature between the different measurements. For clouds which are optically thick (i.e. $\epsilon_c = 1$) equation (1) simplifies to

$$I_{11} = \tau_{hc}^H(\Psi, \theta) B(T_c) + \int_{h_c}^H B(T(h)) \frac{\partial \tau_h^H(\Psi, \theta)}{\partial h} dh. \quad \dots \dots \dots (2)$$

To determine T_c from I_{11} we only need to know the transmission and emission of the atmosphere between the cloud top and the satellite sensor. The atmospheric emission is generally small for channel 4 of AVHRR centred at a wavelength of $10.7 \mu\text{m}$. The atmospheric transmission/emission between 10 and $11.8 \mu\text{m}$ for a range of atmospheric conditions was computed using a line by line atmospheric transmission model (Edwards 1987). Two representative sets of radiosonde profiles of temperature and humidity over the British Isles for January and July were used to compute the atmospheric transmittances and emitted radiances. Given T_c , values for I_{11} were computed from the model using equation (2). These simulated radiance values for I_{11} showed that, as the atmospheric correction term is small at mid-latitudes and normally reduces the measured cloud-top temperature T_c , it can be expressed as a correction factor, ΔT , which allows the cloud-top temperature to be computed simply from the measured $11 \mu\text{m}$ brightness temperature T_{11} (i.e. equivalent black-body temperature integrated over the channel response) by using the expression

$$T_c = T_{11} + \Delta T(T_{11}, \theta).$$

This enables T_c to be computed quickly from T_{11} for each pixel, reducing the overall computation time. A table of ΔT values for a range of values for T_{11} and satellite zenith angles θ is listed in Table I. They were computed by averaging the computed ΔT values for January and July. The differences between the values for the two months were small (e.g. ≈ 0.3 K for T_{11} of 270 K and $\sec \theta$ of 2). ΔT increases for higher values of T_{11} because T_{11} is correlated with the total column water amount. Also ΔT increases with increasing values of θ due to the longer atmospheric path lengths between the cloud top and satellite sensor. For cloud tops with temperatures below 230 K the atmospheric absorption/emission contribution becomes negligible.

For optically thick cloud, one main uncertainty in this approach will be how representative the precomputed ΔT values are of the actual atmospheric state at the time of the satellite measurement. This uncertainty could be as much as 0.5 K for a low cloud top overlaid with a warm, moist atmosphere, but is negligible for high cloud tops. It could be reduced by using a ΔT value calculated from either a

Table I. *Atmospheric correction factors, ΔT , in degrees K to be added to the measured AVHRR channel 4 brightness temperatures, T_{11} , to retrieve cloud-top temperature, where θ is the satellite zenith angle from the cloud top. These factors are for an annual mean atmosphere (i.e. average of January and July factors) appropriate to conditions over the British Isles.*

T_{11} (K)	Sec θ values				
	1.0	1.25	1.50	1.75	2.0
220	0.0	0.0	0.0	0.0	0.0
225	0.1	0.1	0.1	0.1	0.1
230	0.1	0.1	0.2	0.2	0.2
235	0.2	0.2	0.2	0.3	0.3
240	0.2	0.3	0.3	0.4	0.4
245	0.3	0.3	0.4	0.5	0.5
250	0.3	0.4	0.5	0.6	0.6
255	0.4	0.5	0.6	0.7	0.7
260	0.5	0.6	0.7	0.8	0.9
265	0.6	0.7	0.9	1.0	1.1
270	0.8	0.9	1.1	1.2	1.3
275	0.9	1.0	1.2	1.3	1.5
280	1.2	1.4	1.6	1.7	1.9
285	1.5	1.7	2.0	2.1	2.3
290	1.9	2.2	2.5	2.6	2.8

coincident sounder profile (i.e. from the TIROS Operational Vertical Sounder (TOVS)) or a model forecast profile — the latter being easier to use.

In the future this method could be extended to allow for semi-transparent cloud. There have been a number of methods developed to determine the cloud-top temperature of semi-transparent cloud from Meteosat data by using a combination of the window channel (10.5–12.5 μm) and the water vapour channel (5.7–7.1 μm) radiances (e.g. Szejwach 1982). However, AVHRR has no water vapour channel, so these methods for determining an accurate cloud-top temperature for semi-transparent cloud cannot be used. Inoue (1985) has developed a method using channels 4 and 5 of the AVHRR (corresponding to wavelengths of 10.3–11.3 μm and 11.5–12.5 μm respectively) to determine temperature and effective emissivities of semi-transparent cloud. However, it relies on part of the cirrus cloud being optically thick, which is often not the case.

The advantage of AVHRR data as compared with Meteosat data is that the smaller field of view of the former at the cloud top ensures that many cloud-filled pixels can be identified in the image. This, together with the more reliable (≈ 0.2 K) calibration of the AVHRR radiometer, allows a more accurate radiative cloud-top temperature at a higher spatial resolution to be obtained.

The cloud-top temperature is derived from cloud-filled pixels as described above and displayed in the format illustrated by the example in Fig. 3(a). In some situations, for instance over low stratus cloud or fog, the forecaster would be more interested in the cloud-top temperature than cloud-top height.

2.3 Determination of cloud-top height

The cloud-top temperature can now be converted to a height using a representative temperature and humidity profile. The simplest solution would be to use a climatological mean profile for the month of interest over north-western Europe. However, as Kriebel *et al.* (1983) point out, this can lead to errors of 1.8 km in the derived cloud-top height as the climatological profile is often not representative of the

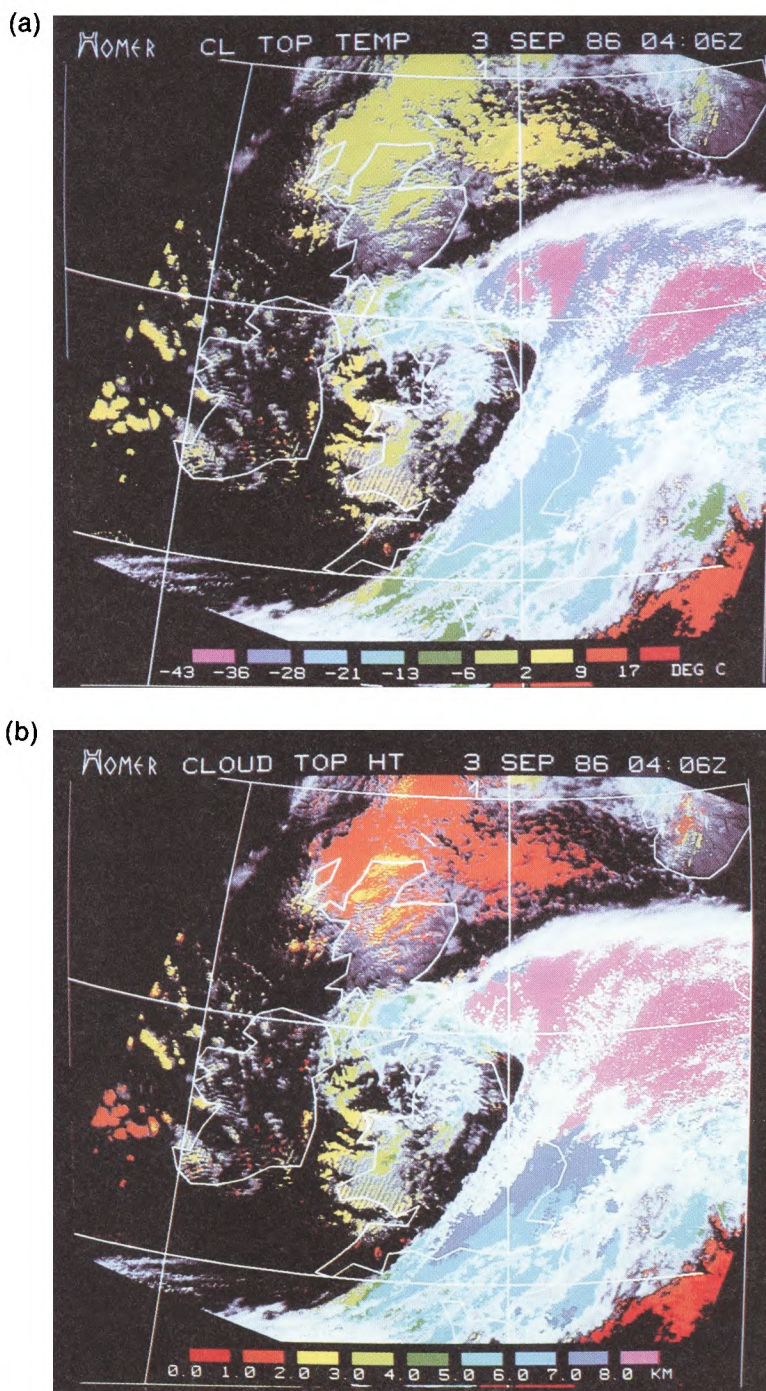


Figure 3. (a) Cloud-top temperature (°C) and (b) height (km) image over the British Isles for 3 September 1986 at 0406 GMT. The linear features over the cloud in south-west Wales are artefacts caused by the noise in the 3.7 μm channel used to identify cloud-filled pixels.

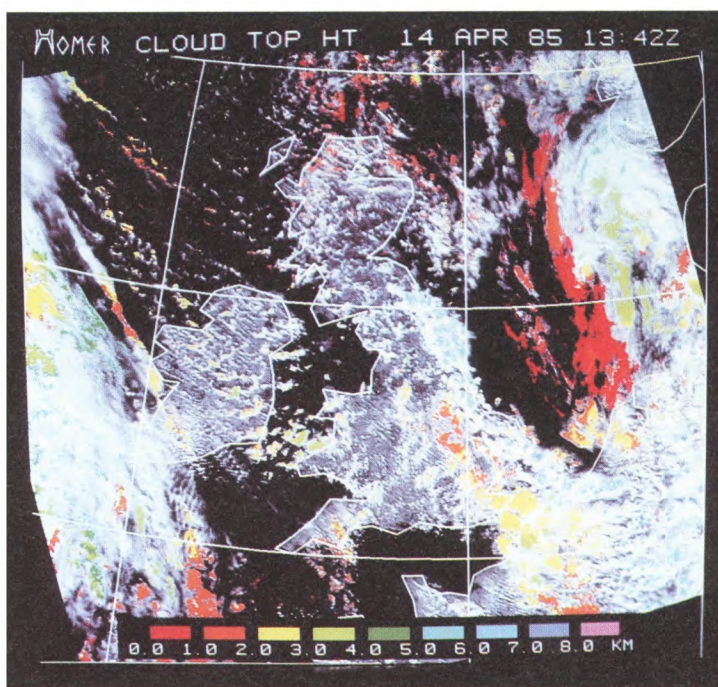


Figure 4. Cloud-top height (km) image for 14 April 1985 at 1342 GMT.

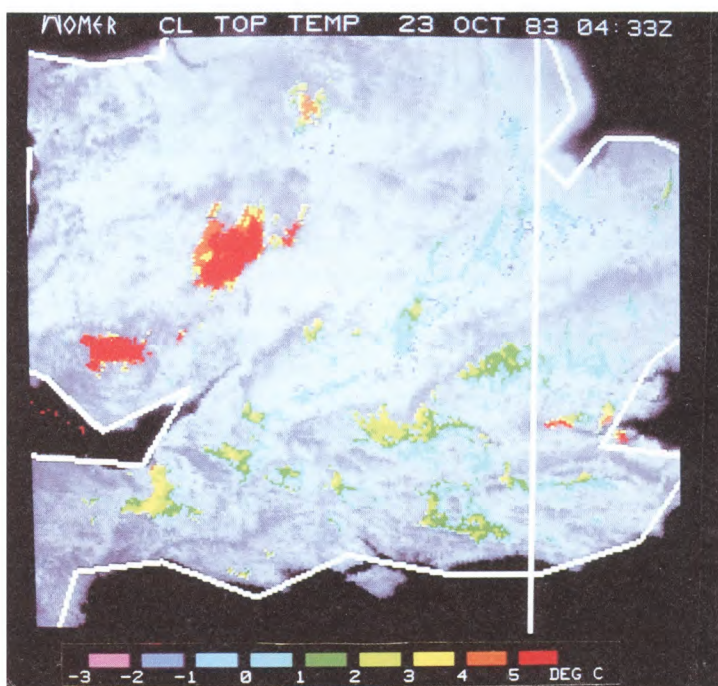


Figure 5. Cloud-top temperature (°C) image for 23 October 1983 at 0433 GMT.

actual atmospheric conditions. For this study, radiosonde profiles closest in time to the satellite overpass were used to relate cloud-top temperature to height and four stations were taken to cover the local area — Lerwick, Hemsby, Camborne and Valentia. The profile from the station nearest to the pixel was taken to be the most representative which was then used to convert cloud-top temperature at a pressure, P , to a height, Z_c , by using the hydrostatic equation given by

$$Z_c = -\frac{R}{gM_a} \int_{P_0}^P \frac{T_v(P)}{P} dP$$

where R is the gas constant per mole, g the acceleration due to gravity, M_a the molecular weight of dry air, P_0 the pressure at the surface and T_v the virtual temperature which allows for the water vapour in the column.

In an operational scheme it would be preferable to take the temperature and humidity profiles from a regional forecast model (e.g. a 6-hour forecast from the Meteorological Office fine-mesh model) as the profiles should be more representative of the real atmosphere in areas some distance from the actual radiosonde ascents. The Meteosat cloud-top height product is currently derived using profiles obtained from the ECMWF forecast model.

The cloud-top height is displayed in the form of a conventional AVHRR visible (daytime) or infra-red (night-time) image which is remapped into a polar stereographic projection. The cloud-filled pixels are then overlaid and coloured according to their cloud-top height or temperature. In this way the cloud coverage as well as the cloud-top heights or temperatures can be observed. The white areas are cloud tops which have been identified as not cloud-filled or optically thick, and so no temperature or height is assigned to them.

3. Examples of cloud-top temperature and height products

To illustrate the application of the scheme described above to AVHRR data, three cases were chosen, one with frontal cloud, one with convective cloud and one with patchy fog over southern England.

3.1 Frontal cloud

The first case-study was for a night-time overpass of NOAA-9 at 0406 GMT on 3 September 1986 where a marked cold front lay across southern England. This case is discussed in some detail by Browning *et al.* (1987) using radar and Meteosat imagery. A surface analysis at 0400 GMT shows the cold front lying across south-east England at this time. The location of the front was also well correlated with the rainfall distribution measured by the radar network. The centre of the associated depression was analysed as being over the North Sea to the east of Flamborough Head, Humberside.

The AVHRR image shown in Fig. 3(a) clearly shows the temperature of the cloud tops associated with this frontal system and Fig. 3(b) shows the corresponding cloud-top heights. The temperatures were as low as -40°C at the triple point (56°N , 1°E) corresponding to a cloud-top height above 8 km. Along the line of the cold front the top temperatures are warmer, being in the range -27 to -18°C (7–8 km) across south-east England. These values are similar to those derived by Meteosat at 0300 GMT (compare with Fig. 3(a) of Browning *et al.* 1987). It was difficult to estimate a cloud-top temperature from the Hemsby midnight ascent as, being in the warm sector, it was saturated most of the way to the tropopause. The Camborne ascent at midnight (see Fig. 5 of Browning *et al.* 1987) clearly shows that the cloud top was around 600 mb, giving a cloud-top temperature of -10°C in reasonable agreement with the satellite cloud-top temperatures off the Devon coast; these cloud tops would have been over

Camborne at that time. Over northern Scotland the cloud-top temperatures of the stratocumulus cloud are in the range -6 to $+2$ °C (corresponding to a height range of 1–2 km) measured by the satellite. The midnight Lerwick ascent shows an inversion at about -2 °C so any cloud tops would be expected to be at or below this inversion layer. Note that parts of the frontal cloud in Fig. 3, which are white, are not assigned a cloud-top temperature/height due to the existence of thin cirrus cloud overlaying the thick frontal cloud.

3.2 Convective cloud

The second case-study was for a NOAA-9 pass over the British Isles on 14 April 1985 at 1342 GMT. There was a warm front approaching south-western Ireland at this time with the British Isles in a north-westerly airstream, as can be inferred from the orientation of the cumulus cloud over Ireland, England and Wales in Fig. 4. A line of convective cloud aligned along the east coast of Britain had formed by 1200 GMT, as is evident in both the Meteosat and radar displays for this time (see Fig. 19 of Browning *et al.* 1987). The surface reports at 1200 GMT indicated that rain and hail showers had occurred. By 1500 GMT (after the NOAA-9 overpass) this line of convective cloud had increased in cloud-top height, as shown by the Meteosat imagery, and the intensity of precipitation beneath the cloud had increased, as revealed by the radar. By 1800 GMT thunderstorms had been reported all along the east coast. Fig. 4 shows the cloud-top height product for 1342 GMT derived from AVHRR data. The line of convective cloud along the east coast of England shows up clearly with measured cloud-top temperatures down to at least -40 °C. The heights corresponding to these cloud tops go up to 7 km. The Meteosat images (see Fig. 19(b) in Browning *et al.* 1987) also show the cloud-top temperatures to be below -30 °C, but the large pixel size in this case has failed to identify clearly the individual convective turrets evident in Fig. 4. This convective cloud extended well into Belgium and northern France where it was more widespread and with slightly colder cloud tops (some down to -46 °C).

The Hemsby midday ascent shows the air to be potentially unstable with 'parcel tops' expected to be about -46 °C (i.e. about 7 km) and 'absolute tops' a degree or two cooler. This compares with the satellite-derived cloud-top temperatures in the region of Hemsby being colder than -38 °C in places but no cloud tops colder than -46 °C. The clouds were still developing at this time and so would probably be expected to have tops lower than the predicted parcel tops.

Regarding the cumulus clouds across the British Isles, only the largest are assigned a cloud-top temperature or height as they are generally too small to fill a pixel completely. The larger clouds have cloud-top temperatures of around -5 °C which correspond to heights of 2–3 km. The midday ascent from Long Kesh (Northern Ireland) shows a marked inversion layer at 790 mb giving cloud-top temperatures around -8 °C. The thicker parts of the cirrus cloud associated with the approaching warm front to the south-west of Ireland have a cloud-top height in the range 6–7 km.

3.3 Patchy fog

The third case-study was for a situation where there was patchy fog over southern England; it has also been studied in some detail by Turner *et al.* (1986). The AVHRR cloud-top temperature product is shown in Fig. 5 at the time of the NOAA-7 overpass on 23 October 1983 at 0433 GMT. A surface analysis at 0500 GMT shows a ridge of high pressure extending westwards across southern England resulting in clear skies. A layer of stratocumulus, associated with a weak cold front across north-west Scotland, covered northern England and most of Ireland. By 0500 GMT many stations over central southern England were reporting shallow fog (i.e. sky still visible) with visibilities down to 30 m reported (see Fig. 1 of Turner *et al.* 1986).

The satellite product shown in Fig. 5 reveals the fog to be patchy in nature over southern England, consistent with the fact that not all the stations were reporting fog. In general the fog appeared to form in

areas associated with the Chilterns and the North Downs, or in flat areas such as the Somerset Levels and the Fens. Most of the fog patches had a fog-top temperature of about 2 °C which was the same as the reported screen temperatures in this region. Over the Fens, fog-top temperatures dropped to about -1 °C which was confirmed by one report of freezing fog just to the north of the Fens at Coningsby. The warmer tops (> 5 °C) over southern Wales and the Severn Valley were assumed to be cloud. This was confirmed over South Wales by an observation of stratocumulus cloud.

4. Discussion and conclusions

The feasibility of deriving a cloud-top temperature or height product from AVHRR data for forecasting purposes is demonstrated for three different meteorological situations. Uncertainties in the atmospheric absorption correction term lead to uncertainties in the computed cloud-top temperature of up to 0.5 K for low cloud/fog but are negligible for high cloud. Uncertainties due to assuming a cloud-top emissivity of 1 are probably greater, but coincident satellite and aircraft measurements suggest errors of only 1 K for low cloud and up to 3 K for high cloud. This level of accuracy is probably sufficient for forecasting purposes. Where possible the AVHRR cloud-top temperature products have been compared with conventional radiosonde or surface observations. For the three cases presented here the AVHRR products were reasonably consistent with the radiosonde measurements. Differences of several degrees could be explained by the differences in both space and time between the satellite measurement and the radiosonde profile. It will be difficult to validate the satellite products to better than a few degrees until coincident satellite and aircraft measurements are made or ascents are available at the same time as the satellite overpass. Reasonable agreement was also obtained between AVHRR cloud-top temperatures and the corresponding values derived from Meteosat-2 reported by Browning *et al.* (1987).

This paper shows a few examples of a cloud-top temperature/height product. The problems of deriving cloud-top temperature from semi-transparent cloud or partially cloud-filled pixels have not been discussed in detail, though several methods to infer cloud-top temperature from these pixels have been developed (e.g. Inoue 1985). The high-resolution infra-red radiation sounder (HIRS), with many more infra-red channels, is also useful for estimating the cloud-top pressure of semi-transparent cloud (Eyre and Menzel 1988). The inclusion of these techniques would increase the coverage of the cloud-top measurements to many more partially cloudy pixels. Another improvement would be to choose the atmospheric correction value listed in Table I by using coincident sounding channels (e.g. from TOVS) or model profiles to determine the total column water amount. This would help to ensure that the atmospheric correction term was more representative of the actual conditions present during the satellite overpass. Eyre *et al.* (1984) also suggest that the magnitude of the brightness temperature difference between AVHRR channels 3 and 4 may be an indicator of fog thickness which is another parameter which could be included along with the cloud-top temperature.

In the future (mid 1990s) the second-generation Meteosat series will become operational. They will have many of the advantages of the current AVHRR instrument and the capability of making at least half-hourly measurements over the British Isles allowing the time evolution of the cloud or fog top to be monitored. A scheme similar to the one described above could be employed to derive cloud-top parameters from second-generation Meteosat data.

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The autumn of 1987 in the United Kingdom

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Summary

The autumn was generally cool and wet in the south, although somewhat drier in Scotland. The main features of note were the violent storm on 16 October followed by the flooding in Wales and Northern Ireland on the 17th and 20th respectively.

1. The autumn as a whole

Rainfall amounts were above normal in all districts of England and Wales, partly as a result of East Anglia, southern and eastern England and South Wales all having had more than twice the normal rainfall for October, whereas in Scotland rainfall amounts were slightly below normal and in Northern Ireland about normal. Sunshine amounts were near average over Scotland as a whole, average over England and Wales and above average over Northern Ireland. Mean temperatures were about normal in England and Wales, but about 0.5 °C below normal in Scotland and Northern Ireland.

Information about the temperature, rainfall and sunshine during September–November 1987 is given in Fig. 1 and Table I.

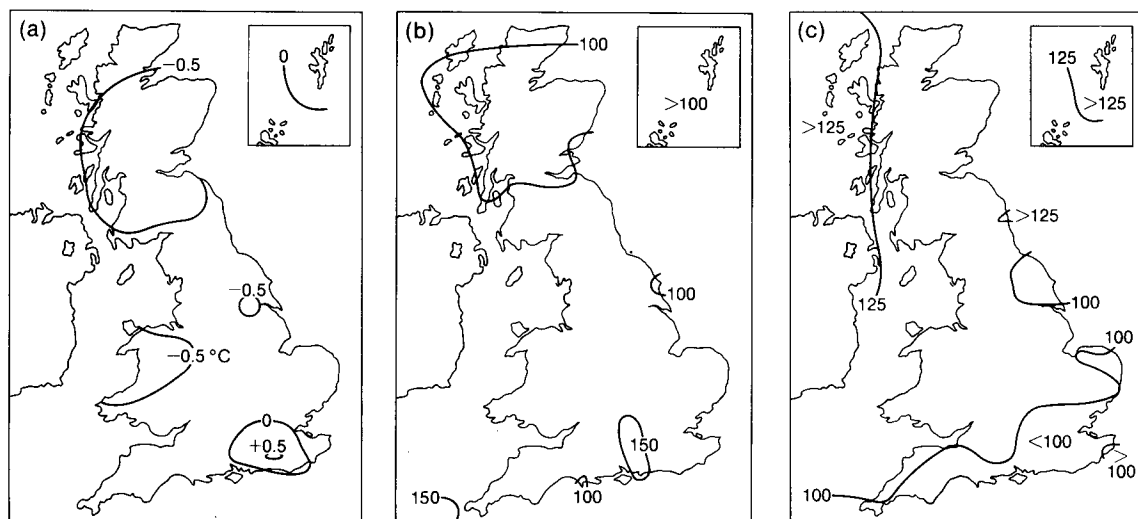


Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for autumn 1987 (September–November), relative to 1951–80 averages.

October. October was a very cool month with mean temperatures below normal everywhere apart from one or two places in southern England, and ranged from about 2 °C below normal in parts of central Scotland to near normal in parts of southern England. It was an exceptionally wet month; provisional figures suggest that it was the third wettest October in England and Wales since records began in 1727. Rainfall amounts ranged from about normal in north-west Scotland to three times the normal in parts of the south and east of England. Sunshine amounts were above normal in most areas, the notable exceptions being parts of the south coast of England, and northern England and eastern areas of Scotland where it was rather dull overall; amounts ranged from 80% in the Isle of Wight to more than 150% in the Western Isles of Scotland.

November. Mean monthly temperatures were near normal everywhere in the United Kingdom and ranged from 0.5 °C above normal in Shetland to 0.4 °C below normal at Aberporth, Dyfed. Monthly rainfall values for all districts were below normal, although one or two places had considerably more than the monthly average; amounts ranged from more than 130% at Brize Norton, Oxfordshire to just over 40% at Edinburgh. Sunshine amounts were below normal in most areas except parts of southern and eastern Scotland, south-west England and west Wales where it was quite sunny; totals ranged from about 60% in central England to 148% at Aberporth, Dyfed.

2. The individual months

September. Monthly mean temperatures were below normal in the north and above normal in the south, ranging from 0.9 °C above normal in parts of southern England to 0.7 °C below normal in southern Scotland. Rainfall totals were mainly below normal in England and Wales, but above normal in parts of western Scotland, ranging from a very dry 26% in the Isle of Wight to 153% in the Outer Hebrides. Sunshine totals for the month were generally above average apart from central southern and south-west England where they were about normal or below; amounts ranged from 158% in Shetland to 68% in the Isles of Scilly.

Table I. District values for the autumn months, September–November 1987, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	−0.3	+1	98	108
Eastern Scotland	−0.6	−1	96	107
Eastern and north-east England	−0.2	−2	118	104
East Anglia	+0.1	+2	137	95
Midland counties	−0.2	+2	125	97
South-east and central southern England	−0.2	+2	135	94
Western Scotland	−0.6	+2	107	116
North-west England and North Wales	−0.3	+1	114	105
South-west England and South Wales	−0.2	+2	125	102
Northern Ireland	−0.6	0	100	126
Scotland	−0.5	+1	94	110
England and Wales	−0.1	+1	123	100

Highest maximum: 26.5 °C in south-east and central southern England in September.

Lowest minimum: −7.6 °C in western Scotland in November.

3. The weather month by month

September. The month began with thundery rain moving slowly eastwards on the 1st, bringing heavy rain to counties to the north and west of London during the night with reports of flooding. It remained unsettled with showers or longer periods of rain at times, becoming widespread on the 11th and 12th as the remnant of tropical storm Cindy crossed central areas of the United Kingdom. Northern parts of the United Kingdom were showery for the next six days, while it became dry in central and southern areas, but later on the 16th and early on the 17th wet weather came to parts of England and Wales. After a dry day in all areas on the 18th it was mostly dry on the 20th, but on the next two days it was wet in the west. Apart from a few showers, mainly in northern England, the rest of the month was dry, though cool. Thunderstorms developed over eastern England and south-eastern Scotland on the 5th, and over south-east England on the 19th. It was showery in most areas on the 23rd and 24th with some hail and thunder, especially in central and south-eastern England. Hail was widespread over the United Kingdom during the 24th and 25th. It was the sunniest September at Tiree, Strathclyde since records began there in 1927 and the second sunniest at Lerwick, Shetland in a record back to 1922, while it ranked third in Edinburgh and Auchincruive, Strathclyde in records back to 1901 and 1932 respectively. In Northern Ireland only September 1986 was sunnier since 1941.

October. After a dry start to October it became changeable with a great deal of rainfall in the first half of the month, bringing widespread flooding to the south and east. Winds became strong to gale force on the 7th and 8th and remained strong until the 11th. On the 9th torrential rain caused flooding and road accidents in south-eastern areas as gales swept the south coast; floods brought commuter traffic leaving London to a standstill, with road tunnels and underpasses, including the London/Heathrow Airport access road, closed. Heavy rain caused severe flooding in many parts of the south-east on the 10th; in Essex some villages were almost cut off when the River Stour burst its banks after more than 50 mm of rain fell in less than 24 hours. Flooding to a depth of 4 metres was reported near Colchester. The storm on the 16th brought violent-storm-force winds and heavy rain to southern England causing chaos. Millions of trees were uprooted or had branches broken off and many crashed

into power lines, leaving a large number of homes without electricity, some for as long as a fortnight, and causing severe disruption to traffic. During the passage of the storm, several gusts of more than 90 kn were recorded across the south-eastern corner of England — 100 kn was recorded at Shoreham-by-Sea, West Sussex. On the night of the 17th/18th there were strong winds and widespread flooding in western and northern areas of Wales; substantial amounts of rain fell in western parts of Wales. Treacastle, Powys recorded 222 mm of rain over the five days from the 14th to 18th, 77 mm more than the monthly normal. Flooding was worst around Carmarthen and the areas of the Rivers Teifi and Tywi; one of the supports of the railway bridge over the River Tywi at Glanrhyd, near Llandeilo was damaged by flood water and debris and a Swansea to Shrewsbury train plunged into the river with the loss of four lives. On the 20th torrential rain brought flooding to large areas of Northern Ireland with flood water nearly 3 m deep in the town of Strabane, Co. Londonderry and extensive flooding in Co. Tyrone and Co. Fermanagh. It remained unsettled for the last week or so, though with some fine and sunny interludes, but gradually become cooler. Hampstead, Greater London reported the wettest October since records began there in 1903. Thunder was heard over a very wide area on the 5th and in western areas around the 17th.

November. November began generally dry except in Orkney and Shetland, but during the first week unsettled weather returned to all parts. The south-eastward passage of the depression across western areas of the United Kingdom on the 8th brought heavy rain to some places. After a brief drier interval, there was a change to an unsettled westerly airstream on the 10th, with rain or showers in most areas although with some drier spells, until the 25th, when brighter weather came to the north-west, spreading to the south-east by the 27th. Further rain reached all areas except south-eastern England on the 29th, with substantial falls in Devon, Cornwall and Dyfed. The 30th was a dry day except in the Midlands and north-east England. Thunderstorms were reported here and there on several days, with an outbreak over the Bristol Channel on the 12th. Hail was widespread between the 10th and 13th, and 22nd and 25th.

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Modelling precipitation in a cold frontal rainband*

G.P. Cox†

Meteorological Office, Bracknell

Summary

A study is made of the ability of a simple 'warm' parametrization scheme (solid phase not taken into account) to represent adequately the microphysical processes acting in a cold frontal rainband. The numerical simulations indicate that a mixed-phase parametrization is required in dynamical models of high resolution.

1. Introduction

Studies of frontal rainbands have highlighted the need for a better understanding of the influence of precipitation processes upon their dynamical structure. Since feedback may occur through diabatic processes (e.g. evaporation and melting) as well as precipitation loading (i.e. the effect of precipitation drag on the surrounding air), it seems likely that the effects become substantial locally. The

* An abridged version of a paper by Cox (1988) which appeared in the *Quarterly Journal of the Royal Meteorological Society*.

† Now at Software Sciences Ltd, Farnborough, United Kingdom.

microphysical processes acting in the production of rainfall are not fully understood and there is considerable doubt over the degree to which these complex processes can, or should, be represented or parametrized in computer models which resolve the mesoscale. The main aspect of this study concerns the ability of a highly parametrized 'warm' microphysical scheme (i.e. one with explicit representation of rain and cloud water but no representation of the solid phase) to simulate precipitation-induced feedbacks in dynamical models of high resolution (< 15 km). Such a scheme is attractive because it requires much less computer space and time than an ice or mixed-phase parametrization and is likely to be easily tuned.

In this study a comparison is made between the results of a two-dimensional diagnostic model using:

- (a) a full parametrization scheme based on that presented by Rutledge and Hobbs (1983, 1984), and
- (b) the 'warm' microphysical parametrization of Tripoli and Cotton (1980).

The microphysical processes represented by these schemes are shown schematically in Fig. 1.

Here a brief description is given of how the two schemes compare when they are applied to a narrow cold frontal rainband. Further details of the results can be found in Cox (1988); this also contains a report of the corresponding results for a frontal rainband which has vertical motions that are weak and uniform over horizontal distances of 100 km or more.

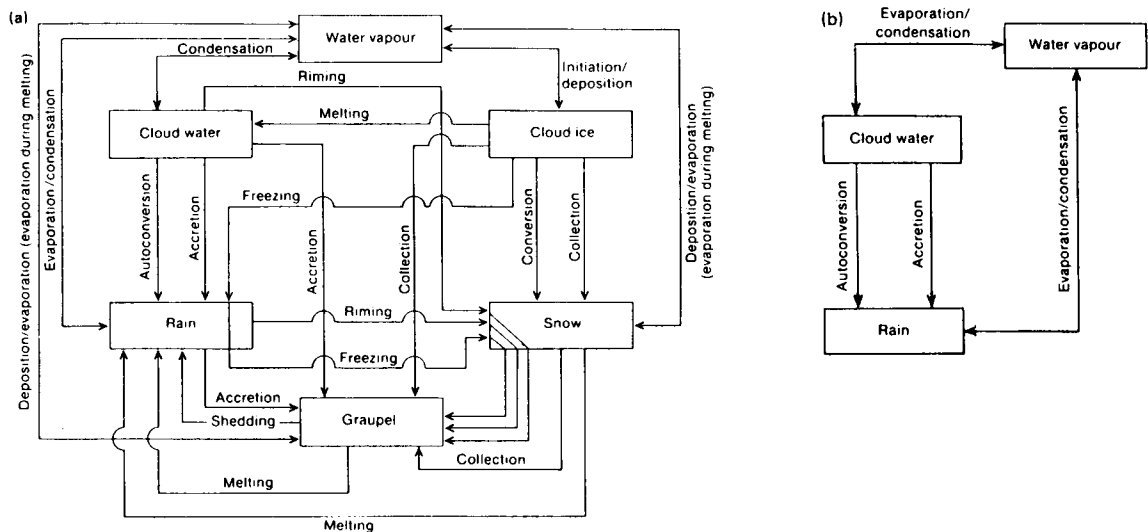


Figure 1. Schematic diagram depicting (a) the cloud and precipitation processes included in the full microphysical parametrization and (b) the processes included in the warm microphysical scheme.

2. The model

The model used in this study is similar to that described by Rutledge and Hobbs (1983, 1984). It is a two-dimensional diagnostic model in the x - z plane, where x is the horizontal distance perpendicular to the front and z is the height coordinate. The model variables fall into two categories:

- (a) The horizontal wind, vertical velocity and pressure are specified and held constant during the numerical simulation.
- (b) The temperature and mixing ratios of water vapour, cloud water, cloud ice, snow, rain and graupel are allowed to vary throughout the simulation, according to the thermodynamic equation and the conservation equations of the various mixing ratios, until a steady state is reached.

The conservation equations used in the model all have the same form. If χ is a mixing ratio, the conservation equation has the form

$$\frac{\partial \chi}{\partial t} = -u \frac{\partial \chi}{\partial x} - w \frac{\partial \chi}{\partial z} - \frac{1}{\rho} \frac{\partial}{\partial z} (\rho V \chi) + \frac{S}{\rho}$$

where u and w are the horizontal and vertical velocities of the air, ρ is the air density, V is the fallspeed of the precipitation (applies to rain, snow and graupel) and S represents the sources and sinks. The sources and sinks and the fallspeed have to be parametrized — the details are given in the papers already cited in section 1.

The non-zero fallspeed of the precipitation means that rain, snow and graupel move with the horizontal wind whilst falling relative to the updraught. However, cloud water and cloud ice have zero fallspeed and so they are simply advected by the airflow.

3. Model results

3.1 Full microphysics

The initial prescribed stream function over the $24 \text{ km} \times 3.5 \text{ km}$ domain is shown in Fig. 2. The wind fields are based upon observations of narrow cold frontal rainbands by Browning and Harrold (1970) and Hobbs and Persson (1982).

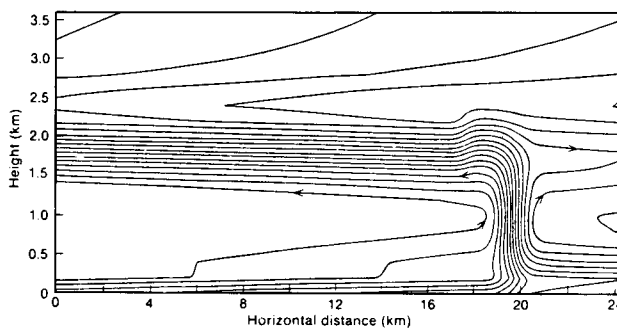


Figure 2. Prescribed stream function in the cold frontal simulation.

The results using the full microphysical parametrization scheme are shown in Fig. 3. The pattern of surface precipitation is almost the same as that observed by Hobbs and Persson (1982) with peak rates of 12 mm h^{-1} occurring about 4 km behind the surface cold front (Fig. 3(a)). Precipitation in the updraught is mainly carried up over the cold air but a fraction is transported back into the warm sector. Such a reverse flow is not uncommon and has been observed by Browning and Harrold (1970) and Hobbs and Persson (1982). This flow increases precipitation efficiency locally by allowing snow to cycle through the updraught. The snow can then grow by accretion and deposition removing cloud water and vapour which might otherwise be advected away from the front at high levels.

The heating rates associated with the diabatic effects are shown in Fig. 3(b). The configuration of the flow, with the updraught outflow overriding the cold air and allowing the precipitation to fall into it and evaporate, is ideally suited to maintaining heat sinks behind the front.

The distribution of the cloud water mixing ratio is given in Fig. 3(c). In many studies of cold frontal zones the region of cold air behind the front is compared to a classical density current. From a consideration of the propagation equation of a density current (Cox 1988) it can be shown that the current's velocity may be increased by around 10% by the action of differential precipitation loading

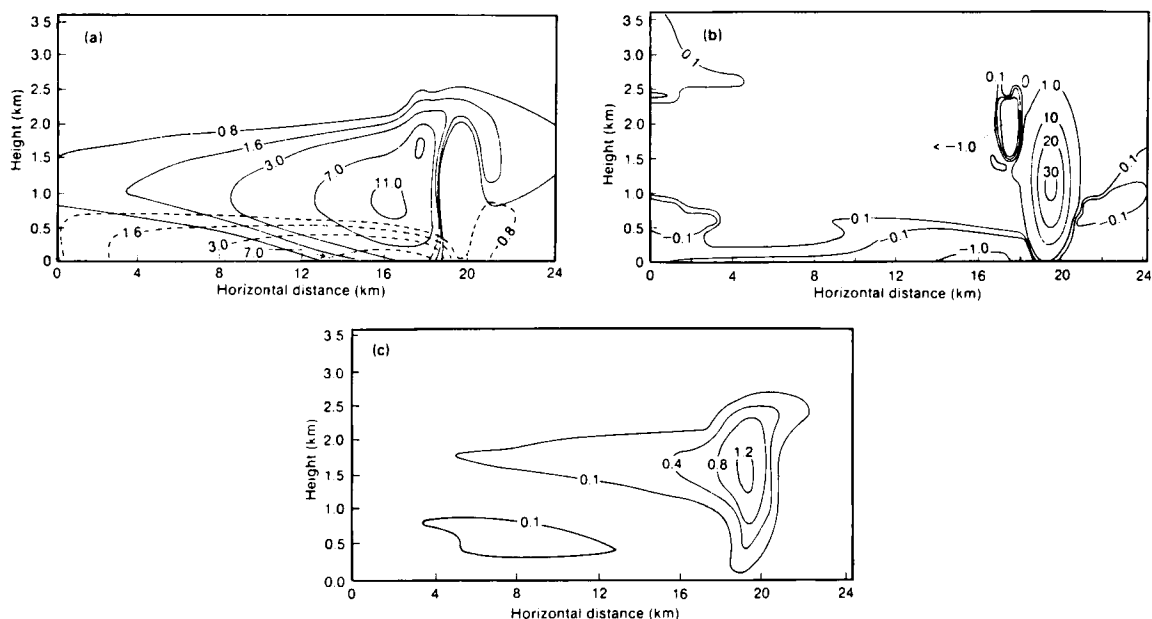


Figure 3. Results from the full microphysical parametrization for (a) precipitation rate (mm h^{-1}), solid lines represent snow (melted equivalent) and dashed lines represent rain, (b) latent heating rate ($10^{-3} \text{ K m}^{-3} \text{ s}^{-1}$) and (c) cloud water mixing ratio (g kg^{-1}).

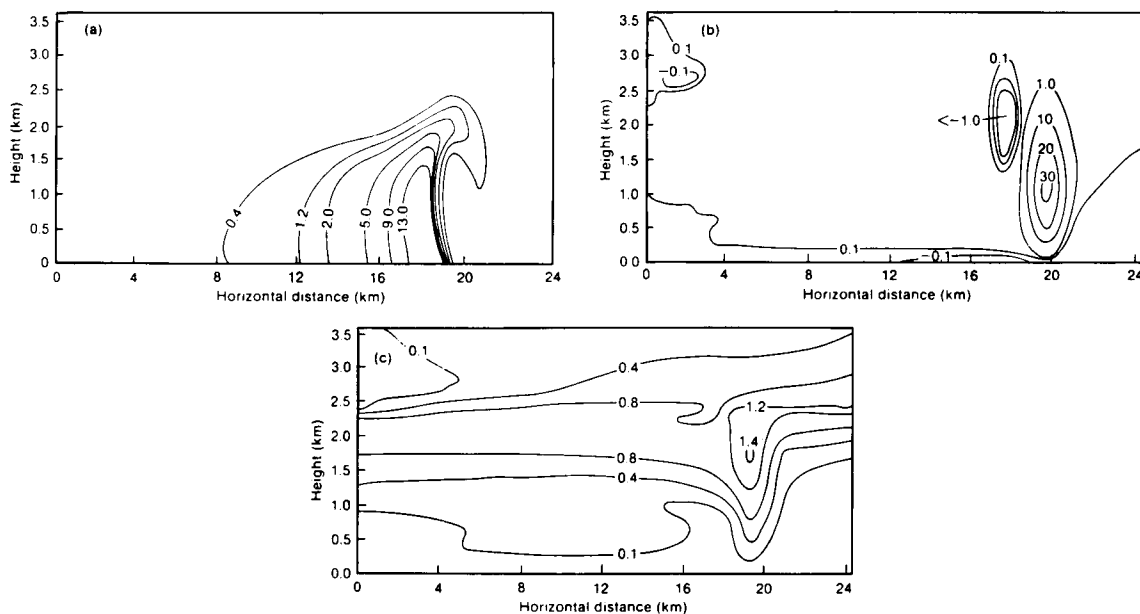


Figure 4. As Fig. 3 but for the warm microphysical parametrization.

seen in these results. The weight of precipitation behind the frontal zone may be an important factor in determining frontal speed.

3.2 Warm microphysics

Fig. 4 shows results from the simulation using the warm microphysical scheme. Since rain falls faster than either snow or graupel there is a very concentrated precipitation maximum close to and behind the surface cold front with the maximum rate exceeding 18 mm h^{-1} (Fig. 4(a)). The cloud liquid water content in the narrow updraught is in accord with observations, but the general value at 2 km (0.8 g kg^{-1}) is higher than observed (Fig. 4(c)). This can be reduced by increasing the parametrized accretion and autoconversion rates but the amount of precipitation inevitably increases. The difference in fallspeed of the various hydrometeor species leads to quite different patterns of mass loading between the two simulations. The major problem with the warm microphysics is the erroneous cloud water at 2 km. Here there is no division between small ice and snow in the full ice microphysics case corresponding to the division between cloud drops and rain in the warm case. Hence the accumulation of cloud particles is less likely to occur with ice microphysics. Since latent heat release is dominated by the condensation of water vapour to cloud water in both simulations, heating rates are generally rather similar (compare Figs 4(c) and 3(c)) except in and below the melting layer.

4. Conclusions

The simulation of the narrow cold frontal rainband using the full (mixed-phase) parametrization gave results comparable with field observations. However, the warm microphysics parametrizations gave less realistic distributions of surface precipitation and precipitation concentration aloft. Since melting and loading effects may provide important feedbacks to the dynamics locally, a highly parametrized warm scheme is likely to be inadequate for dynamical models of high resolution. In corresponding results for a weak warm frontal rainband (Cox 1988) similar conclusions were drawn. In addition, the warm microphysical parametrization did not represent the distribution of latent heat transfer well, particularly at levels where particle melting occurred using the ice phase parametrization.

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W.H. Hogg (1910–87) — an appreciation

J.A. Taylor

University College of Wales, Aberystwyth

'Bill' Hogg was born in Fulham and attended Westminster City School. He graduated in geology (1932) and geography (1934) at University College London. Whilst at university he met the late Marjorie Hutchinson whom he married in 1936.

Following various teaching and research commitments, he joined the Meteorological Office in 1939 as a Temporary Technical Assistant and served in various locations, amongst them Bristol, Upavon, Germany and Headquarters. For the major part of his service he specialized in climatology and agroclimatology, with a spell between 1949 and 1953 as a forecaster in the 2nd Tactical Air Force in Germany. He was promoted to the grade of Principal Scientific Officer in 1957.

Shortly after the end of the Second World War, the then Director of the Meteorological Office (Sir Nelson Johnson) initiated moves aimed at rendering the service of the Office more relevant to a wide variety of user-interests. Amongst these was the Ministry of Agriculture, Fisheries and Food which was engaged, at that time, in consolidating and expanding the advisory functions, some research, and statutory duties which had been performed during hostilities from a network of Regional, County and District Offices of the War Executive Committees, so creating a new organization entitled the National Agricultural Advisory Service (NAAS). Certain members of the Office were posted to a selection of these regional centres, amongst them Bill Hogg who headed the Bristol centre from 1953 to his retirement in 1971. He was eminently suited to such a post, both personally and technically, and earned an enviable and widely appreciated reputation for forging links between the increasing specialism of meteorology and the application of results in the field.

I was fortunate that my early involvement in agroclimatological research led me to seek the advice of three members of the Meteorological Office who were successfully pioneering and establishing agrometeorological services for British farmers. These were Lionel Smith, Ron Gloyne and Bill Hogg, all of whom had a combination of natural skills in applied science with a capacity for communicating on practical issues with farmers and growers. At my invitation all three, Bill Hogg in particular, became regular contributors to the Annual Series of Symposia in Agricultural Climatology which I convened at the University College of Wales, Aberystwyth between 1958 and 1973. We learned so much from spontaneous interdisciplinary exchanges and the ensuing memoranda and books which the Series generated. We reached a wide audience both nationally and internationally. In 1972 Bill and I established 'Environmental Consultants' which continues to prosper, due not least to Bill's major contributions on such consultancies as the fog potential of proposed alternative motorway routes, the best sites for developments in viticulture in south central England and agroclimatological advice for specific farmers and specific enterprises.

During his career he published a number of scientific papers, some solely in his name, some in collaboration with others. In 1965 he was awarded the Royal Meteorological Society Darton Prize.

Amongst his many activities during his retirement were a course of lectures at the University of Bristol and, in particular, the chairmanship of the Bristol and District Branch of the Civil Service Retirement Fellowship, which he held from March 1978 to March 1986.

Bill Hogg's professional and personal contributions to the cause of applied agroclimatology were of a very high order. He combined a meticulous discipline with a warmth of communication with colleague

and customer alike. He combined a penetrating pragmatism with a sympathetic, yet scientific, ability to solve real-world agroclimatological problems. I count it a rare privilege to have known and worked with him, as a friend and colleague. He will be sadly missed by all those who knew him.

He is survived by a daughter, Ruth, and five grandchildren.

Awards

L.G. Groves Memorial Prizes and Awards for 1986

The L.G. Groves Memorial Prizes and Awards were endowed by Major and Mrs Keith Groves in memory of their son Sergeant Louis Grimble Groves, RAFVR, who lost his life in September 1945 while serving as an Air Meteorological Observer with 517 Squadron Coastal Command. The 1986 awards were presented by Mr Andrew Douglas-Bate, a relative through marriage of the Groves family, at HQ Strike Command (High Wycombe) on 26 November 1987. Air Vice-Marshal R.A.F. Wilson, AFC, SASO HQ Strike Command, presided and the citations were read by Squadron Leader J.W. White of the Flight Safety Inspectorate. The ceremony was also attended by members of the Groves family, representatives of the RAF and the Meteorological Office, and the wives of the recipients of the awards. This year's ceremony marked the 40th anniversary of the first presentations which took place on 8 October 1947.



Dr S. Nicholls, winner of the Meteorology Prize, receives a mantle clock from Mr A. Douglas-Bate.



Mr G. Cooper, winner of the Award for Meteorological Observation, receives a printer for a home computer from Mr A. Douglas-Bate.

Meteorology Prize — Dr S. Nicholls

The citation read as follows:

To Dr S. Nicholls for his perceptive use of measurements from the Meteorological Research Flight Hercules aircraft to reveal the relationship between the radiative, turbulent and microphysical properties of the stratocumulus layer clouds and their effects on the evolution of the clouds. An understanding of these relationships is essential for forecasting the presence of clouds and their effects on surface temperature and fog formation, as well as the correct representation of layer cloud in numerical forecasting and climate models.

Dr Steve Nicholls has been involved in several international experiments using the Hercules, including the GARP Atlantic Tropical Experiment, the Joint Air-Sea Interaction Project and, more recently, the First ISCCP Regional Experiment. In addition to his work on the interpretation of aircraft data, he has been involved in the development of numerical models of clouds and with the development of a fast-response instrument to measure the total water content in cloudy and cloud-free air. He joined the Office in 1973 and was posted to the Meteorological Research Flight (MRF) at Farnborough from 1974 to 1982. During this period he also spent a year in the United States working at the National Center for Atmospheric Research in Colorado. On promotion to Principal Scientific Officer in 1982 he joined the Cloud Physics Branch where he combined his expertise on turbulence measurements with the Branch's expertise on cloud microphysics.

Award for Meteorological Observation — G. Cooper

The citation for this award was as follows:

To Mr G. Cooper for his important contribution in installing, testing, modifying and operating many of the instruments which make the Hercules aircraft of the Meteorological Research Flight one of the best equipped meteorological research aircraft available. His work on the droplet sampling instrument in particular called for a wide range of expertise and led to major improvements in accuracy and reliability of the measurements.

Graham Cooper joined the Meteorological Office in 1968. He worked at MRF from 1969 to 1971 and was involved in measurements of sea surface temperature and the design of an instrument to measure water droplet sizes and distributions in clouds. There then followed a period working in various Branches and outstations, but in 1977 he returned to MRF where he again got involved in developing airborne droplet-sizing instruments. In 1980 he joined the Cloud Physics Branch, and worked on the improvement of the droplet-sizing instrumentation and the development of an analysis system for the holograms taken during airborne experiments. Also, whilst working with Steve Nicholls, he contributed to the design and feasibility testing of a rapid-response total-water content meter which is now in the process of being fitted to the Hercules.

Air Safety Prize and Ground Safety Award

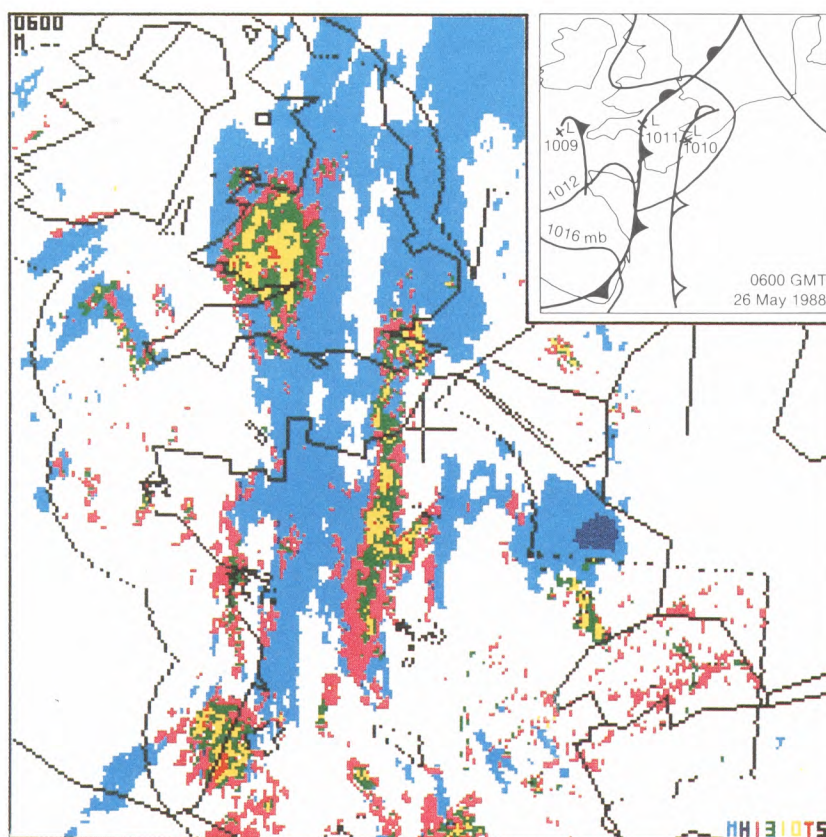
Flight Lieutenant N.B. Goulding from RAF Linton-on-Ouse received the Air Safety Prize in recognition of his work on an improved method of escape through the canopy of a Bulldog aircraft. The judges felt that the submissions for the Ground Safety Award did not quite reach the standards usually expected and so no award was made.

Satellite and radar photograph — 0600 GMT 26 May 1988

The picture covering much of western Europe shows radar data from several countries superimposed on infra-red cloud imagery from Meteosat.

Two bands of frontal cloud and rain are present lying north to south from central Britain to central France. The western band is related to a slow-moving surface front, whilst the eastern band formed during the previous 24 hours within a zone of increasing baroclinicity as warm air over the Mediterranean advected northwards in a southerly flow aloft. The eastern front was therefore drawn by the UK Central Forecasting Office as an upper front. Much of the cloud and precipitation within this band is of convective origin. The front to the west is generally feeble in terms of precipitation. However, the pulse of moderate to heavy rain over Wales (moving north) is associated with a shallow surface wave. The wave had been induced just ahead of a region of enhanced convection, the axis of which is marked as a surface cold front.

Isolated thunderstorms occurring over The Netherlands and eastern France are shown by the localized areas of heavy rain. Outside the area of radar coverage, the region of cold topped cloud (dark blue) almost certainly represents a thunderstorm.



Key. Infra-red cloud-top temperatures (°C): light blue < -15, dark blue < -35. Radar rainfall (mm h⁻¹): pink < 1, green 1-3, yellow 3-10, and red > 10. Coastlines: National boundaries and radar network boundaries are shown in black. The small regions enclosed in black over France are regions of permanent echo. (Much of the apparently light precipitation over Switzerland is also permanent echo or anomalous propagation).

Meteorological Magazine

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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Retirement of D.H. Johnson
Stratus over the UK
Radio ducting
Unusual freezing rain



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Retirement of Mr D.H. Johnson

When Derek Henry Johnson, Deputy Director Forecasting Services, retired from the Meteorological Office on 19 June 1988 he had completed almost 39 years with the Office and a little over ten years as the Deputy Director in charge of the Forecasting Services area.

Derek was born in Wakefield, Yorkshire, but was educated at Tiffins Boys School, Kingston and this mix of the north and south of England has, without a doubt, stood him in good stead over the years. He went on to Imperial College, London, where first he read Mathematics, gaining a B.Sc. and an ARCS in 1948, and then, in 1949, he took an M.Sc. in Meteorology and a DIC studying with Professor D. Brunt after graduation.

He entered the Meteorological Office on 1 October 1949 as a Scientific Officer and, after the usual training period (then at Alexandra House, Kingsway, with Mr Pat Meade in charge), his first posting was to 19 Group at Mount Batten, Plymouth as a trainee forecaster under Mr P.F. Illsley as Senior Meteorological Officer.

In January 1951 he moved to Dunstable where he joined the Forecasting Research Branch (Met O 21). They were exciting times! Mr J.S. Sawyer was the Assistant Director and Professor R.C. Sutcliffe was Director of Research at that time, and the work at Dunstable was leading up to the operational introduction of numerical weather-prediction methods in the early 1960s. Mr Johnson's work was concerned mainly with the understanding, analysis and forecasting of the wind and temperature distributions in the upper troposphere and lower stratosphere, resulting in a number of publications and well merited promotion to Senior Scientific Officer in April 1955.

In 1958 came a move which was to shape Mr Johnson's interests for the next 12 years at least. As part of a special scheme arranged between the Director of the East African Meteorological Department (EAMD) and the Director-General of the Meteorological Office for encouraging weather forecasting research in Africa, and partially funded by a Colonial Development and Welfare Grant, Mr Johnson was seconded to the EAMD as a temporary Principal Scientific Officer in charge of the Forecasting Research Section located in Nairobi, Kenya. For the next three years he was able to concentrate on the problems of tropical meteorology, becoming a leading expert in this field and doing work which led to a succession of papers both during his years in Africa and over the ensuing period. Two WMO Technical Notes on *Forecasting the Weather in East Africa*, and *Forecasting the Weather in West Africa* are of particular note. His enthusiasm for this work was clear to the Director of the EAMD, Mr J.P. Henderson, and his promotion to PSO was made substantive in June 1960.

In May 1961 he returned to the United Kingdom to take up a post in the Climatological Research Branch (Met O 13) where his research projects concerned tropical meteorology, air-sea interaction and energy exchange studies. He was retained as a consultant to WMO at a number of international seminars on tropical meteorology in Africa, and was working alongside Mr G.A. Corby and Mr J.S. Sawyer.

In 1964 after a short forecasting refresher as Senior Meteorological Officer at RAF Uxbridge, he returned to the tropics as Chief Meteorological Officer, HQFEAF (Far East Air Force), Changi, Singapore with responsibility for all the RAF meteorological offices in the FEAF arena. He was an exceptionally good C Met O dealing with the considerable administrative responsibilities competently, but still finding time to act as the UK representative at various conferences and symposia on tropical matters in such varying locations as Bombay, Tokyo, Australia (Perth, Melbourne, Brisbane and Darwin) and Miami mainly at the request of the organizing committees. During this period he also came to know the RAF more closely, and was highly thought of for his handling of major and minor crises with quiet aplomb.

Returning once more to the United Kingdom in 1968 Mr Johnson was posted to the Dynamical Climatology Branch (Met O 20) where he immediately initiated a programme of research into the role of tropical meteorology in the global circulation. This led to his giving a substantial paper on this topic at the Royal Meteorological Society Conference on the Global Circulation of the Atmosphere held at the Royal Society in August 1969.

In January 1970 however, with a posting to become Chief Instructor and Head of the Training School at Stanmore, a new area of experience opened for Mr Johnson. This was a time of intensive planning in co-operation with Mr K.H. Smith who was the Assistant Director Professional and Technical Training (AD Met O(PT)) for the move from Stanmore and the establishment of a new College at Shinfield Park. The move was completed in September 1971 and Mr Johnson became the first Principal of the Meteorological Office College. In April 1972 the jobs of AD Met O(PT) and Principal were merged, and Mr Johnson was promoted to Senior Principal Scientific Officer to take over this new post. He now had wider responsibilities for overall policy and supervision of professional and technical training in the Office, including external study, curricula, training evaluation and like matters.

After a further two years or so the new post was well established, and it was time for a further move, this time to become Assistant Director, Public Services (Met O 7). Here, with responsibility for services to civil aviation and to the general public and commercial customers, his wide experience of a mix of research and operational service posts stood him in good stead. Working for a number of Deputy Directors (Messrs M.H. Freeman, N. Bradbury and F. Bushby) over the next three and a half years his sterling qualities of thoroughness and ability to weigh up complex situations were fully used, and for the first time he came into close contact with a variety of customers (e.g. the CAA, BBC, CEEB, etc.).

On 2 May 1978 came well-deserved promotion to Deputy Chief Scientific Officer (now Grade 5) as Deputy Director of Forecasting Services. This post involves policy responsibilities within the Senior Directorate of the Office for the Defence and Public Services Branches (Met O 6 and Met O 7) and the Central Forecasting Office and its numerical weather-prediction support (Met O 2). The ten years from 1978 to 1988 have involved rapid change and development in all these areas and throughout the period Mr Johnson has steered a carefully thought out and controlled course.

Perhaps the most important negotiations during his first five years involved his work with the Civil Aviation Authority (CAA) on the new ICAO Forecasting System. The negotiations with, and through, CAA and the Department of Transport were difficult, and the successful outcome, in which Bracknell was nominated as one of the two World Area Forecasting Centres as well as a Regional Area Forecasting Centre, was largely due to Mr Johnson's knowledge and negotiating skill.

At the same time he was laying the foundations for the rationalization of the Office's Civil and Defence Outstation organization, which has been carried out during the past five years or so. This rationalization, involving reorganization of RAF stations and public-service Weather Centres, and re-deployment and reduction of staffing levels has not been easy. Much credit must go to Mr Johnson in that his exceptional qualities have enabled these substantial changes to go ahead smoothly and without disruption of the essential services. During a period when pressures to change existing procedures in order to reduce costs and staffing levels have been intense, he has striven and succeeded in maintaining a balanced programme of services, and has encouraged the development of the new commercial attitudes which have been needed while maintaining the Office's reputation for professional and scientific integrity.

It has been my pleasure to have such a reliable and knowledgeable colleague, in particular over the past six or seven years during which we have worked closely together. His wealth of experience across the spectrum of Office activities, particularly with regard to the staff of the Office (some 50% of the total complement came within his remit), coupled to a realistic view of the problems of resource management have been of great value. His judgement in these matters has always been impeccable. He will be missed, and I am sure that all those who have worked alongside and with him will join me in wishing him and his wife all happiness and good fortune in his retirement.

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An investigation into stratus distribution over the United Kingdom

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Summary

Statistics of the distribution of stratus over the United Kingdom are presented in terms of the variation at individual stations with local wind direction and season, and in terms of the spatial distribution for different synoptic flow-types. Three main regimes are found and discussed in relation to the forecasting problem. Two summer regimes affecting the east and west coasts of the United Kingdom are largely associated with the advection of stratus formed by cooling over the sea. The third regime occurs in winter over most of central and eastern England and is probably due to cooling overland, though moistening of the air during its passage across the North Sea or the English Channel plays a role in its existence.

1. Introduction

In the United Kingdom one of the most difficult tasks faced by a local forecaster is the prediction of the onset and dispersal of low cloud. Flying operations, particularly at military airfields, are sensitive to changes of a few hundred feet in the base of low cloud, and on time-scales of a few hours. Improvements in the precision and accuracy of forecasts of visibility and cloud base could lead to large savings for operators by avoiding unnecessary diversions and by maximizing the use of expensive facilities, yet little effort has been channelled into this area over the last 20 years. Much of the research into short-period forecasting in recent years has been concentrated on the analysis and prediction of precipitation patterns. Although this is clearly of use for aviation forecasters it does not solve their major problem of predicting low cloud and visibility. Great progress is also being made with the development of mesoscale numerical-forecast models, but prediction of the required detailed and local changes in the boundary layer is still some years off. This paper describes the initial stages of work being carried out in the Meteorological Office to reduce this imbalance.

Many more data are available and more readily manipulated than say 20 years ago, as a result of increased automation of data collection and processing over the last few decades. It therefore seemed appropriate as a first step in this project to update our knowledge of the climatology of stratus over the United Kingdom. This is a useful exercise not only in defining more clearly the nature of the forecasting problem but also in providing some immediate help to forecasters by quantifying their own local knowledge and making data on the peculiarities of other locations readily available. Since this project is still in its infancy this paper will necessarily be largely confined to describing some of the interesting features of the distribution of stratus, and relating them to possible future forecasting techniques.

2. Data

Basic data on cloud amount and height were taken from the significant cloud groups contained in archived synoptic reports from over 100 stations which had reported hourly or 3-hourly for at least 5 years during the period 1971–1985. The data were sorted according to the height of the cloud base of layers of 3 oktas cover or more up to 1500 ft for different local surface-wind directions for each month, and also for time of day and different wind speeds for each season. The reliability of cloud-base data depends on the availability of cloud-base recorders and the degree of training and experience of the observers. The data were checked by examining the frequency at which individual cloud-base codes were reported. Some stations which exhibited a marked preference for a few round values such as 500 or 1000 ft were noted as suspect.

The data-sorting programs treated reports of sky obscured as 8 oktas cloud below 100 ft; thus, some occasions of dense fog are included in the analysis. These can be eliminated by sorting the data by present weather code in addition to the other parameters. This was carried out for a selection of stations and found to make little difference to the distributions though the overall frequency was reduced by up to 25% of the original value. Since there is no way of distinguishing between dense radiation fog and advection or hill fog, which are closely related to stratus and should be included, all occasions with sky obscured have been included in the analysis.

The second stage of the analysis was to relate the stratus occurrence to the larger-scale flow rather than to local conditions. A data set of 'Lamb' types (Lamb 1972) defined once a day was created by H.H. Lamb and has since been updated regularly by the Meteorological Office and more recently by the Climatic Research Unit of the University of East Anglia. This divided the flow, defined by the surface pressure pattern over an area slightly larger than the United Kingdom, into eight wind directions which could then be subdivided into straight flow, and anticyclonically and cyclonically curved flow types. Allowing for three extra classes for purely anticyclonic, cyclonic and undefined flow patterns there are a total of 27 types. However the synoptic types defined in this way may change rapidly during a 24-hour period. We have, therefore, created an hourly data set of 'synoptic types' based on the geostrophic wind direction defined from the surface pressure at four stations (Fig. 1). Because of the shape of the British Isles and the distribution of stations this was carried out separately for England and Wales, and Scotland. An estimate of the geostrophic vorticity was obtained by using finite differences from the non-uniform grids defined by the crosses in Fig. 1. The pressure at the centre of the cross was taken as that at Abbotsinch for the northern cross and the average of Ringway, Watnall and Elmdon for the southern cross. The vorticity was often dominated by the shear whereas we are primarily interested in



Figure 1. Distribution of stations used to calculate the synoptic type, and other locations mentioned in the text. Shaded areas denote land above 600 ft.

curvature, since different curvature for the same mean direction could result in the exposure of different locations to low cloud. An estimate of the contribution of the shear term to the vorticity was made by comparing the pressure gradient to the right and to the left of the mean wind direction. This value was then subtracted from the total vorticity to leave the contribution due to the curvature. Values of the geostrophic wind speed and 'curvature' were then used to determine if the type was straight flow, cyclonically or anticyclonically curved, purely cyclonic or anticyclonic or undefined. Before 1982, pressure values were available only every 3 hours, so values of the geostrophic wind components and the curvature were linearly interpolated to intermediate hours. Subjective assessments for two months chosen to contain a full selection of types were used to select the values of these parameters bounding the different flow types. A further two months were then used to verify the objective types against subjective assessments. On about 3% of occasions the objective type was deemed to be wrong owing to small-scale features in the pressure field affecting the estimated vorticity. On about 25% of occasions the assessments differed by adjacent categories and the remaining 72% agreed exactly.

The advantages of the 'synoptic type' defined in this way is its objectivity and the greater number of events available with hourly data. The main disadvantage is the rather small area over which the type is defined.

3. Stratus regimes

The frequency of stratus below 400 ft for given 30° sectors of local surface wind was plotted against wind sector and month. From these, the month and direction most prone to stratus were found for each station. When these data were plotted (Fig. 2) three main regimes were indicated. There are two essentially maritime regimes with maximum frequency in summer affecting (i) the west coasts of Scotland and Wales and the south-west coast of England and (ii) the north and east coasts of Scotland

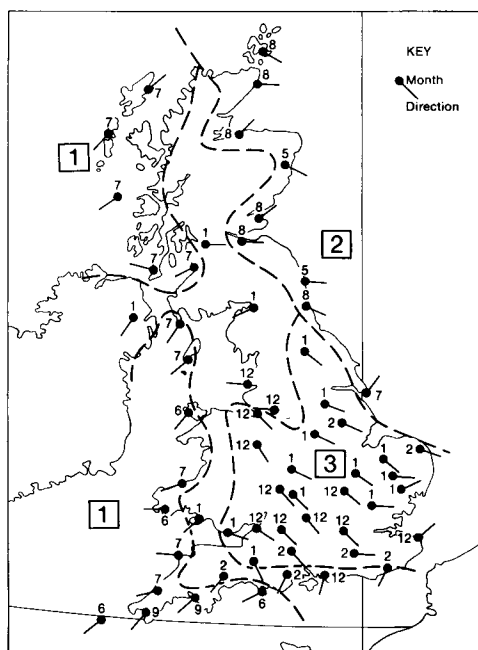


Figure 2. Month and surface wind direction most prone to stratus below 400 ft. The numbers in boxes denote the three main stratus regimes.

and the east coast of England. The third regime has a maximum frequency in winter and mainly affects most of central, southern and eastern England. There is some overlap of the second and third regimes over southern England, where the former extends all the way down the east coast and inland as far as central southern England but is masked on Fig. 2 by the higher frequencies in the winter regime. Those locations which do not fall into any of these classes have only low overall frequencies.

3.1 *South-westerly regime*

The south-westerly regime has a maximum frequency in summer and is restricted to the coastal regions by the high ground in most of western Britain; only in southern England is there much inland penetration of stratus and even here it is only a problem on relatively high ground. This regime is clearly associated with advection of moist Atlantic air as it moves north-eastwards over increasingly colder sea. An example of the distribution of stratus below 400 ft by wind direction and month is shown in Fig. 3(a) for the Scilly Isles, off south-west England. The frequencies are the percentage of occasions for each month of cloud below 400 ft, given that the wind is in the specified 30° sector. Therefore, if winds from that sector are relatively infrequent, the peak values will not necessarily indicate the direction with the greatest total number of events. At Scilly, stratus is present throughout the year, but with a maximum frequency in June. There is also a broad spread of directions affected, reflecting the exposed position of the islands. Further north, up the west coast, local shelter restricts the directions prone to low cloud and the summer maximum becomes more marked.

3.2 *Easterly regime*

This regime has a maximum frequency in August, with wind directions between north-east and south-east. Again the stratus is formed by cooling of air over a cold sea surface and the slightly later time of maximum frequency than in the south-westerly regime is probably due to the tongue of cold water that persists throughout the summer off the east coast of England and Scotland. In the south the stratus is most frequent with a wind from north of east giving a long sea-track over the North Sea whereas in the north a longer fetch over the sea is associated with south-easterly winds. However, in the north local orography has more influence on the most vulnerable direction. Also, fog or very low stratus sometimes enters the North Sea between Scotland and Norway and is advected down the east coast by north-easterly winds (Findlater *et al.* 1988). Fig. 3(b) gives an example of the distribution of stratus with local wind direction and time of year for Leuchars.

3.3 *Winter south-easterly regime*

The explanation of this regime is less obvious than for the others as it occurs in south-eastern Britain with winds from a continental source. The distribution by month and local wind direction is typified by that of Waddington (Fig. 3(c)). There is a very marked peak in December with winds from between 080 and 150°, accentuated in this case by slight upslope flow from these directions. Low stratus is very infrequent with winds between 200 and 300°, and also during spring and summer except for winds between north and north-east. This latter exception shows that this station is also affected by the easterly regime.

There is an overall increase in frequency away from the coast. This suggests that the stratus is formed in part by nocturnal cooling over land. This will be discussed further in the next section in connection with the spatial distribution of stratus for given synoptic types.

4. *Spatial distribution by type*

The statistics described above can be a useful aid for the forecaster concerned with a spot forecast for his own location but much of the commitment at RAF stations is for forecasts for areas remote from the

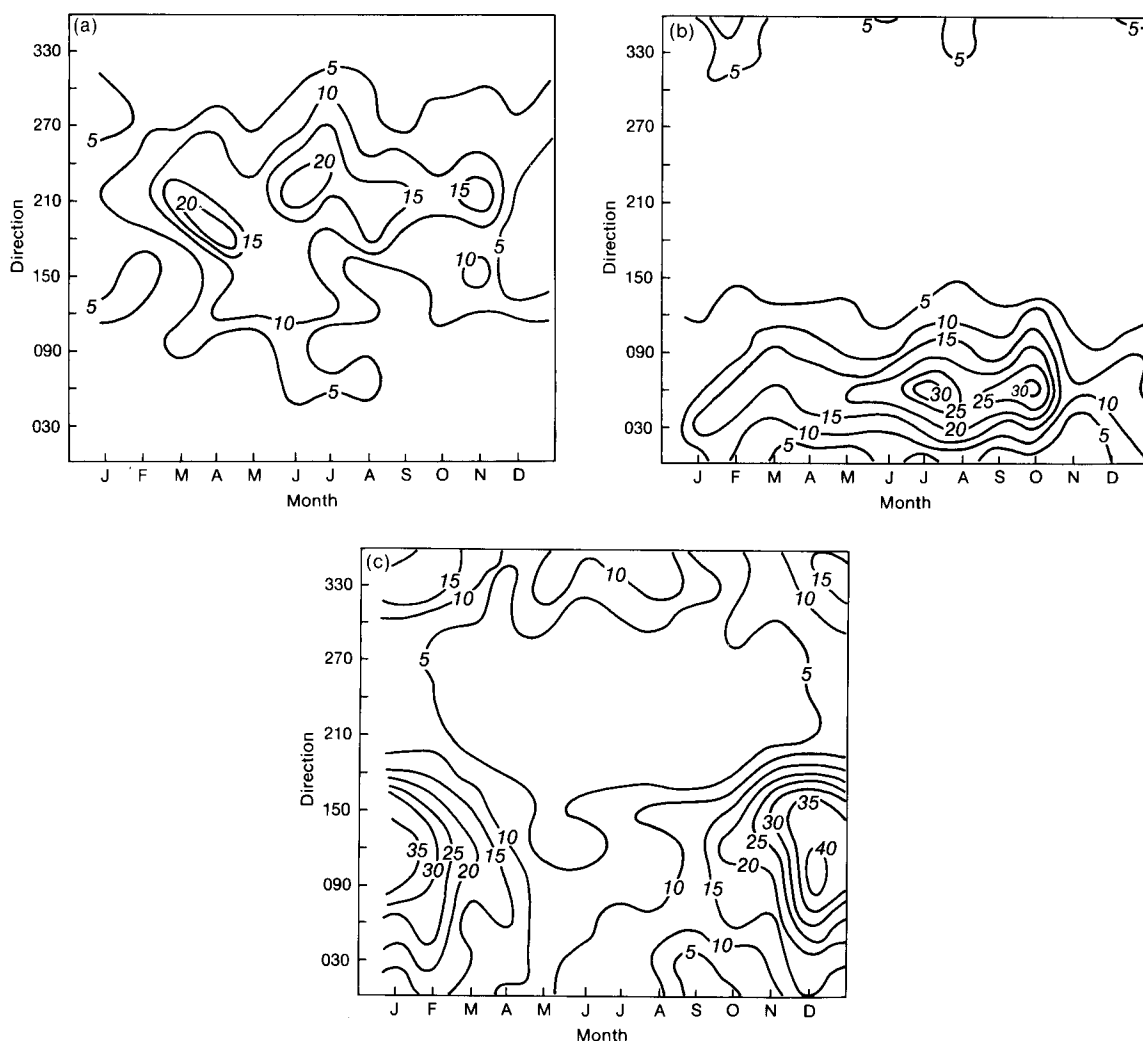


Figure 3. Percentage frequency of stratus below 400 ft given the local surface wind direction and time of year at (a) Scilly, south-westerly regime, (b) Leuchars, easterly regime, and (c) Waddington, south-easterly regime.

station. In this case it would be helpful to have an indication of how stratus is likely to be distributed spatially for a given weather situation. This has been tackled by defining synoptic types as described in section 2. The frequency of stratus below three heights (300, 700 and 1500 ft above station level, corresponding to frequently used RAF operating limits) were plotted for each of four seasons. There was an encouraging agreement between neighbouring stations, even in the less frequently occurring types with a small sample size. However, a large proportion of the variation between stations can be attributed to the height of the station. Assuming the air below the stratus base is reasonably well mixed, apart from development due to cooling or warming, even over rising ground the cloud base will be at a constant height above sea level until the cloud intercepts the hills. It therefore makes sense to correct frequencies to a common height above sea level if isopleths of equal frequency are to be drawn. This then enables the likelihood of stratus occurring at locations remote from observing stations to be estimated.

Heights above station level for spot airfield forecasts can be found by applying the correction in reverse. When winds are very light and the air is not mixed, stratus may form at a lower height on windward slopes. In this situation local effects will dominate and this approach is no longer useful.

To enable the correction to be estimated, the variation of frequency with the height of the base was found for each station and each type. The rate of increase in frequency with height varied markedly with flow type and between stations, but was nearly linear for any given station and type. The distribution of the rate of increase in frequency with height for anticyclonic southerly flow in winter is illustrated in Fig. 4. A consistent pattern appears with generally good agreement between neighbouring stations, so a reduction of frequencies to a common height using these values would appear to be valid. The increase with height in this winter case is largest furthest from the windward coasts. This is to be expected if the stratus forms owing to cooling as it moves inland. The dryer the air the higher the base, and the further air has to travel before it forms, giving a higher frequency of high bases inland. In addition any very low stratus advected onshore will be intercepted by the topography, and inland valleys will be sheltered; hence the relative frequency of high bases will increase inland. In the summer, stratus at any height is less likely to penetrate inland during the day so inland the rate of increase with height is low reflecting the overall lower frequency. There are, however, notably higher rates of increase over windward slopes.

The resultant distributions are shown for three types representing the three regimes in Figs 5, 6 and 7. Frequencies are given for 500 ft above sea level for the winter case because this height corresponds to the previously chosen 300 ft above station level at many stations. Cloud at the surface is implied at only one station (Lyneham). A height of 700 ft above sea level is chosen in the summer because of the generally higher bases in this season.

In the case of anticyclonic southerly flow in winter we see that the frequency of stratus below 500 ft generally increases with distance inland. The effect of even very modest topography is illustrated by the very low frequencies in the lee of the Cotswold Hills (situated just to the south-east of the Welsh hills). A further interesting feature is the tongue of low values extending north-westwards across south-east England, downwind of the Strait of Dover. This suggests that the stratus is perhaps being formed due to moistening of the flow over the English Channel and the North Sea, and subsequent cooling over the land. The very short sea passage across the Strait of Dover does not allow enough moistening of the air for stratus to form, at least below this height. However, there is probably also an effect due to the reduced cooling over the London area which also lies downstream of Dover.

For south-westerly flow in summer, stratus is confined to the west coasts and parts of southern England where slight upslope flow enhances its frequency.

The distribution for summer north-easterly flow illustrates the spread of stratus inland over central and eastern England in this regime. The decreasing frequency inland reflects the change in diurnal variation with distance from the coast. A further interesting feature is the appearance of a second area prone to stratus down the west coast.

5. Diurnal variation

The diurnal variation of stratus frequency is controlled largely by time of year and distance from an upwind coast. It is desirable, therefore, to investigate the variation at each station for each synoptic type and each season. In practice it is necessary to combine types having similar spatial frequency distributions to avoid spreading the data too thinly.

Fig. 8(a) shows the diurnal variation for three stations at different distances from the coast for south-westerly types in summer. There is a clear diurnal variation even at Scilly, only 1 km from the coast (though the author is at a loss to explain the phase). At Culdrose, 5 km inland, the slight increase in frequency after 10 GMT is probably associated with an increase in onshore wind due to sea-breeze effects, a more marked increase taking place after 18 GMT as the insolation begins to decrease rapidly.

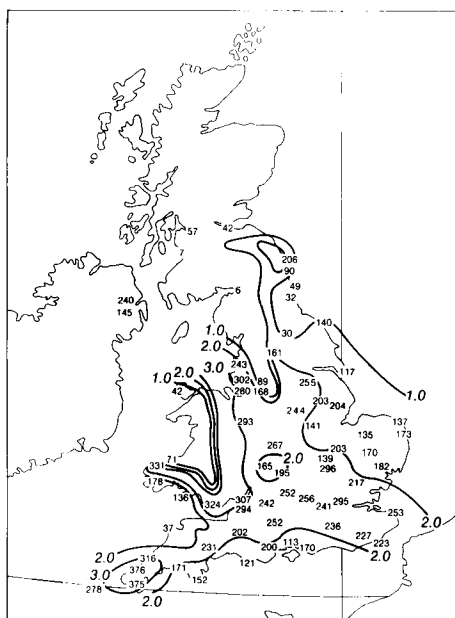


Figure 4. Distribution of increase in stratus percentage frequency with height for anticyclonic southerly type in winter. Contours in per cent per 100 ft.

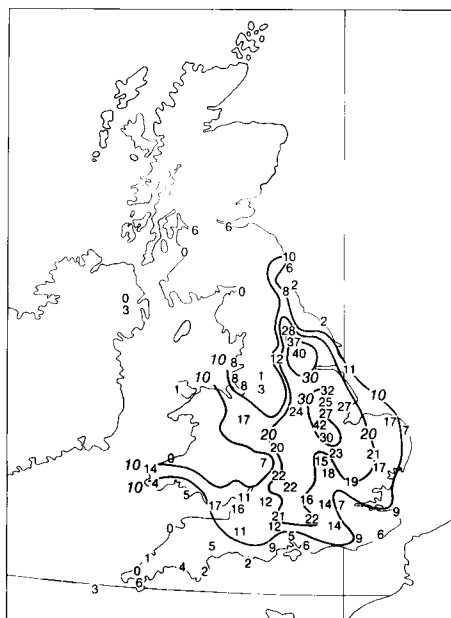


Figure 5. Distribution of percentage frequency of stratus below 500 ft above mean sea level for anticyclonic southerly type in winter.

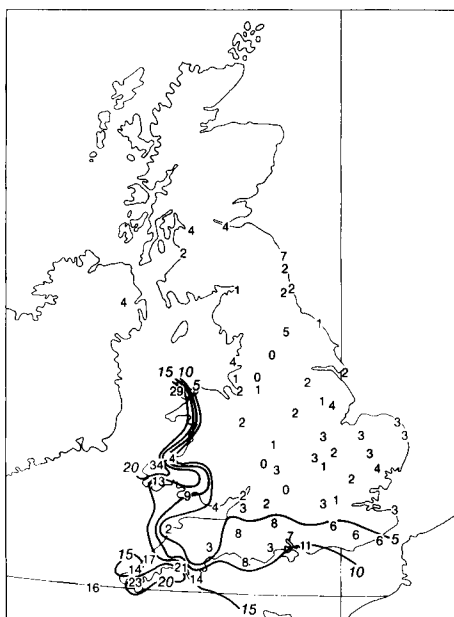


Figure 6. Distribution of percentage frequency of stratus below 700 ft above mean sea level for summer south-westerly type.

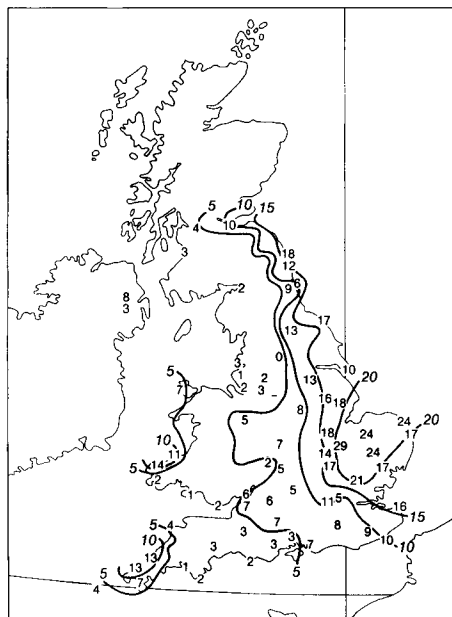


Figure 7. Distribution of percentage frequency of stratus for summer north-easterly type.

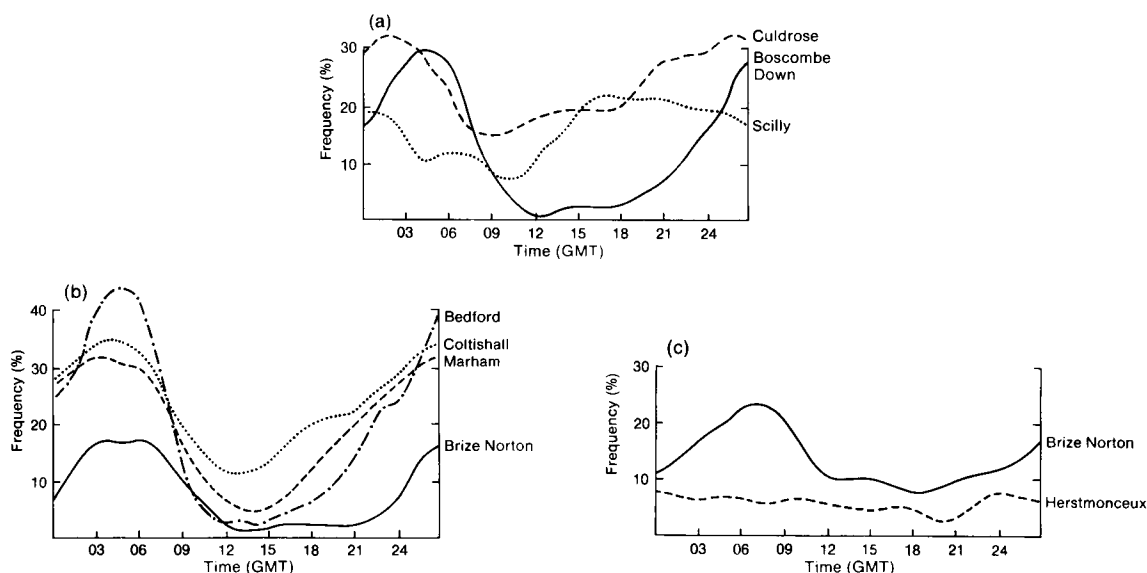


Figure 8. Diurnal variation of stratus frequency. (a) Base < 700 ft above sea level for south-westerly and cyclonic south-westerly types in summer, (b) base < 700 ft above sea level for anticyclonic northerly, north-easterly, anticyclonic north-easterly, easterly and anticyclonic easterly types in summer, and (c) base < 500 ft above sea level for anticyclonic easterly, south-easterly, anticyclonic south-easterly and anticyclonic southerly types in winter.

The overall higher frequency at Culdrose (268 ft above sea level) than Scilly is probably due to ascent over the coast. Well inland at Boscombe Down, in the early morning, stratus is almost as frequent as at the coast, but will almost always lift to above 700 ft above sea level (300 ft above station level) during the day.

A similar pattern is evident for the easterly regime (Fig. 8(b)). At Coltishall (15 km from the Norfolk coast) the frequency is reduced to about a third of the peak value by midday but begins to increase thereafter, again showing the effects of sea-breeze type circulations. Further inland at Marham and Bedford (65 and 165 km from the east coast respectively) the peak frequency is maintained showing that on most nights stratus will penetrate this far inland, but 260 km from the east coast at Brize Norton the maximum frequency has fallen by 50%. (The higher maximum frequency at Bedford is probably due to the inclusion of fog with sky obscured in the analysis.) Solar heating causes the base to lift at a similar time at all four stations but it returns at a later time with increasing distance from the coast suggesting advection is the dominant mechanism here.

In the winter regime there is again a marked diurnal variation inland as shown in Fig. 8(c) but there is very little variation close to the coast. The weak minimum at 20 GMT at Herstmonceux, 8 km from the south coast, may be the effect of diurnal heating over France. The increased frequency inland, both day and night, suggests formation by radiative cooling and by contact with a cold surface.

Graphs such as those in Fig. 8(b), where the diurnal variation is well defined, can be used to estimate typical clearance and formation times which can then be plotted to give the spatial variation. In this case the clearance time would not vary much, but if the time by which the frequency has risen to 50% of its peak value is plotted there appears a very coherent and physically sensible pattern over much of England which can be interpreted as an estimate of relative formation/advection times (Fig. 9). In the early evening as the insolation begins to decrease rapidly, stratus can be expected to begin to affect the Norfolk coast and then to spread steadily inland. Several sensible effects can be discerned such as the

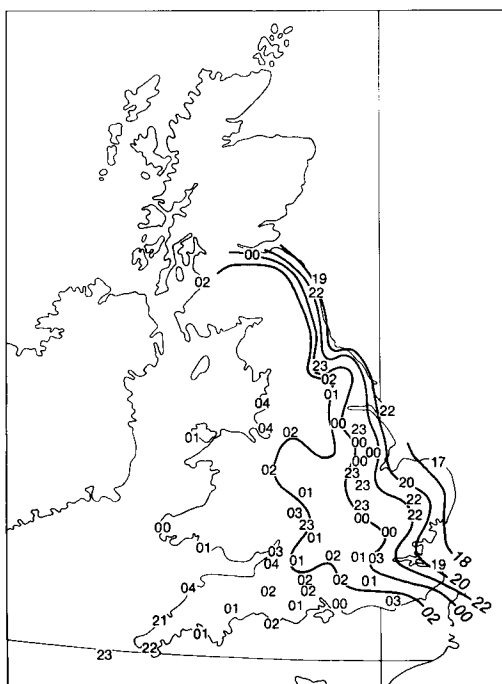


Figure 9. Distribution of typical times (GMT) of formation or arrival of stratus below 700 ft above sea level for anticyclonic northerly, north-easterly, anticyclonic north-easterly, easterly and anticyclonic easterly types in summer. See text for details.

sheltering of the Vale of York (south of Leeming) by the North York Moors, and more rapid penetration downstream of The Wash and through the gap between the Cotswold and Chiltern Hills towards Brize Norton. Bristol and the Severn Valley are well protected by the Cotswolds, and Herstmonceux near the Sussex coast is protected by the North and South Downs. Further west, local cooling of moist air advected inland by sea breeze circulations is probably responsible for the earlier formation times. In the extreme west, advection off the sea to the north is important. The effect of the London heat-island is indicated by the late arrival of stratus at the London Weather Centre.

6. Discussion

The stratus in the first two (summer) regimes is mostly advected over the United Kingdom from the sea. The forecast problem is then partly that of identifying and tracking areas of fog or low stratus. The development of techniques to detect fog and very low cloud on night-time satellite pictures using different infra-red channels will bring considerable improvements in this area. During the day there is still the effect of local circulations such as sea-breezes to consider and also the time at which stratus, advected inland overnight, will clear during the morning. For accurate assessment of the latter it is necessary to know the depth of the cloud layer and whether there are further cloud decks above. Again the advancement of satellite techniques will help. The Meteorological Office is also setting up a system of minisonde ascents to be made from key stations as the situation demands. This will enable the boundary-layer structure to be ascertained in regions remote from the regular radiosonde stations and at the time required rather than at set intervals. This will clearly help with prediction of both the formation and dispersal of stratus and fog. The problem of the effect of local circulations is being tackled by both modelling and observational studies. In recent years research has been carried out into the interaction

between sea fog and the local circulation of northern Scotland using radiosonde and aircraft data (Findlater 1985, Findlater *et al.* 1988). Experiments with the Meteorological Office mesoscale model (Taylor 1987) have demonstrated its ability to reproduce the local circulations crucial to the correct forecasting of low cloud and fog in this area.

The forecast problem in the winter regime appears to be more difficult in that there appears to be a mix of cooling, probably by surface contact and by radiation, causing formation *in situ*, and advection of pre-existing stratus from over the sea. However, the air mass can probably be traced back to the Continent where its initial conditions can be reasonably well defined. It therefore seems that this situation may best be tackled using a Lagrangian boundary-layer model with the boundary conditions supplied by larger-scale forecast models. However, the modelling of the stable boundary layer, which is likely to exist most of the time in this situation, is notoriously difficult. As part of a continuation of the studies of sea fog mentioned above it is planned to carry out flights this summer using the Hercules aircraft of the Meteorological Research Flight to investigate the development of sea fog and low stratus off south-west England by flying a low-level saw-tooth pattern into the low-level wind. As well as providing more direct guidance to forecasters on the structure of fog and stratus in its formative stages, this will provide an ideal data set against which to test any model of stratus development.

In the shorter term it is to be hoped that the dissemination of some of the statistical data discussed here will give forecasters a clearer idea of the behaviour of stratus over the country as a whole as well as at their own location.

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An introduction to radio ducting

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Summary

Anomalous propagation of radio waves in the atmosphere has been recognized as a problem with radar and radio communications for many years. The propagation characteristics of radio waves depend upon the meteorological conditions, and several different propagation regimes can occur. In particular, radio ducting is a condition where detection and reception ranges are severely modified by atmospheric conditions. This paper summarizes the relevant aspects of radio propagation theory, the meteorological conditions that lead to ducting, and discusses the various techniques that can be used to predict ducting.

1. Introduction

The occurrence of anomalous propagation of radio waves has been recognized since the early days of radar during World War II. The term ‘anaprop’ is now normally used to describe conditions when radar detection distances are significantly greater than usual. Such conditions occur fairly frequently.

The phenomenon known as 'ducting' is an extreme form of anaprop, and describes those occasions when radio waves become trapped in a shallow quasi-horizontal layer. In such conditions, greatly enhanced radar-detection ranges occur, owing to the concentration of energy within the duct. However, since energy is concentrated within the duct, this results in a reduction in the amount of energy reaching the region immediately above or below the duct and can lead to what is termed a radio or radar 'hole'. The presence of radar ducts and holes is of great importance to military operations, and there is a need to be able to forecast them so that their effects can be exploited or avoided.

The effects of anaprop are also important to the Meteorological Office Weather Radar Network, as illustrated in the example shown in Fig. 1. On this occasion, although most of Britain had a dry night, the radar display showed many returns across central England, and also from the Isle of Man; these were not caused by precipitation, but were due to anomalous propagation. Such spurious echoes, which have to be removed before rainfall intensities can be estimated, are a common problem with the weather radars (Smith 1981).

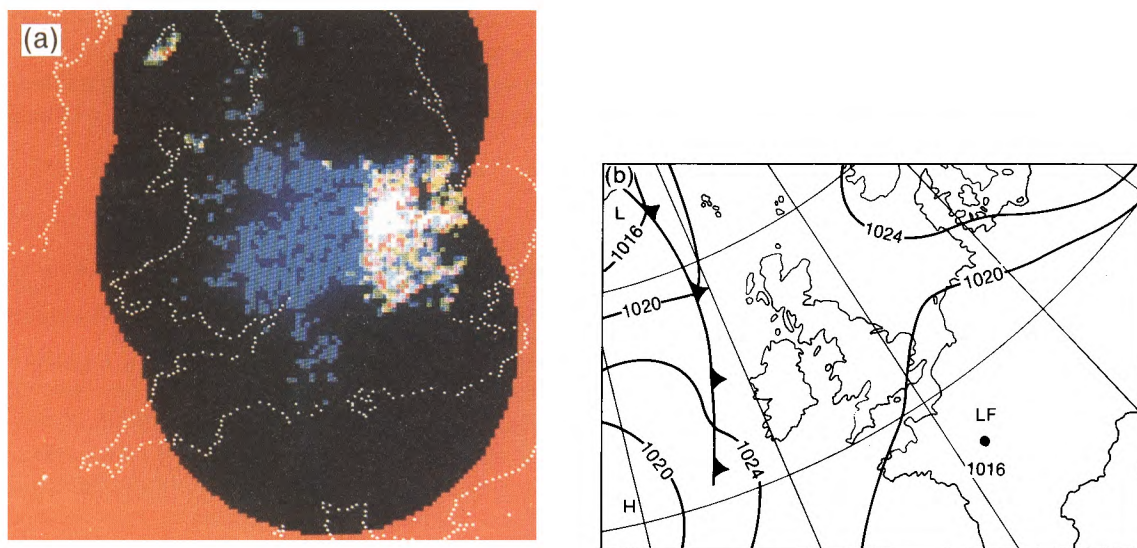


Figure 1. (a) An example of spurious returns due to anomalous propagation as seen by the Meteorological Office Weather Radar Network at 2200 GMT on 21 June 1983, and (b) synoptic chart for 0000 GMT on 22 June 1983.

2. Theory of radio propagation

2.1 Propagation characteristics

When radio waves, which are a form of electromagnetic radiation, travel through the atmosphere, they follow curved rather than straight paths. This occurs because the refractive index of the atmosphere varies with height, and so the rays are refracted. The curvature of a ray depends upon the rate of change of the refractive index of the air with height. The refractive index, n , is a function of the air pressure, p , temperature, T , and vapour pressure, e . At sea level in mid-latitudes a typical value of n is 1.00035 and so it is usually more convenient to define the refractivity, N , where

$$N = (n - 1) \times 10^6.$$

When n is 1.00035 the corresponding value of N is 350 (in N units). The refractivity is given (Bean and Dutton 1966) by

$$N = (77.6/T)(p + 4810e/T) \quad \dots \quad (1)$$

where p and e are in millibars and T is in degrees Kelvin. The vapour pressure can be determined from the dew-point temperature, T_d , using Tetens' equation

$$e = \exp \left(1.8099 + \frac{17.27 T_d}{T_d + 237.3} \right)$$

where T_d is in degrees Celsius.

The refractive index of the atmosphere normally decreases with height, which results in a downward bending of the wave path. To a high degree of approximation the curvature, K_0 (i.e. the reciprocal of the radius), of a near horizontally propagating radio wave is given by $K_0 = -dn/dz$ (Director of Naval Oceanography and Meteorology 1984) where K_0 is in km^{-1} and z is the height (km) above the earth's surface. In a well-mixed atmosphere, the value of dn/dz is such that a near horizontal ray is bent downwards with a curvature roughly equal to one quarter that of the earth's surface. This enables the radar to see 'over the horizon' as illustrated in Fig. 2. (Note that the ray path shown here is for an initial elevation which is below the horizontal.)

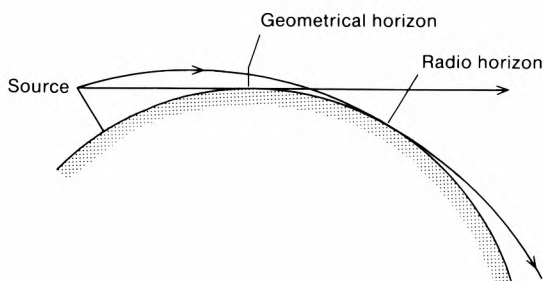


Figure 2. Schematic diagram illustrating the bending of a radio wave beyond the geometric horizon due to atmospheric refraction (vertical scale greatly exaggerated).

Fig. 3 illustrates the various refraction propagation categories. Standard refraction conditions refer to those that occur when the atmospheric state is close to that of a well-mixed atmosphere, for which the refractivity gradient $dN/dz = dn/dz \times 10^6$ is about -40 (N units km^{-1}). Standard conditions, where dN/dz is in the range from 0 to -79 N units km^{-1} , are representative of the mean state of the atmosphere.

If the decrease of refractivity with height is greater than that for standard conditions, then the curvature of the wave path is increased, and in extreme conditions can become comparable with the curvature of the earth $K_E = 1/R$, where R is the radius of the earth ($= 6371$ km), and therefore $K_E = 157 \times 10^{-6} \text{ km}^{-1}$ ($dN/dz = -157$ N units km^{-1}). If the curvature of the ray becomes greater than that of the earth, i.e. when $dN/dz < -157$, then the ray is bent to such an extent that it intersects the ground and the propagation characteristics become very different. This process is referred to as 'trapping', and the layer in which the ray is bent back downwards is called the trapping layer. The 'duct' is that region below the top of the trapping layer in which the radio wave is propagated. (Some examples of trapping layers and ducts will be considered in section 2.2.)

If the refractivity gradient lies between -79 and -157 N units km^{-1} (i.e. the curvature exceeds the standard value), but the ray is not brought back to the surface, the conditions are described as

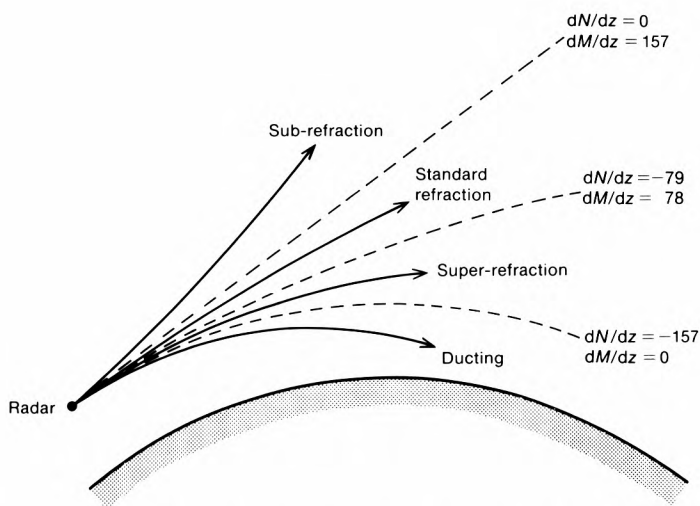


Figure 3. Refractive propagation categories. Note that the ray-paths all result from an initially horizontal ray. For explanation of lettering see text.

'super-refracting'. An initially horizontal ray is bent down with an increased curvature, and there is an increase in detection range.

Under some circumstances the refractivity may increase with height, and the wave is then bent upwards as shown in Fig. 3. Such conditions are described as 'sub-refracting' and detection ranges are then less than the standard values.

Because of the marked change in the propagation characteristics of radio waves, when their curvature exceeds that of the earth's surface, it is useful to consider the difference ($K_o - K_E$), given by

$$K_o - K_E = - (dn/dz + 1/R) = -dm/dz,$$

where m is the modified refractive index, $m = n + z/R$, and the propagation characteristics depend upon the sign and magnitude of the vertical gradient of m . It is convenient to define a modified refractivity M as

$$M = (N + z/R) = N + 157z,$$

where z is in km. Then $dM/dz = dN/dz + 157$ and the gradient of M is zero when the curvature of the ray is equal to that of the earth, i.e. $dM/dz < 0$ for ducting conditions. M is therefore a useful index for diagnosing ducting.

The various classes of propagation, as discussed above, can be defined in terms of dN/dz and dM/dz , and are summarized in Fig. 3.

2.2 Types of duct

As noted above, ducts can be identified from examination of the vertical profile of modified refractivity. Fig. 4 shows the three basic forms of the M profile under ducting conditions and illustrates how the duct depth is determined. In Fig. 4(a) the duct exists from the local minimum to the surface, and the trapping layer, where $dM/dz < 0$, extends throughout the duct. In Fig. 4(b) the duct again extends to the surface, in spite of the fact that the trapping layer does not, as dM/dz is positive close to the surface.

This is because the value of M at the surface is greater than the value at the top of the duct (i.e. at the local minimum), hence the average value of dM/dz below this level is less than zero. Fig. 4(c) shows the structure associated with an elevated duct. Here the value of M at the surface is less than the value at the top of the duct, and so the duct cannot extend down to the surface. Its depth extends from the local minimum to the height at which the M value equals that at the top of the duct.

Fig. 5 illustrates the type of propagation paths that occur in the three different types of duct described above. Not all rays are trapped in a duct. In practice only those rays entering the duct at a very shallow angle to the local horizon (typically less than 1°) are trapped. In each case the presence of a radio/radar hole above the duct is indicated (i.e. where there is little penetration of the radio/radar beam as a result of the duct). In reality, all ducts are 'leaky' and some energy will escape through the top of the duct into the region above. Thus it is possible to detect targets within a radar hole, although detection ranges will

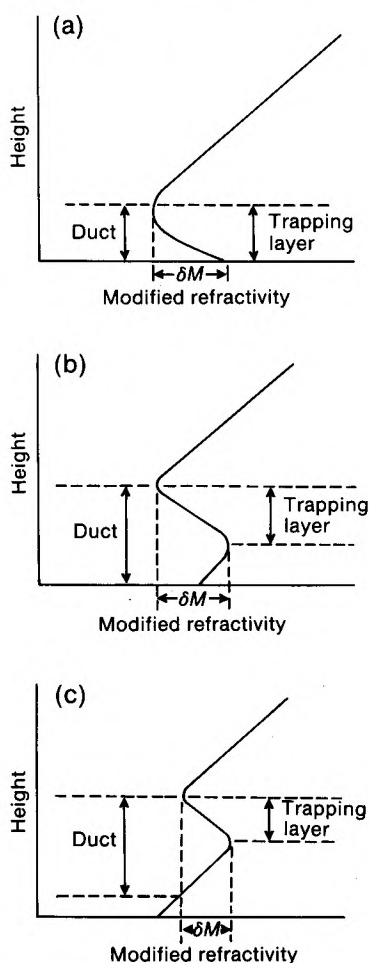


Figure 4. Typical modified refractivity (M) profiles for (a) simple surface duct, (b) surface S-shaped duct, and (c) elevated duct. The depth of the ducts and the trapping layers are indicated.

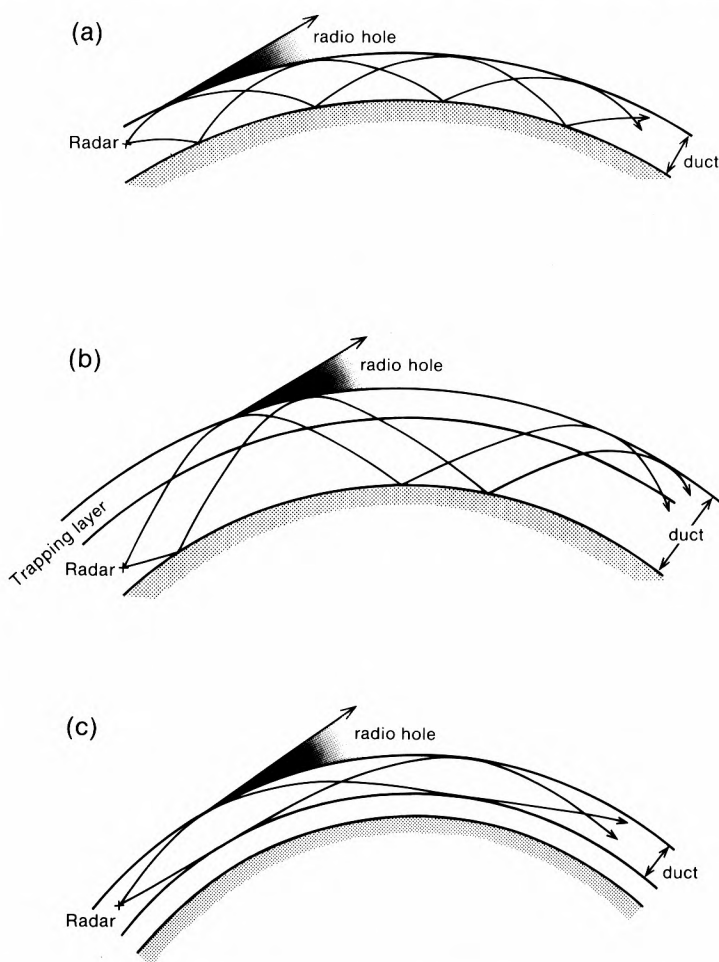


Figure 5. Typical radio propagation paths that occur in the presence of a (a) simple surface duct, (b) surface S-shaped duct, and (c) elevated duct.

be greatly reduced when there is little energy propagated into the region. Consequently the ability to forecast ducts and holes is of great importance to a wide variety of military operations.

2.3 Intensity of duct

The intensity, or strength, of a duct is given in terms of the maximum wavelength which is trapped by the duct. Using a simplified mode theory (Kerr 1951) gives the following expression for estimating the duct intensity:

$$\lambda_{\text{MAX}} = C \int_{z_L}^{z_U} (M(z) - M_U)^{1/2} dz \quad \dots \dots \dots (2)$$

when λ_{MAX} is the maximum wavelength (m) trapped by the duct, and z_U and z_L are the upper and lower limits of the duct; $C = 3.77 \times 10^{-3}$ for a surface-based duct and $C = 5.66 \times 10^{-3}$ for an elevated duct. This leads to the following expression for the duct intensity, assuming linear refractivity profiles in the trapping layer and for the layer beneath:

$$\lambda_{\text{MAX}} = (2C/3)[\delta M^{1/2}t + \{(\delta M^{3/2} - (M_L - M_U)^{3/2})(d-t)/(\delta M + M_U - M_L)\}]$$

where δM is the modified refractivity difference through the trapping layer ($\delta M = M_B - M_U$, where M_B is the modified refractivity at the base of the trapping layer), d is the depth of the duct (m) and t is the depth of the trapping layer (m). For both a simple surface duct and an elevated duct this expression simplifies to give

$$\lambda_{\text{MAX}} = 2Cd \delta M^{1/2}/3$$

as given by Hall (1979). Note the different values of C for surface-based and elevated ducts. For a simple surface duct and an elevated duct the intensity of the duct depends upon the change in refractivity through the trapping layer and the thickness of the duct.

Table I shows the maximum wavelength propagated for elevated ducts with various characteristics. A large value of λ_{MAX} means that the duct is strong because all shorter wavelengths are trapped.

Table I. The maximum wavelength λ_{MAX} in metres propagated by an elevated duct for given duct characteristics

Duct thickness d (m)	Values of δM (M units)			
	5	10	20	50
5	0.04	0.06	0.08	0.13
10	0.08	0.12	0.17	0.27
20	0.17	0.24	0.34	0.53
50	0.42	0.60	0.84	1.33
100	0.84	1.19	1.69	2.67

It should be noted that atmospheric ducts do not have a sharp cut-off wavelength above which waves will not propagate, but that the effects of ducting fall off gradually such that wavelengths longer than λ_{MAX} will still be affected by the duct to some extent.

In practice radio waves are often referred to in terms of their frequency f . The minimum frequency f_{MIN} (in Hz) which is trapped by a duct is given by

$$f_{\text{MIN}} = c/\lambda_{\text{MAX}},$$

where c is the propagation speed of the radio wave ($c = 3 \times 10^8 \text{ m s}^{-1}$).

3. Meteorological aspects of duct formation

It can be seen from equation (1) that the refractivity is a function of pressure, temperature and vapour pressure. The sensitivity of N to changes in these parameters can be investigated by partially differentiating equation (1). It can be shown that on most occasions the change of vapour pressure is the dominant term with a smaller contribution due to the change of temperature; pressure changes are the least important.

The meteorological conditions which lead to duct formation are the existence of a strong hydrolapse, and to a lesser extent the presence of a marked temperature inversion. There are five main types of meteorological processes where such conditions occur

- (a) evaporation over the sea,
- (b) anticyclonic subsidence,
- (c) subsidence at frontal surfaces,
- (d) nocturnal radiative cooling over land, and
- (e) advection.

In addition ducting can occur as the result of more localized effects, e.g. sea breezes and thunderstorm outflows.

3.1 *Evaporation ducts*

A shallow surface-based duct is frequently observed over the oceans and results from the large hydrolapse normally present immediately above the sea surface. The evaporation duct exhibits a geographical, seasonal and diurnal variation with greater depths at lower latitudes, during summer months and during daytime. For example, the mean duct depth over the North Sea is about 5 m, but is 10–14 m in the Mediterranean. It is primarily of interest to shipping and can be critical in naval operations, but also affects coastally sited radars.

Evaporation ducts may also form over land areas as a result of evaporation over wet surfaces after rain, or over lakes when steam fog is observed. However, land-based evaporation ducts are generally short-lived features.

3.2 *Ducts associated with anticyclonic subsidence*

The most common reason for the formation of elevated ducts in mid-latitudes is subsidence associated with anticyclones, where a temperature inversion is formed by the subsiding air. Depending on the strength of the hydrolapse, elevated ducts may form in association with the anticyclonic inversion. Usually such ducts form up to a height of about 3 km above the surface. In particular, when stratocumulus cloud forms in the boundary layer beneath an anticyclonic inversion it is usually characterized by a strong capping inversion and hydrolapse, and ducting might well be expected to result. Stratocumulus sheets are a very common feature around the British Isles and western Europe and the potential ducting could be important to low-level flying operations undertaken by the RAF. Semi-permanent areas of stratocumulus also occur in the subtropics, which could result in semi-permanent regions of ducting.

3.3 *Ducts associated with frontal systems*

The temperature inversion through a frontal zone is not usually associated with a marked change of refractivity as the moisture content of the air is higher in the warmer air above. However, layers of subsided air are often found beneath a frontal zone (especially in warm fronts), and can lead to the formation of elevated ducts which are generally found ahead of the rain belt in a warm front and behind it in a cold front. Such ducts are relatively transitory features.

3.4 *Ducts associated with nocturnal cooling over land*

Night-time radiative cooling of a land surface under clear skies leads to the formation of a temperature inversion, whilst dew deposition leads to an increase of humidity with height. Whether a duct forms will depend on whether the wind is sufficiently light to reduce the deposition of dew. Such conditions are often associated with the formation of radiation fog, and a duct may form during the early stages of the fog. However, as the fog thickens, the temperature inversion migrates to the fog top, where a negative hydrolapse may develop, thus weakening the duct.

3.5 *Advection ducts*

Advection ducts may form when warm, dry continental air passes over a cooler sea, thus cooling and moistening the lowest layers. This effect can reinforce a pre-existing evaporation duct and so increase its depth. Advection ducts are usually confined to within 100 km downwind of a lee shore. Such ducts are particularly important for coastally sited radars and to low-level coastal operations. Advection ducts are also sometimes observed when warm moist air is advected over a cooler sea, resulting in the formation of sea fog with a duct near the top of the fog.

4. Forecasting techniques

Forecasting the existence of ducts depends upon being able to predict the vertical profiles of temperature and humidity in the region of interest. This is achieved by a combination of conventional manual and modelling techniques.

4.1 *Conventional forecasting*

It is relatively straightforward to determine the refractivity profile from a tephigram. The main problem is in constructing a tephigram for the time and place of interest, and to assess the representativeness of the profile. N and M may be calculated from a tephigram either by using standard overlays or by using a simple program on a desk-top computer.

Fig. 6(a) shows part of a tephigram for the radiosonde ascent at Crawley at 0000 GMT on 13 August 1987. The modified refractivity (M) profile has been calculated from this ascent and is shown in Fig. 6(b). In this example a duct is found to exist from 889 mb down to 919 mb. At 900 mb a moist spike in the humidity profile due to the lag of the sensor is apparent. However, this feature makes no difference to the depth determined for the duct, although it should be accounted for in calculating the intensity (equation 2).

On occasions when the radiosonde data suggests the existence of a surface-based duct, this should be interpreted carefully as the low-level humidity measurements from the sonde are sometimes unreliable. Also there may be a mismatch between the surface observations and the sonde measurements near the surface. Consequently radiosonde data should be used with caution to infer the presence of surface-based ducts. In addition, when a sonde emerges from cloud, the lag in the humidity element means that the sharpness of the hydrolapse may be misrepresented. Also the temperature element may be subject to evaporative cooling. These effects should be taken into account when assessing ducting from radiosonde data.

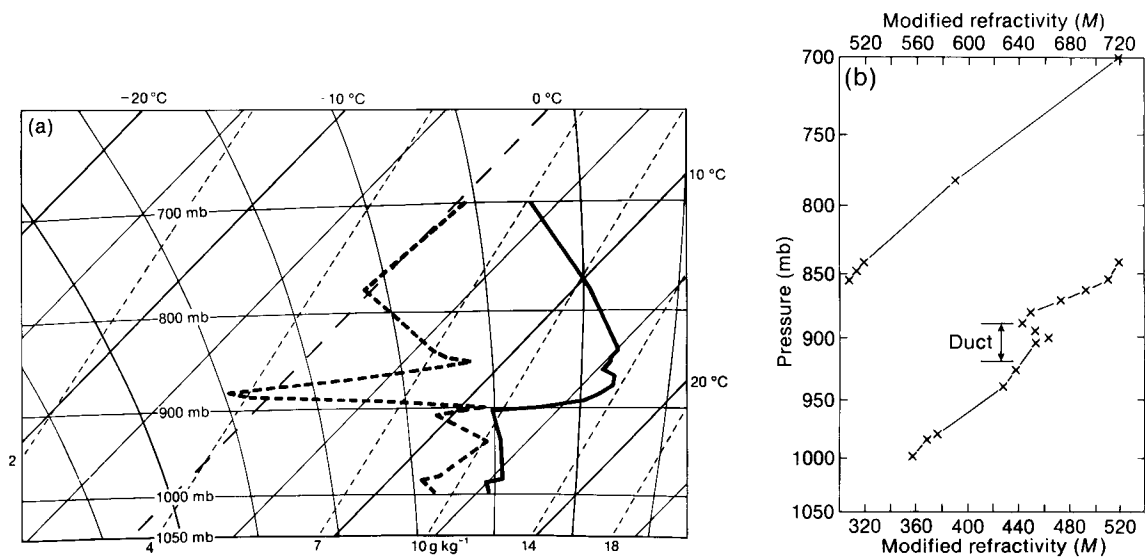


Figure 6. (a) Tephigram for the radiosonde ascent for Crawley at 0000 GMT on 13 August 1987, and (b) the modified refractivity (M) profile determined from the ascent.

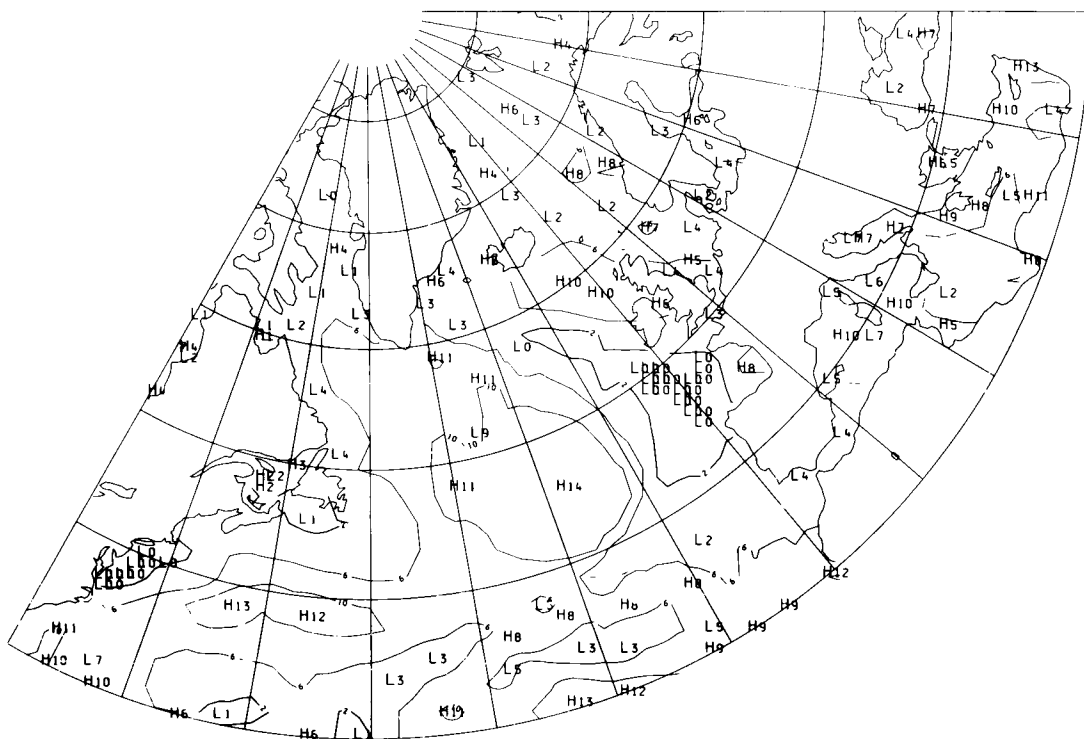


Figure 7. A fine-mesh model 24-hour forecast from 1200 GMT on 21 November 1986 of the evaporation-duct depth (m) over the North Atlantic.

4.2 *Modelling techniques*

Although numerical models can help identify the relevant air mass and give good guidance to the general synoptic development, they cannot provide vertical profiles of temperature and humidity to the accuracy required to predict ducts. This is due to three factors:

- (a) lack of vertical resolution,
- (b) the forecast humidity fields lack the necessary detail and accuracy, and
- (c) the boundary-layer parametrization is too simple to represent the evolution of the boundary layer with sufficient detail.

A comparison of fine-mesh model profiles with actual radiosonde data on occasions when ducts were known to be present shows that the model profiles do not represent the fine structure associated with the ducts. A possible solution to this problem is to use a method based on model output statistics. This approach is currently being investigated in the Special Investigations Branch of the Meteorological Office.

Numerical models are, however, able to provide forecasts of the evaporation duct over the sea. A simple model has been developed based on bulk aerodynamic formulae to estimate the surface fluxes of heat and water vapour, and using similarity theory to predict the low-level profiles of temperature and humidity. This model has been coupled to the fine-mesh model to produce forecasts of the evaporation duct over the sea. An example of the model output showing predicted duct depth is shown in Fig. 7. (A similar output for duct intensity, i.e. λ_{MAX} , is also produced.) The usefulness of these forecasts has been assessed by the Royal Navy, and they are to be produced routinely.

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An unusual example of freezing rain

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Summary

On 2 March 1987 a narrow band of freezing rain, probably no more than 30 km wide, occurred over northern areas of the Netherlands and the Federal Republic of Germany. At Gütersloh the freezing rain persisted for 9 hours, resulting in considerable damage to power and telephone lines, and especially to trees.

1. Synoptic situation.

A well-marked cold front, which had initially moved eastwards, returned slowly westwards through Gütersloh on 1 March. At 1800 GMT it was about 30 km south-west of Gütersloh and stationary. An active warm front was crossing Belgium from the west and by midnight there were signs that the two frontal zones were merging.

Fig. 1 shows the synoptic situation at 1200 GMT on 2 March 1987. It is no longer possible to distinguish between the two fronts at the surface over north Germany and they are shown as one warm front. Despite the ridge to the east collapsing, there was no sign of the front making any progress eastwards. Later in the day a depression moved south-eastwards over Germany, the front then moving away to the south-west.

Fig. 2 shows part of the radiosonde ascent from Fritzlar for 1100 GMT on 2 March 1987 with the warm 'nose' above a sub-freezing surface layer (the text-book conditions for freezing rain). Fritzlar is about 100 km south-east of Gütersloh and although colder at the surface it can be considered a representative ascent.

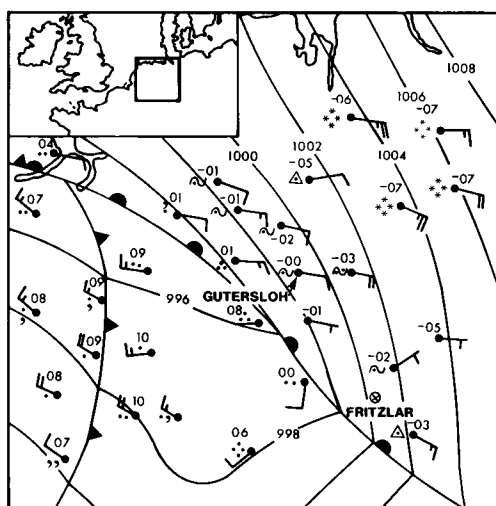


Figure 1. Synoptic situation at 1200 GMT on 2 March 1987 — the analysis from Gütersloh Meteorological Office. Observations show wind speed, temperature and present weather. Note that the observation approximately 90 km south of Gütersloh is from a high-level station, which was believed to be in the warm sector.



Some photographs showing the effects of the freezing rain at Gütersloh.

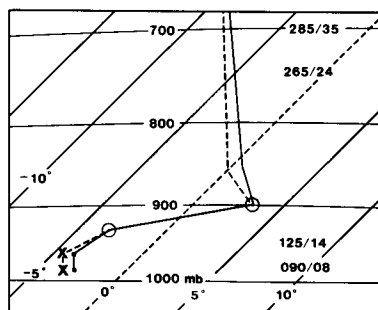


Figure 2. Part of the radiosonde ascent from Fritzlar at 1100 GMT on 2 March 1987; the location of Fritzlar is shown in Fig. 1.

2. Freezing rain and its effects.

Freezing rain is usually a transitory feature, occurring as warm air displaces a cold, continental air mass. This event is noteworthy because the freezing rain persisted for 9 hours at Gütersloh, despite the band of freezing rain being only about 30 km wide.

Rain began at Gütersloh at 2300 GMT on 1 March 1987 when the air temperature was 1.8 °C, and was continuous thereafter. Freezing rain commenced at 0600 GMT on 2 March with the air temperature hovering around zero and the grass temperature -0.2 °C. The rain was freezing on most surfaces, including the grass, but not on concrete or tarmac roads. After about 9 hours, the freezing rain gave way to snow, with the air temperature -2.2 °C. At 1800 GMT the grass temperature had fallen to -2.7 °C but solid ground surfaces were still wet. Skies cleared early on 3 March and there followed a period of cold, clear weather.

While the freezing rain caused considerable damage to telephone and power lines the main victims were the trees. Within two hours of the onset twigs and small branches were snapped off and, as the deposits grew, countless trees were brought down or damaged under the weight of ice. A local British Forces school project found that, in one example, the weight of ice on a twig was six times the weight of the twig itself. For some weeks the authorities were cutting down trees that were in a dangerous state or damaged beyond recovery. Silver birch were particularly prone to damage, bending double under the immense weight with their tops touching the ground. They then froze in this position and stayed that way even after the thaw which followed several days later.

3. Conclusion

Freezing rain, while not unknown, is rare over western Europe and is nearly always a transitory feature; this occurrence over north Germany was unusual in that it was so prolonged — local inhabitants with memories going back over 50 years could not recall having seen anything like it before.

The event illustrates vividly not only the ability of cold continental air to persist at the surface, despite the apparent encroachment of warm air, but also the marked difference between the cooling rates of grass and solid surfaces. This latter property is well known, but in this case it was surprising that after nine hours of freezing rain, with sub-zero temperatures, roads and paths were still wet, whilst most other surfaces were covered in ice.

Acknowledgements

The authors would like to express their thanks to S. Thompson of the Meteorological Office Gütersloh for his assistance with the diagrams and to the Photographic Section, RAF Gütersloh for providing the photographs.

Notes and News

Retirement of Mr D.M. Houghton

Mr D.M. Houghton, Assistant Director in charge of Marketing Services, retired from the Meteorological Office on 7 June 1988.

David Maurice Houghton joined the Office in September 1951 after studying physics at the University of Manchester, and postgraduate meteorology at Imperial College, London. He had no sooner completed the Scientific Officers Course at Stanmore than he was invited to meet his national service obligations. He elected to take a Short Service Commission in the Instructor Branch of the Royal Navy where, not surprisingly, he was given forecasting duties. During his three-year spell he opened a forecasting office at RNAS Yeovilton, where one remains in being to the present.

After a short period in the Long-range Forecasting Branch at Dunstable on his return to the Office, which resulted in a paper in this magazine on heat sources and sinks, David was promoted to Senior Scientific Officer and soon found himself in the Director-General's Office where he took part in the international work of the day as a UK delegate to the Third Congress of the World Meteorological Organization and as Secretary to the Conference of Commonwealth Meteorologists, both held in 1959. The next step was a move into forecasting, first on the upper-air bench in the Central Forecasting Office (CFO) at Dunstable and later, following the move of CFO to Bracknell, as a senior forecaster and Principal Scientific Officer. David remained in CFO until 1970 and established a reputation there for being a very sound, if sometimes adventurous, forecaster who was always on top of the situation and always up-to-speed with his work. His personal qualities fitted him particularly well for the senior forecaster post and he showed himself to be a natural leader, energetic, unshakeably good-humoured and enthusiastic. The period in CFO spanned the introduction into the forecaster's armoury of operational numerical weather-prediction products and of satellite picture analysis, and David was chosen to open discussions at the Royal Meteorological Society and in the Office on the topics of synoptic analysis and the use of satellite data.

During 1970 he was selected for the Joint Services Staff College, No. 39 Course at Latimer and later took up the post of Deputy Chief Meteorological Officer at Headquarters, Strike Command, High Wycombe, with the responsibility there of managing the Principal Forecasting Office. However, as a result of his abilities in staff management and an interest in his fellow men, he was moved again, after two years, into the Personnel Management Branch at Bracknell where he was given charge of recruiting, career management and overseas matters. At this time the Fulton concepts in management were being introduced to the Office and it fell to David to bring in the new job appraisal review system and to see through the programme of training associated with it. This called for a great deal of hard work and a degree of personal commitment to the aims of the programme which were not necessarily shared by all with whom he came into contact at the time. The system, however, came to stay and handsomely justified both itself and David's original faith in it.

The next appointment, in 1975, as Head of the London Weather Centre was tailor-made for David Houghton's talents. He was untiring in the promotion of its services. The Office was coming increasingly under pressure to recover the costs from its clients in industry of services that had acquired a high technology base and whose value in commercial terms was becoming increasingly appreciated by them. Notable were those in the offshore industry amongst whom David was personally active. The repayment income grew by leaps and bounds. His stock was high, too, at the BBC where he was seen as the harbinger of changing Office attitudes in the areas of radio and television presentation. Acceptance that the attention of the audience might best be held by more informal and less stereotyped styles was in sight!

The London Weather Centre had long been noted for its *esprit de corps* and the pride it took in its work but under David it acquired a bright professional image as well.

The promotion in 1977 to Senior Principal Scientific Officer came as no surprise, but the posting to Head of the Synoptic Climatology Branch, a research unit committed to the pioneering of long-range forecasting techniques, was a little unexpected. With typical resilience David set about the rationalization and streamlining of the experimental long-range forecasting procedures and he encouraged firms that might have the capacity to exploit somewhat slender margins of success to take a commercial interest in the results. This work was not without its rewards for him but he left it in 1981 to return to staff management work as Assistant Director in charge of the Personnel Management Branch. Again, perhaps, this would not have been a posting of his choosing but he tackled it with his customary diligence making his mark with management, unions and staff alike.

When, in response to the recommendations of the Rayner Resource Control Review, a Marketing Services Branch was set up in 1984 for the benefit of the commercial services of the Office as a whole, David Houghton was the natural choice as leader. He is a true marketing man, ever watchful for fresh commercial opportunities and enjoying the cut and thrust of negotiation with commercial contacts. In the course of his work, both at this time and previously at the London Weather Centre, he has set out to change Office attitudes, often being impeded by bureaucratic procedures. Disappointment or discouragement has never lasted long, however, and at the end of the day it is the system that has yielded. He leaves a very well found Branch that has taught the Office, amongst other things, the principles of marketing, how to use consultants in its commercial work, and how to face up to the discipline of market planning.

David's promotion of meteorology has not been confined to the Office and he has played a very full part in the work of the Royal Meteorological Society as a Member of its Council and of several of its committees. His interest in sailing led him to propose to the Society that it should include as part of its Field Study programme a course on Weather and Sailing. He organized and ran, as well as providing one of the two sets of lectures, the first very successful Field Study Courses at Falmouth in 1962 and was responsible for their repetition over the following eight years. Through these courses David's expertise became recognized by the Royal Yachting Association (RYA) and he was co-opted as instructor and adviser to successive British Olympic Yachting teams beginning in 1968. He is currently engaged in preparations for sailing races to be held in Korea. The Olympic involvement led Edward Heath, when he was Prime Minister and Captain of the British Admiral's Cup team, to seek David's services for that event, too. He has also been in demand for America's Cup preparations. He was awarded the Fitzroy Prize for Applied Meteorology by the Royal Meteorological Society in 1973.

In 1963 David joined the Editorial Board of the Royal Meteorological Society's *Weather* and when he relinquished this task in 1969 he was launched upon a career as author which has gained him increasing recognition, not least amongst the sea-going fraternity. The seeds were sown perhaps in his *New Scientist* article (with John Woods as co-author) on the Slippery Seas of Acapulco and the 50-page booklet *Weather Forecasts* written for the RYA, also in 1969. Other books have been *Weather* in the Jonathan Cape Jackdaw series (1971), *The Weathermen* in Gunn and Co's Wider Interest Series (1972), *Weather at Sea* (British version, 1986), *Wind Strategy* (Fernhurst Books, 1984) and, to be published, an American edition of *Weather at Sea* written with co-author Fred Sanders. David has also been on the Editing Committee of the Royal Meteorological Society's *Journal of Climatology* since 1980.

A further hat that David has worn has been that of Press Officer for the Meteorological Office. In his many contacts with the media over the years he has shown himself to be a consummate spokesman whether on radio or television.

One might think that amidst all this endeavour David's family life might have suffered. Not a bit. His wife, Verna, whom he married in 1955, is a practising doctor of medicine. They have four children at ages

ranging from 18 to 30. Those who have visited them over the years recall manifestations of David's skill in carpentry, plumbing, electrical installation, decorating and gardening. A few years ago Verna and David rather astutely acquired a riverside mansion at Wargrave, then in need of renovation. They plan to continue to live after David's retirement (in some style) at Wargrave Court. David has a number of irons in the fire for the future. He will leave a very empty office at Bracknell behind him but, one suspects, his family will scarcely notice the change. The armchair and slippers are a very long way off.

D.H. Johnson

Correspondence

551.553.6:003

Comments on 'Exceptionally strong winds of 16 October 1987 over the south of England'

The Advisory Services Branch's article (*Meteorol Mag*, 116, 389–390) is a very sloppy presentation. The table of wind speeds, which is the crux of the article, does not say:

- (a) Whether the mean speed is a 15-second, 10-minute or 1-hour mean. Hence valueless.
- (b) Whether the approximate return period is an all-year or October figure. Hence valueless.

The relationship between the Gatwick return periods for mean wind and gust seems to be wildly inconsistent with other return periods, although it may well be correct.

Generally, wind speeds were not out of the way. The 1952 Cranwell gust exceeded all the tabulated values and yet no damage was caused there to buildings or trees. The critical additional factors which caused the havoc in October — and not mentioned in the article — were the exceptionally wet ground (which reduced anchorage) and the fact that trees were in leaf, hence increased drag coefficient. Practically all the damage and disruption was caused by trees falling on roads, power lines. Without that damage the storm would have passed virtually unnoticed.

A. Blackham

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Reply by G.P. Northcott

Because of the need to respond quickly to the demand for publication of interesting wind data it was not made clear that the winds in question were synoptic (10-minute) winds and that the return periods were computed from annual data. This information was clear in the original preliminary report produced by the Advisory Services Branch but unfortunately was inadvertently omitted from the abridged version published in the *Meteorological Magazine*.

The present anemometer site at Gatwick (dating from 1983) is somewhat sheltered, especially from the south-east quadrant, and this is probably the reason for the anomalously low mean wind speed, although gust values were similar to those generally occurring over south-east England.

G.P. Northcott

Advisory Services Branch
Bracknell, Berkshire

Gorleston wind speeds October 1987

When wind charts were received at Bracknell after the storm of 16 October 1987 it was known that the Gorleston direction trace was defective because the vane had been vandalized about a month earlier. The speed trace was accepted as read, however, and quoted in official reports on the storm in the *Meteorological Magazine*, *Weather* and elsewhere. Subsequently it was discovered that the cups were also damaged and were bent downwards by 45 degrees.

Accordingly the anemometer head was removed and sent to the Operational Instrumentation Branch of the Meteorological Office, where tests in the wind-tunnel showed that the speed was over-registering by about 20% at most levels. The revised assessment of the highest wind speeds at Gorleston gives a mean of 54 kn (not 68 kn) and the highest gust of 85 kn (not 106 kn). These corrected values will be published in due course in the back-page corrections for Table 6 in the *Monthly Weather Report*.

G.P. Northcott

*Advisory Services Branch
Bracknell, Berkshire*

Reviews

General circulation of the ocean, edited by H.D.I. Abarbanel and W.R. Young. 170 mm × 248 mm, pp. xii + 291, *illus.* New York, Berlin, Heidelberg, London, Paris, Tokyo, Springer-Verlag, 1987. Price DM 160.00.

The collected articles in this book are based on lectures which were presented at the Scripps Institution of Oceanography in 1983, by speakers who are well-known in the fields of physical and dynamical oceanography. I found each of the five contributions enjoyable and instructive in various ways; Pedlosky, Veronis and Young concentrated on their own particular areas of research, while Niiler and Hendershott gave broad overviews. The specialized material has lost its original 'hot off the press' immediacy, but this is compensated by the careful presentation, and many of the pointers to future developments remain valid today.

As stated in the introduction, the aim is to give 'viewpoints of the essential dynamics of the general circulation', as applied to our understanding of the average, basin-scale state of the oceans. These viewpoints contain a lot of theory, with good reason; the sparseness of observations, particularly direct current measurements (especially at depth), means that dynamical theories are needed both to understand the available data and to fill in the substantial gaps in a rational way. Given hydrographic data (relatively plentiful), currents can be calculated from 'thermal wind' relative to some baseline. That elusive reference level, virtually an oceanographer's Holy Grail, is a recurrent theme in the book.

The opening lecture by Niiler is a well-illustrated development of such links between observations and dynamics. The few equations will be recognized by meteorologists, being based on the thermal wind and the β -plane. For oceanographers, this chapter is a useful reminder of basic ideas closely tied to observations.

Although Hendershott's article is the last in the book, it is logically the next to read as it offers a good summary of the development of circulation theories. It is textbook in style and content, with derivations of quasi-geostrophy etc. The classical steady theories are described in turn; the mathematics gets quite dense on some pages (and observational links correspondingly sparse), but diagrams make the results clear. Rossby waves are briefly reviewed, including a tropical mention. Ocean boundaries have crucial effects, so equations familiar to meteorologists have unfamiliar solutions!

The first of the specialist articles concentrates on an (as yet) unsolved problem; what determines the density structure of the ocean, particularly the thermocline? Pedlosky gives the reader a very useful overview and commentary on some of the main theories, old (late 1950s) and new. Due to density advection the general thermocline problem is fundamentally non-linear — even simple-seeming relations lead to daunting equations. With a layered approach (of which Pedlosky is a founder), interesting solutions are presented that are readily understandable and that offer considerable insight. New papers on this topic appear regularly; I shall be using this lecture as an excellent reminder of the basic assumptions and techniques.

The reference-level problem is directly addressed by Veronis, who describes various procedures for determining the circulation from observations, including the difficulties posed by data noise and sparseness. The pitfalls and ambiguities associated with various assumptions (and some are always needed) are made clear. Some specific, instructive, examples are provided. The mathematical load is lighter here, apart from a carefully explained excursion into matrix algebra.

The chapter on baroclinic theories is a return to idealized theories, in what amounts to a guidebook on two-layer quasi-geostrophic flow (see the contents list!). Basic equations are derived (there is considerable overlap between chapters in this regard) and a succession of examples used to illustrate the role of potential vorticity contours. In certain 'unblocked' regions inviscid flow is not uniquely determined and dissipation is needed to resolve the ambiguity — in this treatment, dissipation is related to mesoscale eddies which thus influence the large-scale circulation. Young gives, in some detail, a rationale for the hypothesis that the effect of eddies is to make potential vorticity uniform in unblocked regions: this idea is supported by some observational and numerical-model evidence. This new approach offers a way of calculating large-scale circulation with eddies taken into account.

Overall, this collection of articles, well produced and illustrated, takes the reader to the leading edge of ocean circulation theory, while keeping sight of observational facts and limitations. My chief regret is that there was no way to somehow bridge the gap between the time of the lectures and the year of publication.

I expect that meteorologists would find Niiler's contribution the most useful and the easiest to assimilate: the remainder is rather too specialized to recommend individual purchase for general reading. For the dynamical oceanographer — highly recommended.

M.K. Davey

The weather of the 1780s over Europe, by J. Kington. 212 mm × 303 mm, pp. x + 164, *illus.* Cambridge University Press, 1988. Price £35.00, \$70.00.

This very interesting volume presents daily synoptic maps of mean-sea-level pressure over Europe and the adjacent seas from 1781 to 1785. Analysis of the years 1786–90 is yet to be completed. The author begins by describing the sources of data, which are surprisingly plentiful, and gives a brief account of the development of the understanding of synoptic meteorology in recent centuries. There is next a description of the reduction and plotting of the data, and of the analysis procedures, which include considerations of synoptic continuity. The maps themselves cover 120 pages. Following these is a chapter describing the classification of the daily fields into H.H. Lamb's weather types and into the Grosswetterlagen (weather types). These classifications are used to compare the atmospheric circulation in the period from 1781 to 1785 with that in more recent times.

There are some shortcomings in the areas of quality control and subjectivity. In chapter 4 there is no discussion of the treatment of suspect values in the data from the observing stations. The author has clearly taken wise steps in the selection of the more reliable data by, for example, using observations around the middle of the day, thus avoiding frost-hollow effects and highly ageostrophic night-time winds, but there is no indication of any allowance for sea-breeze effects at near-coastal stations. Furthermore, has the author adjusted the mean-sea-level pressure data to standard (45° N) gravity? This adjustment would be about +1 mb at 60° N.

The attractively produced maps could have been interpreted more readily if the locations of pressure and wind data had been marked, preferably with separate symbols, though it would have been impracticable to have plotted the data themselves. As the maps stand at present, the reader cannot be sure how well founded they are, especially over the ocean and near the edges of the analysed area, though the use of continuity from chart to chart is good. For future work, an objective analysis scheme could also be considered, and applied not only to some of the fields of data for the 1780s but also to data for recent times, limited to a station network corresponding to that available for the 1780s. The latter analyses can then be compared with maps based on the full modern network; this comparison can then be used to assess the reliability of the objective analyses for the 1780s and, to some extent, the reliability of the subjective analyses published in this book.

Subjectivity is an inherent feature of the Lamb and Grosswetterlagen classifications, and the book would have benefited from inclusion of objective classifications, based on values at particular locations or grid points, both for the 1780s and for modern times, so as to confirm any differences in atmospheric circulation characteristics. The author should have discussed the apparent divergence between the indications of the Lamb classifications and the Grosswetterlagen classifications for 1781–85. The former, according to his results, suggest more frequent blocking or non-progressive situations in comparison with more recent times. The latter (Table 6.20) are ambiguous in this respect. Furthermore, this reviewer examined the charts classified as Lamb's 'north-westerly' and considers that 7 (5%) of them are better classed as 'westerly'. This difference would not significantly affect the overall results in Table 6.13 and 6.14 but suggests that the subjective classifications, which are useful in that they relate to well-known published schemes, should be replicated by several independent analysts.

The author could have indicated how the 1781–85 curve in Fig. 6.2 compares with individual 5-year periods from 1861 onwards, e.g. did any of these have maxima of blocking in March and December? Both Figs 6.1 and 6.2 could usefully be updated in the forthcoming volume.

Better omitted could have been the section on sunspot-blocking relationships — the record may be too short to establish these properly. The author does not indicate whether the apparent relationship has applied since 1950. A further point, incidental to the volume, is that though (page 2) man-made warming is likely to result from increasing concentrations of carbon dioxide and other 'greenhouse' gases in the atmosphere, industrially produced heat is expected to have a much smaller effect on the globe as a whole.

The volume is well presented and will be of interest to local as well as national and international historians. It is also a useful contribution to research into climatic variations and the causes and characteristics of the 'Little Ice Age', though its usefulness in this area is somewhat limited by the lack of objective tests of the analyses and classifications, and by the incomplete presentation of the quality controls carried out. The book makes enjoyable, fascinating reading. The publication of the charts for 1786–90 is awaited with interest — in that volume the author could usefully make his treatment more complete.

D.E. Parker

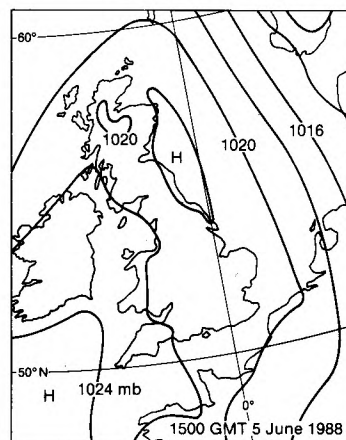
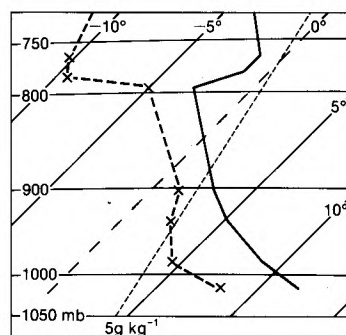
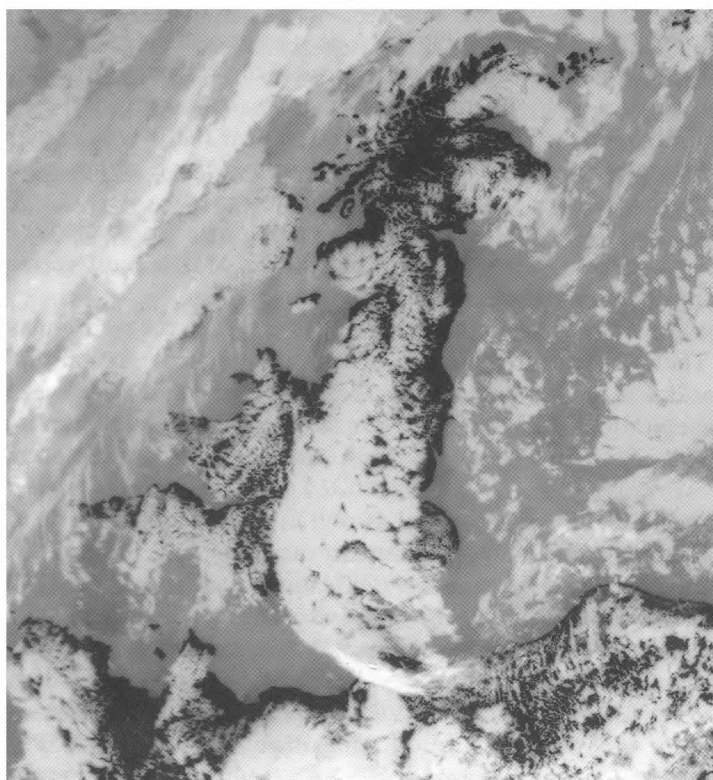
Satellite photograph — 5 June 1988 at 1427 GMT

This infra-red image was taken when the British Isles lay within a shallow ridge of high pressure at the end of a cold, unstable spell of weather. By 5 June some subsidence had occurred, resulting in the convection top being constrained by an inversion. The midday Aughton (near Liverpool) radiosonde ascent, representative of the air over England and Wales, suggests the cloud top to be within a layer of sub-freezing temperatures at about 2000 m above sea level.

The convective cloud, seen mostly over the land, has generally spread out into areas of stratocumulus, especially over Ireland and south-east Britain. Convective cloud which developed over Scotland the previous day drifted southwards overnight, partially dissipating. Renewed convection due to surface heating on the day of the photograph enhanced this pre-existing cloud area now located over south-east Britain on the picture. The sharp western boundary lay along the west coast of Scotland the previous day.

Over England and Wales, a northerly airflow is suggested by the imagery since north facing coasts are generally cloud free (the air being stable to the sea temperature), and where the cloud remains broken, it is organized into north-south bands. Over Ireland, where winds were very light, cloud terminates close to the coast, and even Lough Neagh is cloud free (best seen in visible image — not shown). The more general cloud over western Ireland is ahead of an advancing warm front.

Dry air over the Highlands of Scotland (relative humidity as low as 40%) probably inhibited general cloud formation.



Photograph by courtesy of University of Dundee.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

Severe weather in Greece
Rainfall comparison
Analysis differences
Joint Mesoscale Centre

September 1988

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THE METEOROLOGICAL MAGAZINE

No. 1394, September 1988, Vol. 117

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The extremely severe local weather in northern Greece on 21 July 1983

N.G. Prezerakos and T. Petroliagis

National Meteorological Service, Athens, Greece

Summary

A description is given of a detailed investigation of the wind storm (*bourini*) which hit the northern and central parts of Greece, particularly the coasts of Macedonia, Thessaly and the city of Thessaloniki, on the evening of 21 July 1983. It is concluded that the wind storm was due to an interaction of local and synoptic-scale meteorological factors.

1. Introduction

One of the most serious problems facing Meteorological Services is the precise forecasting, in space and time, of severe local weather phenomena. This problem has not yet been solved despite recent technological and scientific progress and the effort which has gone into improving the observation, diagnosis and prediction of mesoscale weather systems.

Diagnostic studies are an effective way of understanding the physical and dynamical processes which affect the occurrence and severity of severe local weather phenomena, though such studies have tended to be made as part of the investigation of the larger-scale atmospheric circulation. There has been an enormous increase in the number of diagnostic studies, and much of this work has been pioneered by Fujita in the USA and Browning in the United Kingdom.

Here consideration is given to the diagnosis of an exceptionally severe wind storm which occurred suddenly in Macedonia (the central part of northern Greece) on the evening of 21 July 1983. The storm mainly affected the coasts of Macedonia and Thessaly where the winds reached 80 kn, though less severe winds stretched from the islands of the northern Aegean to Samos in the south (see Fig. 1). In the vicinity of Thessaloniki the storm was particularly severe and the daily newspapers reported the following loss of life and damage:

- (a) Nine people were drowned along the coast of Thessaly and the gulf of Thessaloniki.
- (b) A large number of fishing boats were damaged.
- (c) Many roofs were destroyed.
- (d) Electrical services were interrupted with the result that many people were trapped in elevators.
- (e) Telephone services were interrupted.

Sudden wind storms associated with thunderstorms which occur on the coast of Greece are called '*bourini*' by Greek sailors (Giles *et al.* 1985). Such winds do not appear often in Greece. Consequently

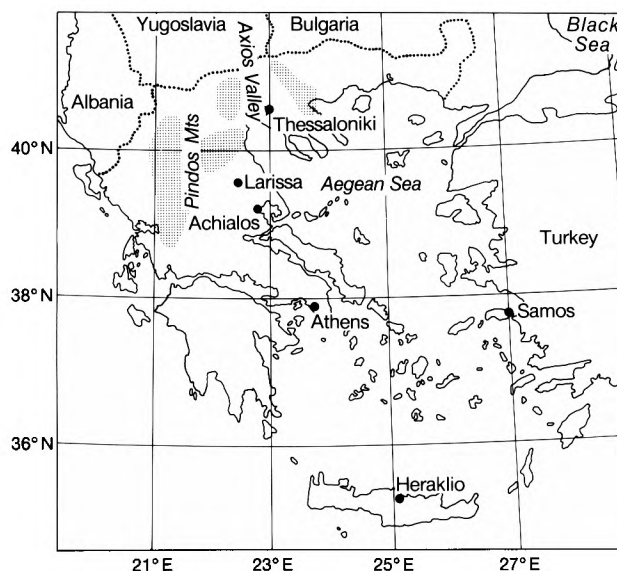


Figure 1. Places and geographical features referred to in this study.

this storm was considered to be a phenomenon of great meteorological importance, the accurate diagnosis of which would contribute towards a better understanding of the physical and dynamical processes which produced a storm of such rare strength.

The diagnostic study described here was based on the following data:

- (a) Surface and upper-air observations in the area 30°N – 65°N , 20°W – 40°E from the Global Telecommunication System.
- (b) All the observations from the synoptic, aeronautic and climatological stations in Greece.
- (c) The autographic records (pressure, moisture and temperature) from eight synoptic stations.
- (d) Imagery from the NOAA-6 and NOAA-8 satellites.
- (e) Relative geostrophic vorticity and its advection calculated from the ECMWF initialized analyses.

It is impossible to describe all the material studied in this investigation; however, a brief account of the main features is given.

2. Synoptic-scale evolution

2.1 Synoptic situation

At 0000 GMT on 21 July 1983 a ridge dominated the upper-air flow over the central parts of the Mediterranean and north Africa, while central Europe was dominated by a deep low (Fig. 2(a)). South-west of this low there was a region of strong north-westerly flow with cyclonic curvature. In the vicinity of the maximum winds there was a well formed trough. Also there was an associated baroclinic zone at all levels above 700 hPa, though below this level the flow was from the north-west without there appearing to be a trough in either the height or thermal fields. East of the Alps there was a slow-moving cold front (Fig. 2(b)). As it moved southwards there was a rise in pressure behind the front and a ridge of high pressure formed. In the vicinity of the cold front sporadic thunderstorms appeared; these were mainly ahead of the ridge.

Twelve hours later at 1200 GMT the thermal trough at 300 hPa had strengthened while further north a cold pool had formed (Fig. 3(a)). At this time Greece lay in the south-western part of a diffluent trough

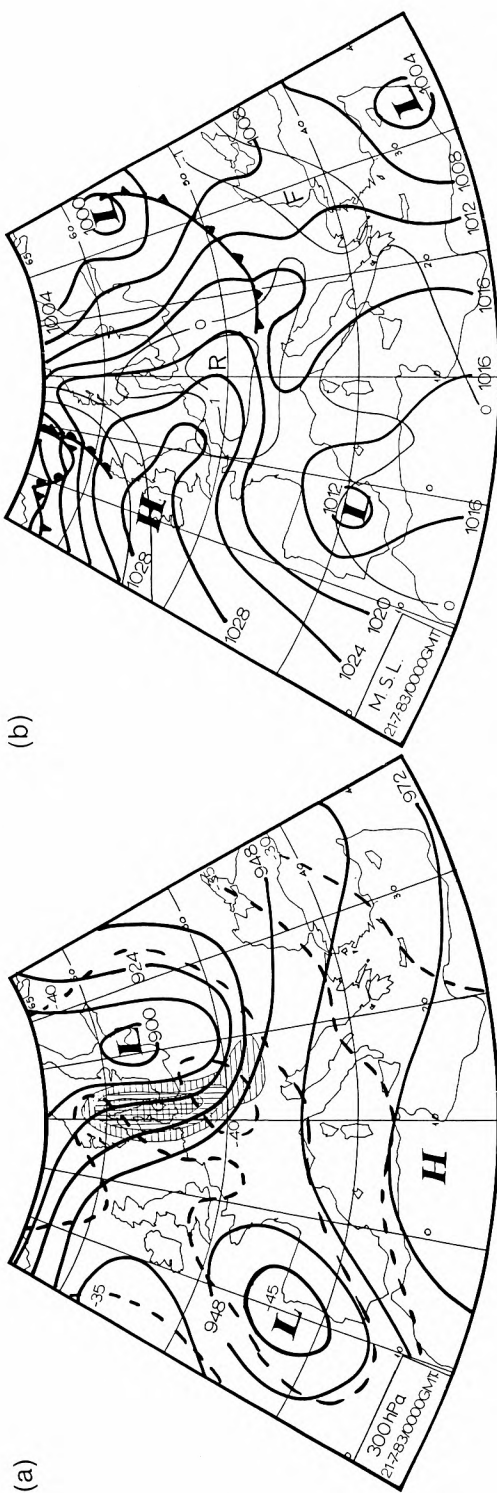


Figure 2. Subjective analyses at 0000 GMT on 21 July 1983. (a) 300 hPa surface: continuous thick lines are contours (dam) and dashed lines are isotherms ($^{\circ}\text{C}$); wind speed ranges 60–80 kn, 80–100 kn and 100–120 kn are indicated by horizontal, vertical and cross hatching respectively. (b) Surface pressure: thick lines are mean-sea-level isobars (hPa) and thin lines are isallobars (hPa per 3 hours); R and F indicate centres of rising and falling pressure.

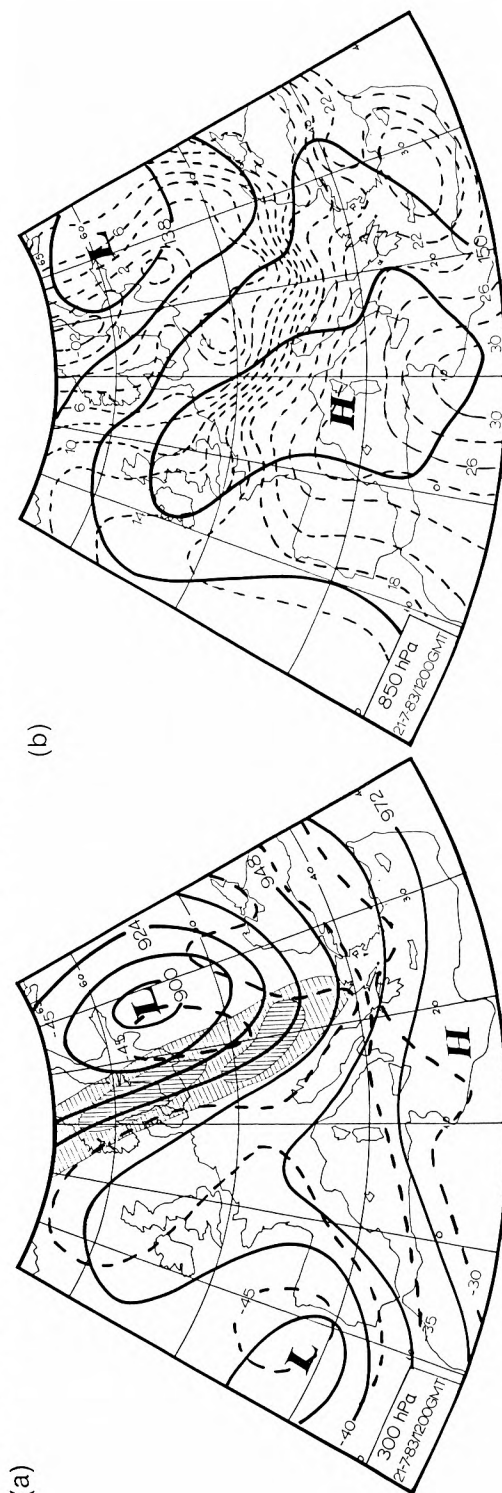


Figure 3. Subjective analyses at 1200 GMT on 21 July 1983 for (a) 300 hPa surface and (b) 850 hPa surface (notation as in Fig. 2(a)).

with strong north-westerlies in the north-west of Greece. Also note that in the Thessaloniki region there was an extension of the thermal trough which showed a relatively small-scale outbreak in the upper troposphere — this increased the static instability in the area. The 850 hPa isotherms over the northern Balkans were orientated west-east and were closely packed — thus indicating the presence of a strong low-level front (Fig. 3(b)). In the vicinity of the cold front it was overcast with a covering of middle-level cloud. However, there were significant amounts of cumuliform clouds and some showers, though there were no thunderstorms reported. The temperatures ahead of the front were well above normal for the season while behind the cold front the temperatures were lower than usual.

As the front accelerated and swept over Greece (Fig. 4) in the afternoon of 21 July, thunderstorms were reported by some stations behind the front though the winds remained at less than 25 kn. There was nothing reported by the synoptic stations to indicate the severity of the phenomena that occurred in the vicinity of Thessaloniki between 1400 and 1800 GMT (1700 to 2100 Local Civilian Time).

At 0000 GMT on 22 July the flow at upper levels, especially at 300 hPa, had still not changed significantly, though a small trough had passed over northern Greece (Fig. 5(a)). At the surface the front was situated over Turkey and the central Aegean (Fig. 5(b)). In Turkey showers and thunderstorms were observed, but in Greece the shallow cold front did not produce any precipitation.

Shallow cold fronts often appear in Greece during the summer months, especially in July and August, and their passage is associated with the commencement of the etesian winds — the well known summer north-easterlies (Constantacopoulos 1959, Metaxas 1971, Prezerakos 1978). These fronts come from the north and are modified over northern Greece. The subtropical jet stream which controls the circulation in the lower stratosphere and upper troposphere (above 500 hPa) in the region is usually situated over Greece during the summer. Thus when a front reaches Greece the subtropical jet stream prevents the cold air from advecting southwards above 500 hPa. In consequence there is no upward extension of the front, and the cold advection and the front are limited to the lower troposphere with the prevalence of descending synoptic-scale motion. Because of this, rainfall and thunderstorms occur only in northern Greece where there is still some ascent associated with the front. In the central and southern parts of the Greek mainland, where the upward extension of the front has been limited, only relatively cold northerly winds appear (Prezerakos 1978).

2.2 Synoptic-scale factors which contributed to the occurrence of the storm

The dominant feature on the morning of 21 July 1983 was the slow-moving cold front over the northern Balkans with an associated strong baroclinic zone in the lower troposphere (the intense packing of the 850 hPa isotherms (Fig. 3(b)) is remarkable).

As the cold front strengthened and moved southwards, a vorticity maximum which was apparent in the upper troposphere must also have contributed to the subsequent developments. At 1200 GMT the vorticity maximum was situated north of Greece causing positive relative vorticity advection towards the northern Balkans, mainly in the region of the cold front, while over Greece there was positive advection at 500 hPa but not yet at 300 hPa (Fig. 6).

The upper flow clearly indicated that after 1200 GMT the positive vorticity advection should strengthen in the vicinity of the cold front and move towards Greece mainly in the east of the Pindos, a mountain range on the western Greek mainland and orientated north-south (see Fig. 1). Anyway, while the main positive vorticity advection and main cold front were situated over the western coast of the Black Sea, the front was especially intensive along its southern edge in the eastern Pindos because a secondary vorticity maximum existed at the 500 and 300 hPa levels along the northern borders of Greece. This indicates that a small wave had developed in the north-western flow west of the main trough; the shape of the cloud over Thessaloniki indicates the presence of this secondary vorticity maximum. The cold front appeared to have its greatest movement between 1500 and 2100 GMT. While

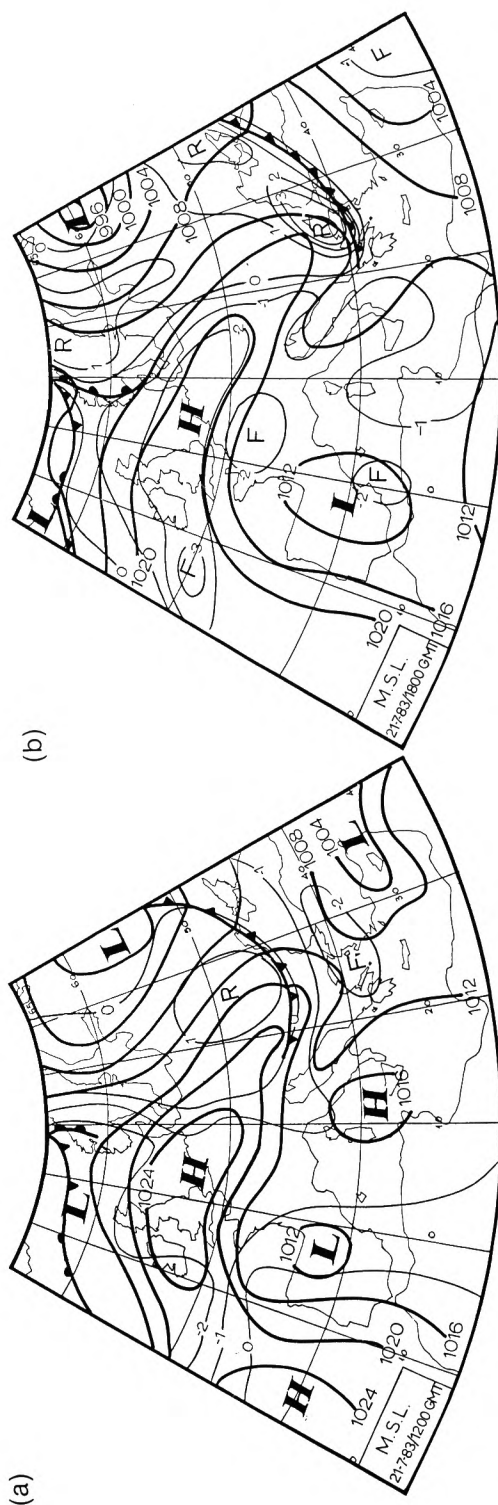


Figure 4. Subjective analyses of surface pressure at (a) 1200 GMT and (b) 1800 GMT on 21 July 1983 (notation as in Fig. 2(b)).

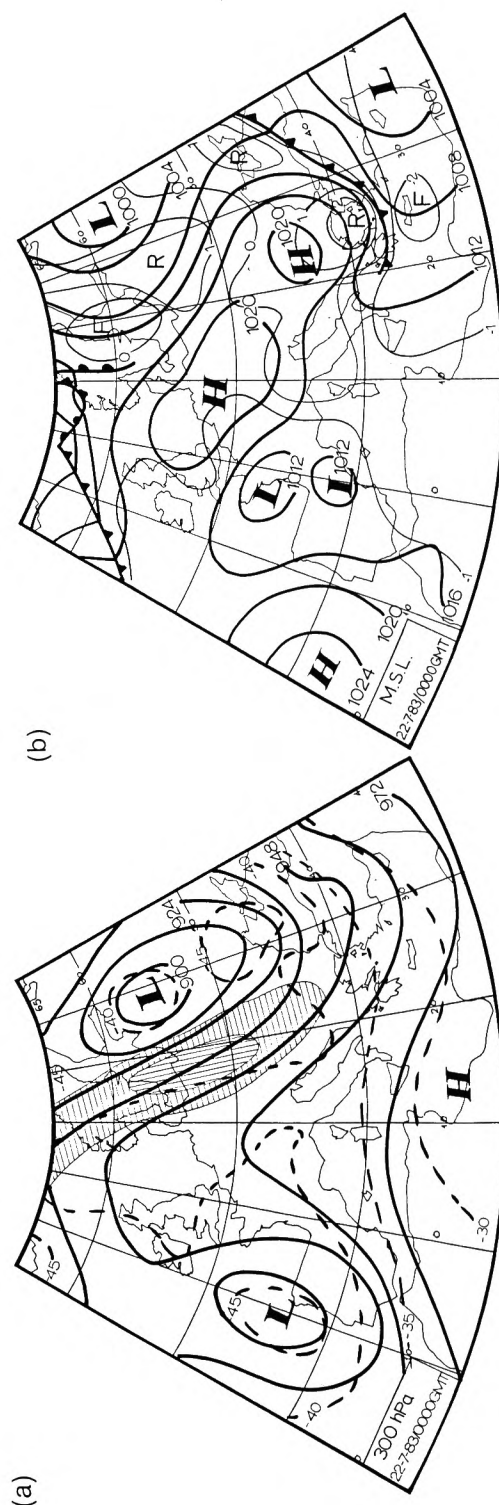


Figure 5. As Fig. 2 but for 0000 GMT on 22 July 1983.

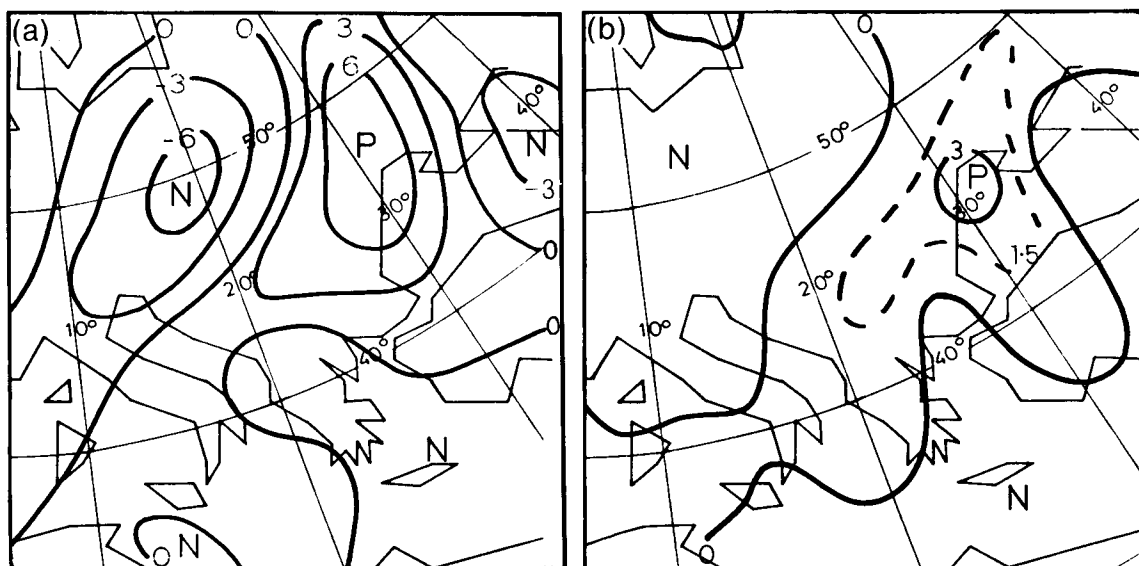


Figure 6. Objective analyses of geostrophic relative vorticity advection (10^{-9} s^{-2}) at (a) 300 hPa and (b) 500 hPa calculated from the ECMWF initialized analyses for 1200 GMT on 21 July 1983. N indicates negative and P positive advection.

the front moved southwards, the secondary vorticity maximum moved towards Turkey across the Aegean. This behaviour is illustrated by the two satellite images given in Fig. 7 and the next one taken at 0120 GMT on 22 July which is not shown here. (Fig. 7(b) also shows that at 1700 GMT the main frontal action appeared to be limited to east of the Pindos and that the Thessaloniki area was on the south-western extremity of the frontal cloud.)

3. Investigation of the problem on the mesoscale

Trying to investigate the wind storm with only the synoptic observations indicates that these observations are unsatisfactory for the study of something which is basically a mesoscale phenomenon. Thus it is necessary to have available precise observations on a smaller space scale and time-scale than the usual synoptic observations. Such observations, however, are lacking in Greece.

In order to overcome this obstacle, a selection of observations has been made which, in a broad sense, can be considered as belonging to a smaller scale than the synoptic one. These observations are mainly those from the aeronautic stations and records from autographic instruments. Also the temperature, humidity and wind profiles can provide small-scale information.

3.1 A detailed study of the weather

Fig. 8 has been prepared from aeronautic observations. It illustrates the situation when the weather phenomena accompanying the *bourini* (strong winds, fall of temperature, rainfall) appeared, and their variation in space and time.

Mikra Airport, situated 15 km from the centre of Thessaloniki, is the most northern of the three stations displayed and it was here that the *bourini* occurred with its greatest strength. At 1450 GMT the surface pressure started to show an anomalous variation and there were 15 kn winds from the north-west. Also the temperature was decreasing and reached its minimum value at 1650 GMT. At this time the

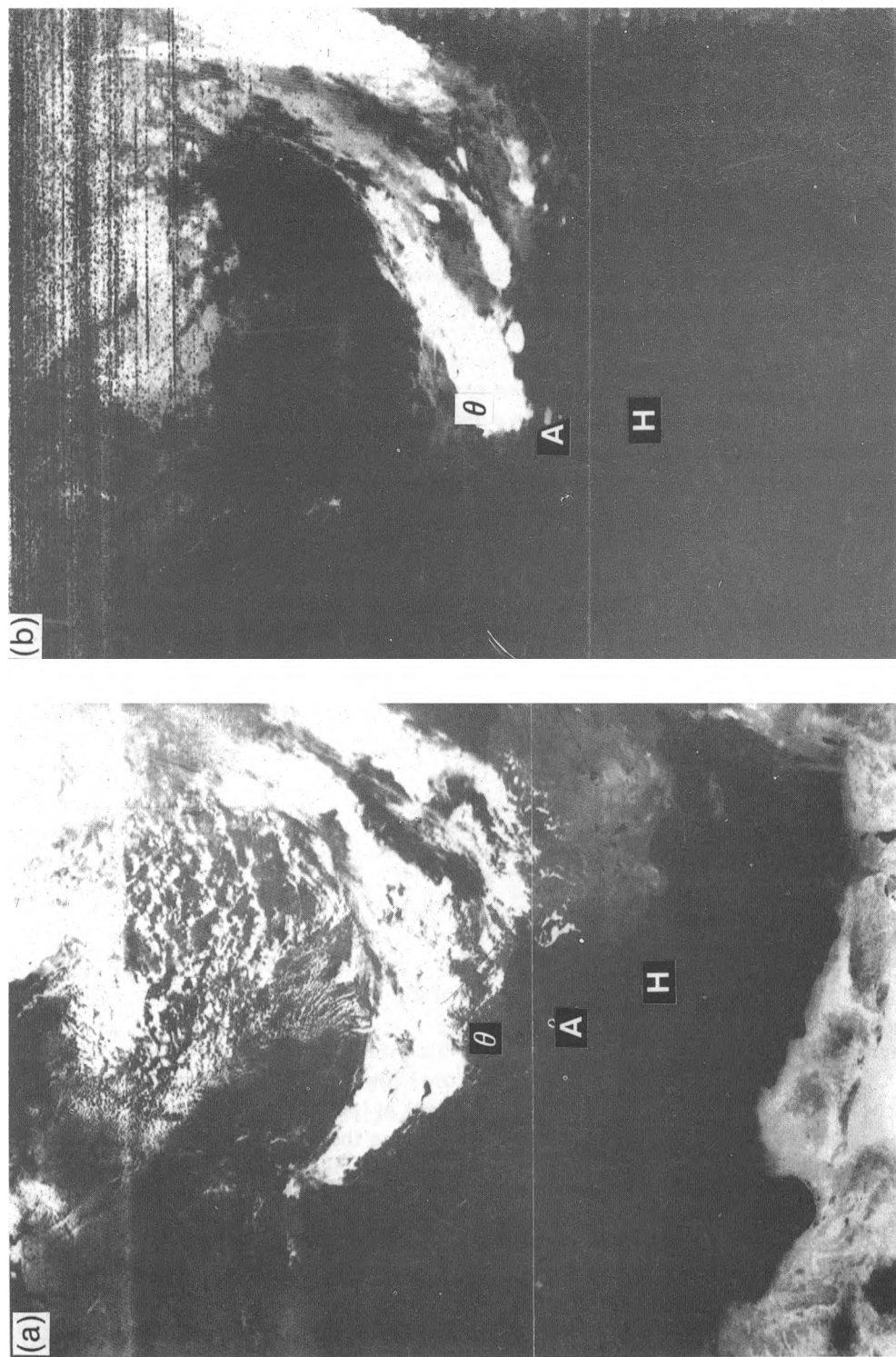


Figure 7. (a) Visible imagery from NOAA-6 received at 1320 GMT on 21 July and (b) infra-red imagery from NOAA-8 received at 1700 GMT on 21 July 1983.
 θ — Thessaloniki, A — Athens and H — Heraklio.

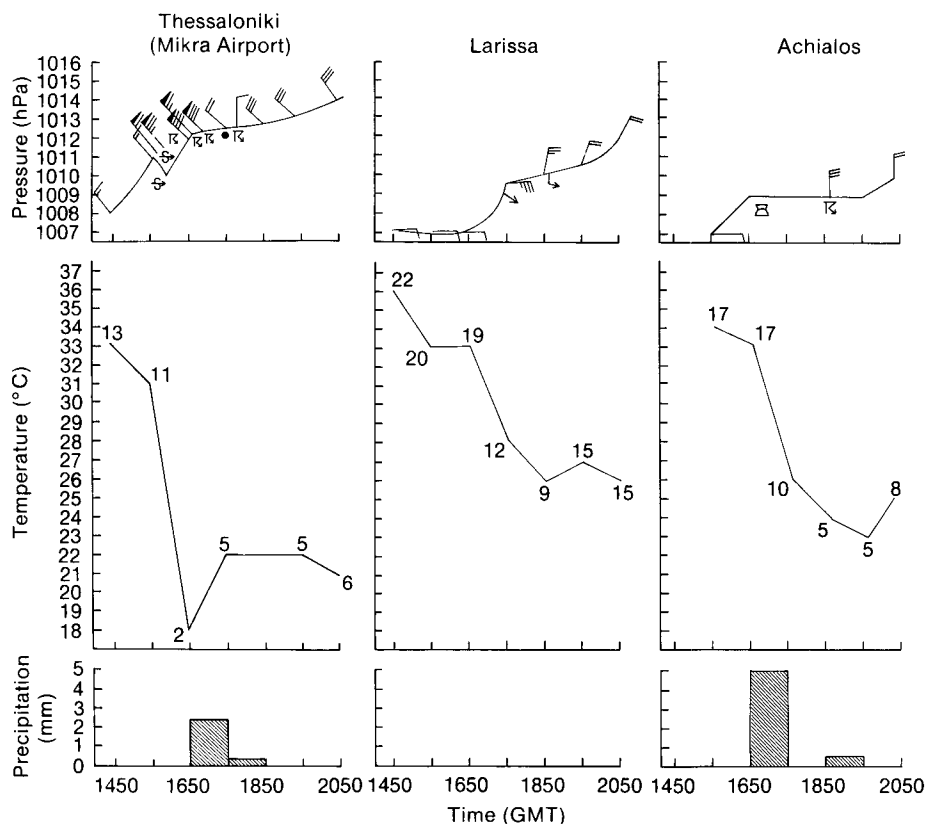


Figure 8. Time section based on aeronautic observations of pressure, wind (kn), temperature, dew-point depression, precipitation and significant weather at three stations in almost a straight line orientated north-south. The numbers plotted on the temperature lines are the dew-point depressions (°C) and the significant weather is indicated by ☁ for lightning, ☁ for thunderstorm, ☁ for cumulonimbus ● for rain and ☁ for wind storm.

relative humidity reached a maximum as a result of the decrease in temperature and commencement of the rain. By 1615 GMT the wind had reached 55 kn with gusts to 65 kn. Around 1700 GMT mature thunderstorms appeared over Thessaloniki accompanied by lightning, strong winds, high humidity and low temperature.

The autographic records show the same as already described but in greater detail as far as time is concerned. One interesting feature that the pressure record showed was that the pressure was decreasing until 1450 GMT and then increased suddenly showing a peak at 1600 GMT. Then the pressure decreased irregularly producing a local minimum at 1630 GMT before there was another sudden increase at 1700 GMT. At this time, according to the aeronautic observations, the thunderstorm was at the zenith of its mature stage. The first increase could have been the pressure jump in advance of an approaching thunderstorm which, in this case, could have been the trigger for the release of the latent instability in the Thessaloniki region (see Tepper 1950). The second increase in the pressure could have been due to the first gusts from the new thunderstorm which developed over Thessaloniki.

From the aeronautic observations and the autographic records it appears that the thunderstorm occurred at Mikra Airport around 1650 GMT when it started raining. The thunderstorm remained until

1850 GMT having its greatest strength during the period 1700 to 1720 GMT. During the same period the rainfall reached its highest rate, the temperature reached its lowest value and the wind speed reached 80 kn (though high speeds occurred from 1615 to 1730 GMT).

The observations from the other stations (see Fig. 1) given in Fig. 8 present almost the same variations in pressure, temperature and humidity, but the variations are neither as sudden or as intense as at Thessaloniki. The significant point is that from the moment when the storm occurred at Thessaloniki the strong winds spread out into the whole region of eastern Thessaly and the northern Aegean Sea.

3.2 Factors influencing the location of the storm

It is interesting to consider why such a strong wind storm developed in the region of Thessaloniki but not further south.

Thunderstorms occur when there is conditional instability and some trigger to release the instability causing the boundary-layer air to ascend to the level of free convection. On 20 July, although there was conditional instability, no thunderstorms appeared because there was no thermal or dynamical trigger.

On 21 July the lower troposphere, in comparison with that of the previous day, was warmed to above 730 hPa whereas there was a sudden cooling of the troposphere above this level — the result was a significant increase in the conditional instability. Thus, on the 1200 GMT tephigram from Mikra Airport (Fig. 9) there is a large area of conditional instability with a convective temperature of 35.7 °C; the maximum temperature which occurred at 1500 GMT was only 34.0 °C. However, at the University

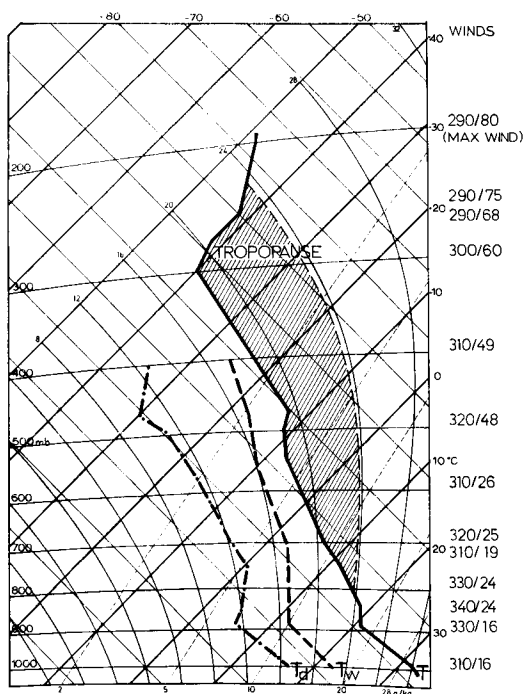


Figure 9. The sounding from Thessaloniki (Mikra Airport) at 1200 GMT on 21 July 1983. The continuous line is the temperature, the dot-dash line the dew-point and the dashed line the wet-bulb temperature. The hatched area is the positive area of the conditional instability. The direction (degrees) and speed (kn) of the winds are given for standard and significant levels.

of Thessaloniki situated in the city, the maximum temperature was 36.3°C at 1300 GMT and the convective temperature was reached at 1130 GMT (assuming that the convective temperature at the university and the airport was the same). Thus for the city of Thessaloniki there was an apparent thermal reason for the release of the conditional instability after 1300 GMT because the convective condensation level almost coincided with the lifting condensation level. However, there was no thermal reason for the release of the instability near the airport.

It is likely that the basic reason for the release of the instability in the Thessaloniki region was the high speed of the approaching cold front and/or a pressure jump which was associated with the thunderstorms accompanying the cold front as it crossed the Balkans towards northern Greece.

Just before the arrival of the cold front, the air in the Axios valley (see Fig. 1) just north-west of Thessaloniki, and further south in the region of the city and the airport, was dry with humidities of about 40% up to 800 hPa. The wedge of cold air behind the front passed through the Axios valley after having released the instability which resulted in new cumulonimbus cells. The thunderstorms occurred over the airport of Thessaloniki at 1700 GMT. At the same time the rain and downdraughts lowered the temperature to 24°C , whereas until 1615 GMT, when the very strong winds started blowing, the air reaching Thessaloniki was warm air which had stagnated in the Axios valley ahead of the cold front. This front, though almost stationary between 0600 and 1200 GMT, moved southwards at 42 kn during the following 9 hours (Fig. 10).

It may be concluded that the combination of the conditional instability in the region of Thessaloniki and the passage of the rapidly moving cold front (which coincided with the period of maximum instability) caused the thunderstorms over Thessaloniki. Also, because of the low humidity, the main feature was the wind rather than the precipitation. The passage of the cold front further south did not result in the same effects because the instability was much less.

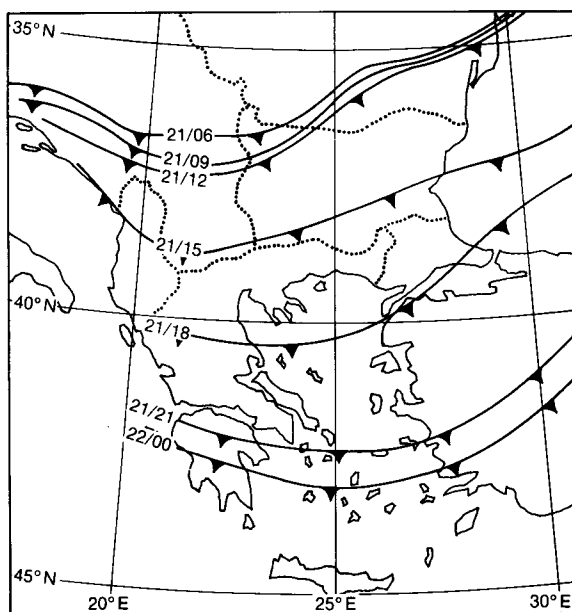


Figure 10. Continuity chart for the position of the cold front from 0600 GMT on 21 July to 0000 GMT on 22 July 1983.

4. Conclusions

This diagnostic study of the *bourini* which occurred in the evening of 21 July 1983 showed that the *bourini* was the result of the interaction of a number of synoptic and local factors. The local factors were responsible for the kind and severity of the weather which accompanied the *bourini*, while synoptic factors were responsible for triggering it.

The main meteorological features on 21 July which emerged from the study are as follows:

- (a) Over the southern Balkans during the morning the air in the lower troposphere was warm and relatively dry. However, the air in the coastal regions was more moist.
- (b) In the region of the Alps and further east there was a strong baroclinic zone in the lower troposphere which began moving southwards just before noon.
- (c) Along the northern edge of the stationary baroclinic zone there was a vorticity maximum moving southwards. Just before noon the maximum arrived above the baroclinic zone and changed it into a strong cold front which moved southwards.
- (d) In comparison with the preceding days, the lower troposphere was warmer and the upper parts colder. This resulted in a great deal of conditional instability.
- (e) In the city of Thessaloniki the maximum temperature was greater than the convective temperature, while in the surrounding countryside it was slightly lower. This meant that a thunderstorm was more likely in Thessaloniki even without the appearance of the cold front.
- (f) The rapidly moving cold front arrived at Thessaloniki just after the time the temperature reached its maximum value. This was responsible for the sudden large ascent in the lower troposphere which forced the air up to the level of free convection and the development of severe thunderstorms.
- (g) As the cold front moved southwards it was accompanied by the usual thunderstorms. The associated gust front could have affected the unstable air which was downstream (Tepper 1950). Thus the *bourini* may have been triggered by the gust front as well as the synoptic-scale vertical motions accompanying the cold front.
- (h) The strong winds were due to the sudden increase in pressure behind the cold front and to the channelling of the Axios valley. However, the gusts up to 80 kn were basically due to the strong downbursts from the thunderstorm. The small amount of precipitation which accompanied the *bourini* was due to the lack of sufficient humidity.

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A comparison of radar and gauge measurements of rainfall over Wales in October 1987

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Summary

Comparisons are made of radar and gauge measurements of rainfall totals over Wales and nearby areas for the period 14 to 19 October 1987. Up to distances of about 130 km from the Cleve Hill radar the radar-measured rainfall amounts are mainly within one half to twice the rainfall measured by co-located gauges, but beyond this distance the radar increasingly underestimates the gauge rainfall.

1. Introduction

The weather of mid-October 1987 in England and Wales was dominated by an area of low pressure to the west of the United Kingdom with active secondary depressions moving in from the south-west.

In central Wales heavy rainfall occurred on the evening of 14 October as a depression moved from the Bay of Biscay to the North Sea. This was followed by further heavy rain in the same area from a depression travelling north-east across central England during the early hours of 16 October. This depression also brought destructive gales to many areas of southern and eastern England. Thundery showers and a near-stationary front to the west of Wales brought yet more rain to this area during the weekend of 17 and 18 October. Flooding occurred in many parts of central Wales following this prolonged period of rainfall (14 to 19 October) with totals greater than 100 mm in many places.

In this paper a comparison of rainfalls for this period over Wales and nearby areas as recorded by gauges and radar is presented.

2. Rainfall observations

2.1 From gauges

Both the climatological network of densely distributed gauges and the synoptic network of sparsely distributed gauges were used in this comparison. The synoptic gauges provide daily 09 to 09 GMT rainfall total observations which are reported in near real-time and are a subset of the climatological daily gauges whose observations are not available until several months after the event.

2.2 From radar

Radar observations are provided by the PARAGON radar data-processing system (May 1988). Those used in this comparison were derived from rainfall intensity data recorded every 5 minutes at the Cleve Hill (see Fig. 1) radar installation in Shropshire. These intensity measurements are integrated to give 09 to 09 GMT rainfall totals averaged over 5 km \times 5 km squares. The off-line single-site PARAGON radar data are of a quality similar to the composited on-line intensity data that are available every 15 minutes to weather forecasters and hydrologists.

All UK radar data have two types of correction applied on site in real time (Collier 1986). These are:

- (a) a calibration which varies with rainfall type and locality, optimized within a range of about 100 km from the radar and derived from observations from a few interrogable gauges, and
- (b) a long-range correction, mainly effective beyond 100 km, independent of rainfall type and direction from the radar, which is intended to compensate for the loss of radar sensitivity due to the

beam not detecting rain-producing clouds; this as a result of the curvature of the earth and other effects.

The radar data used here showed the presence of 'spokes' of apparently smaller rainfalls radiating from the position of the radar; these are spurious and are caused by the partial occultation of the radar beam by obstructions. Data suspected of being affected in this way were omitted from the comparison.

3. Comparison of gauge and radar rainfall totals

An objective analysis of rainfall totals from the climatological gauges for the 5-day period 09 GMT on 14 October to 09 GMT on 19 October is shown in Fig. 1. A background field of average annual rainfall was used to improve the detail in some areas, mainly over high ground.

Large totals were recorded in many parts of Wales with a maximum of 268.0 mm at Waen Sychlwch in south Powys. Smaller maxima of 173.5 mm and 164.3 mm were observed at Llydaw Intake in Snowdonia, and at Nevern in the south-west respectively. The totals decreased rapidly to about 50 mm along the Wales-England border (and to about 20 mm in central England).

Fig. 2 shows the corresponding map of 5-day totals derived from radar data from PARAGON. Generally, similar patterns were observed by radar and gauges, for instance the large rainfalls over the high ground in central south Wales, although the maxima in the south-west and over Snowdonia in Fig. 1 are absent from Fig. 2.

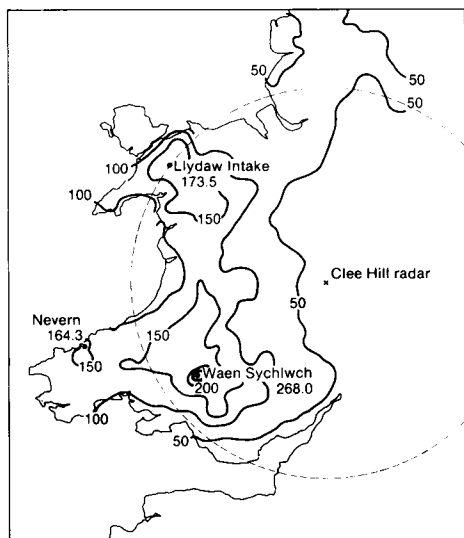


Figure 1. Rainfall field (mm) for the period 09 GMT on 14 October to 09 GMT on 19 October 1987 based on observations from the climatological daily gauge network. Dashed line shows 130 km radius of Clew Hill radar.

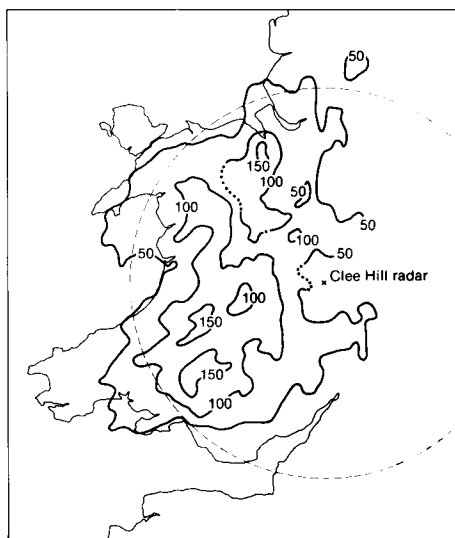


Figure 2. Rainfall field (mm) for the same period as Fig. 1 based on observations from the Clew Hill radar. Dotted lines indicate where data were contaminated by occultation. Dashed line shows 130 km radius of Clew Hill radar.

A more detailed comparison was carried out between co-located synoptic daily gauge and radar rainfalls, both being accumulated automatically during the routine operation of PARAGON. Five-day total radar rainfalls for 5 km × 5 km squares centred on the gauges were estimated by linear interpolation within the 5-day totals for the surrounding squares. These were used to calculate r/g (the assessment factor AF) at each gauge location (where r and g are the radar and gauge rainfalls respectively). In Fig. 3 the AFs of large rainfall over Wales and surrounding areas are plotted at the gauge locations with smooth contours being drawn by eye. These AFs show values slightly greater than

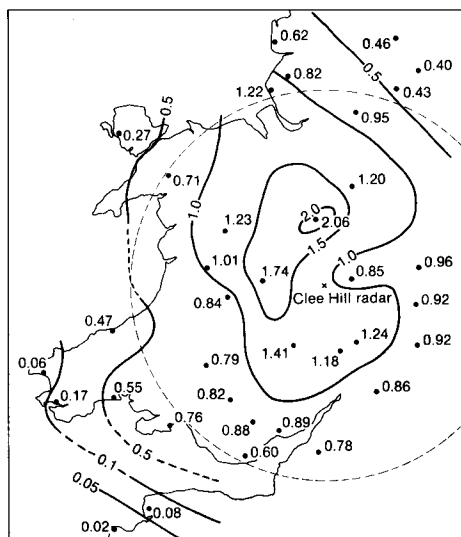


Figure 3. Assessment factor (see text) field for the same period as Fig. 1, determined from synoptic daily gauge observations. Dashed line shows 130 km radius of Cleve Hill radar.

1.0 close to the radar with an area of values greater than 1.5 to the north-west. In general the AFs decrease with distance in any direction. In Fig. 4 the AFs are plotted as a function of distance from Cleve Hill. The majority of the AFs are within the range 0.5 to 2.0 for distances less than 130 km but decrease smoothly and rapidly beyond this distance. The scatter of the AFs in Fig. 4 is not related to rainfall amount and this is supported by a comparison of the location of areas of large AF and large rainfall in Fig. 3 and Fig. 1. Although there is a component of variability in AF, due to the ratios being of area to point rainfalls, this is unlikely to be large for the small rainfall total gradients encountered here and does not appear to conceal the variation of AF with location and distance from Cleve Hill.

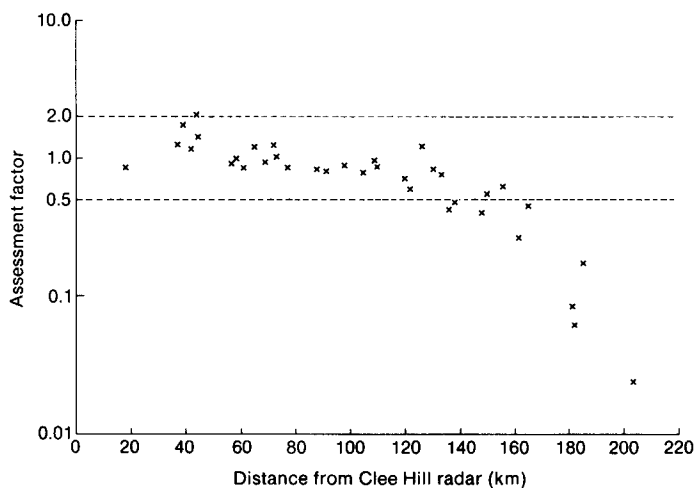


Figure 4. Variation with distance from Cleve Hill radar of assessment factor (see text) for the same period as Fig. 1.

In practice, in England and Wales few areas are more than 130 km from the closest radar (and the number of these areas will diminish as further radars are installed) so the loss of sensitivity is not a problem except for some regions around the edge of the total radar coverage. In PARAGON the daily synoptic gauge observations are used to adjust further the radar data to help remove errors remaining after the on-site calibration and long-range correction are applied. This is done by constructing the spatial field of daily adjustment factor g/r (the inverse of AF) and applying it to the radar daily total field (see May 1988 for an example of this process).

4. Conclusion

Within 100 km from Clee Hill the on-site calibration has been effective in keeping radar totals to within one half to twice the gauge-measured ones. However, it is apparent that the long-range correction applied primarily to improve the 15-minute intensity data for operational use is not effective beyond a range of 130 km for time-integrated data for the rainfall types encountered in this period. This comparison indicates that for such rainfall intensities radar can be used to provide rainfall totals of sufficient accuracy for many operational purposes.

5. References

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The impact of analysis differences on a medium-range forecast

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Summary

This case-study of a medium-range forecast highlights the sensitivity of numerical model forecasts to the initial conditions and shows how relatively minor analysis differences grow rapidly and progress. The reasons for the differing evolution of the operational Meteorological Office and ECMWF global models are examined using a variety of techniques. Further tests using a revised version of the Meteorological Office analysis scheme are also presented.

1. Introduction

The sensitivity of medium-range forecasts to initial conditions is well known (e.g. Hollingsworth *et al.* 1985). The forecasters in the Central Forecasting Office at Bracknell have access to the products of several numerical weather prediction centres, in addition to those produced by the Meteorological Office model, and are often faced with forecasts showing different evolutions. Clearly the differences can result either from differing initial conditions or from the different model formulations. We have examined in some detail six cases which occurred during the autumn/winter of 1985/86 where the Meteorological Office operational forecasts disagreed significantly with those from ECMWF. Here just one of these case-studies is presented.

The basic technique for comparing operational forecasts from the two centres involves running the ECMWF model from an interpolated Meteorological Office analysis, and running the Meteorological Office model from an interpolated ECMWF analysis. This enables us to ascertain the relative

importance of the different initial conditions and model formulations for a particular case. We have found that in most instances similar forecasts are produced from both models when using the same analysis. Also a transplant technique has been used to isolate a particular geographical area where one analysis might be deficient; this involves the replacement of a portion of one analysis by a portion of another analysis. No consistent difference between the analyses has been found but the technique has enabled us to identify cases which are sensitive to initial conditions, and has proved useful in developing new analysis algorithms.

Throughout the discussion presented here, the forecasts will be identified by analysis and model. Therefore UK/UK indicates a Meteorological Office analysis followed by a forecast from the Meteorological Office model and EC/EC an ECMWF analysis followed by a forecast from the ECMWF model; EC/UK and UK/EC represent the cross comparisons. The forecasts are from a data time of 12 GMT on 8 January 1986. Fields other than 500 mb heights were examined (e.g. surface pressure, 1000–500 thicknesses, 250 mb heights and winds), but the 500 mb fields illustrated here highlight the evolution differences best. Further details about this case* are given in Downton and Bell (1988).

2. The observed and forecast developments

2.1 *The observed developments*

The Meteorological Office analysis showed that at 12 GMT on 8 January 1986, upper vortices were centred over Arctic Canada and just south of Greenland with a strong mid-latitude upper westerly flow extending from the Pacific across the United States to the eastern Atlantic. This was poised to break down a temporary block that had developed over Scandinavia during the previous two days. By midday on the 9th an upper ridge crossed the United Kingdom ahead of the deepening vortex which was still to the south of Greenland. This vortex had moved east 24 hours later to be just to the south of Iceland, with a strong south-westerly flow over the United Kingdom.

The sequence was almost repeated during the next 72 hours (see Fig. 1). The deep upper low to the north of Scotland on the 11th filled and moved east into the Baltic. Another intense development took place as an upper trough, which had been moving east across the United States, moved into the Atlantic on the 12th. By 12 GMT on the 13th this trough had developed into a vortex which was situated to the south of Iceland.

2.2 *Comparison of the forecasts*

A careful comparison of the operational forecasts from the Meteorological Office and ECMWF was made. Figs 2(a) and 2(b) show the 500 mb UK/UK and EC/EC forecasts at day 5, with Fig 1(c) the verification chart. Clearly there are considerable differences between the forecasts. Overall the EC/EC forecast is better than the UK/UK one. The two cross runs, UK/EC and EC/UK forecasts, at day 5 are given at Figs 2(c) and 2(d).

Comparison of all four runs indicates a similarity in each pair of forecasts from the same analysis. Clearly not all the difference between the two operational forecasts can be explained by the analysis differences, but the analysis differences seem to be giving a dominant signal. In order to avoid confusing any model differences with the analysis signal, it is preferable to examine the UK/UK and EC/UK forecasts to try to understand the failure of the operational UK/UK forecast. This procedure may result in a loss of detail from the ECMWF analysis due to interpolation, but the similarity in the forecast in this and other cases indicates that this is not of great importance. The evolution of these forecasts was

* This case was used as an example of the interpretation of numerical forecast products at the Meteorological Office Summer School on 'Diagnosis of Numerical Weather Prediction Products', 6–10 July 1987.

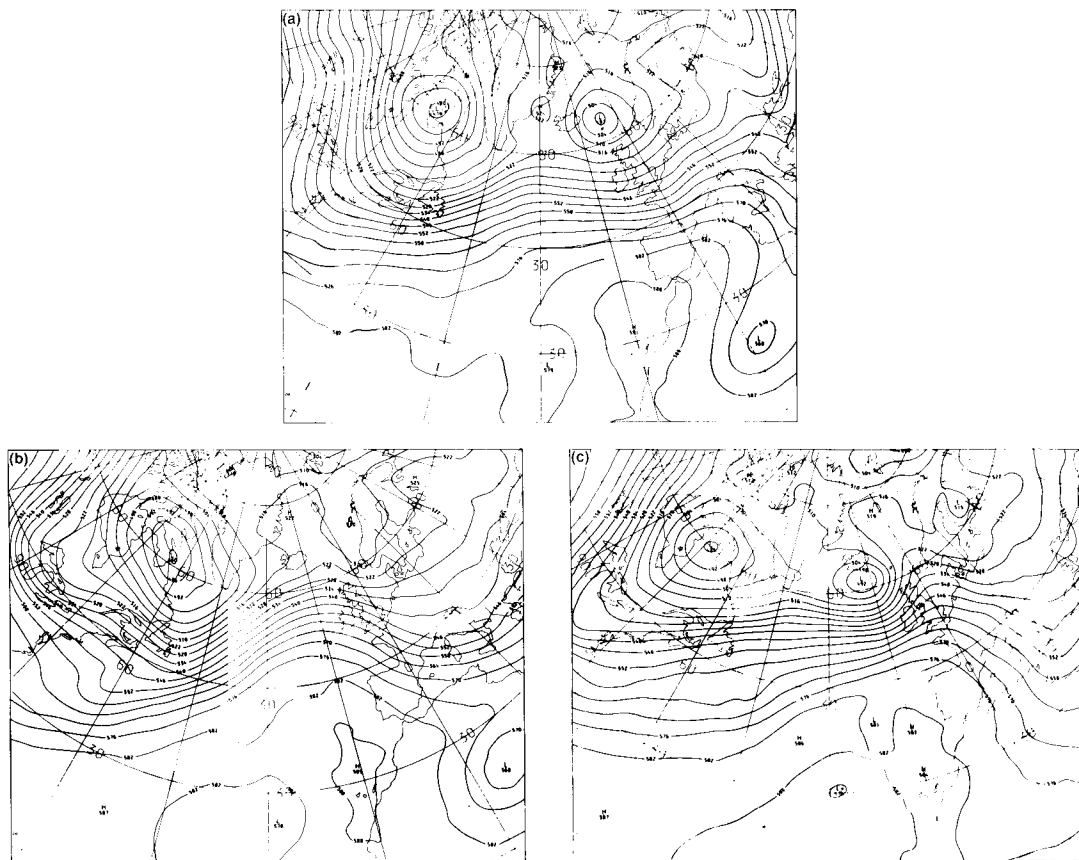


Figure 1. The Meteorological Office analysed 500 mb height (dam) at 12 GMT on (a) 11 January, (b) 12 January and (c) 13 January 1986.

studied carefully to identify the reasons for the large day-5 differences. Substantial differences first became evident by day 3, when the EC/UK forecast had well developed lows just east of Iceland and near the coast of Labrador, with a ridge over the mid Atlantic. A further upstream trough, originating in the east Pacific, had moved through the Rockies ridge to be near 105° W. The corresponding UK/UK forecast showed a much smaller low to the north of Iceland with a very minor ridge in mid Atlantic. During days 4 and 5 developments from the EC/UK forecast were considerably different from the UK/UK forecast with the mid Atlantic ridge amplifying over the United Kingdom thus slowing the eastward movement of the low near Labrador. The trough over North America continued to be moved east at a faster rate than on the UK/UK forecast. At day 5 it is near 30° W as an extension of the 500 mb low (Fig. 2(d)). The speed of this trough appears to be critical in that the slower movement from the UK/UK forecast allowed it to engage warm air that had been moving north-eastwards along the eastern seaboard, thus causing it to deepen with its position near 40° W by day 5 (Fig. 2(a)). We can also see that the low near Iceland and the ridge across central Europe have been moved too quickly eastwards.

Fig. 3 shows the difference between the 500 mb forecasts at day 5 from the UK/UK and EC/UK runs (Fig. 2(a) minus Fig. 2(d)). The negative shaded areas north-east of the United Kingdom (maximum -29 dam) and at 45° W (maximum -20 dam) correspond to the ridge in the EC/UK forecast and the trough in the UK/UK forecast respectively, whilst the positive area over the eastern Atlantic, where a

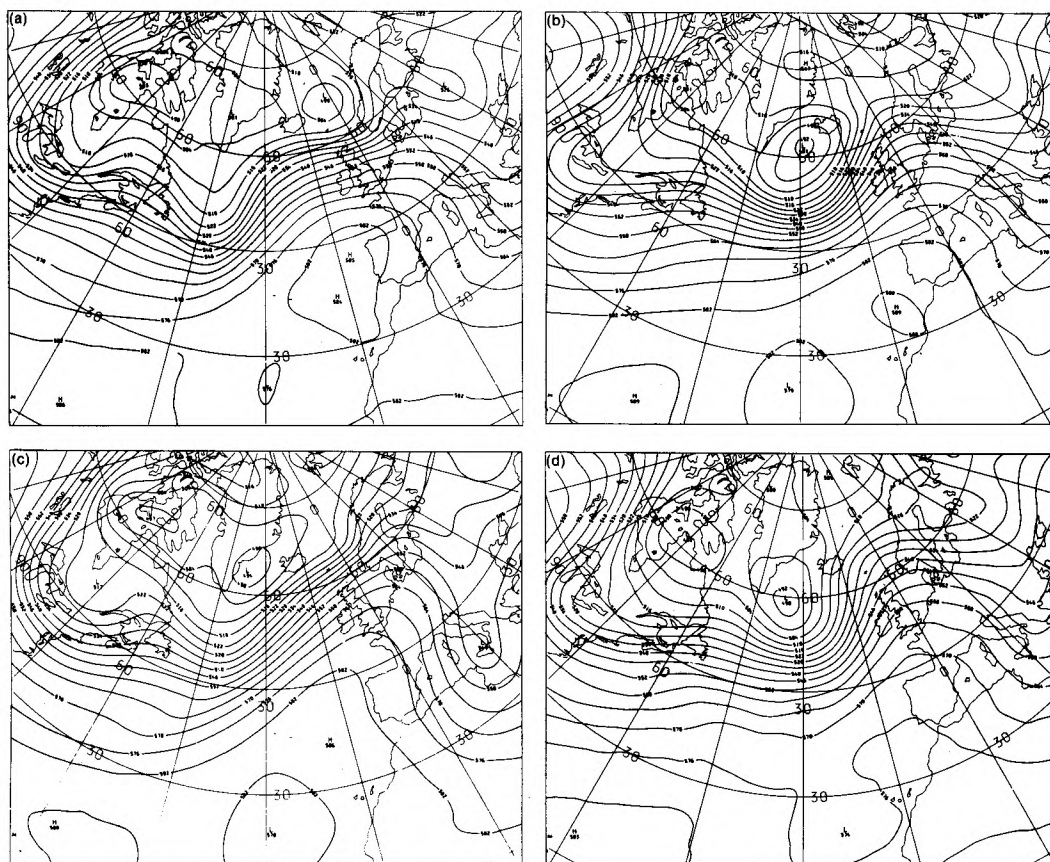


Figure 2. The 5-day forecast from 12 GMT on 8 January 1986 of the 500 mb height (dam) using (a) UK analysis/UK model, (b) EC analysis/EC model, (c) UK analysis/EC model and (d) EC analysis/UK model. For explanation of initials see text.

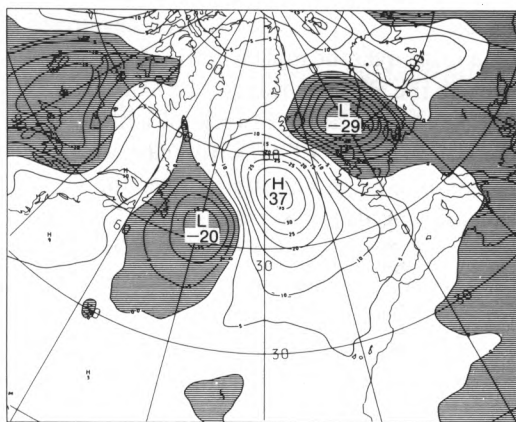


Figure 3. Difference between the 5-day forecasts from 12 GMT on 8 January 1986 of the 500 mb height (dam) from the UK/UK and EC/UK runs (Fig. 2(a) minus Fig. 2(d)). Shaded areas indicate negative values.

maximum difference of 37 dam occurs, shows the difference between the trough in the EC/UK forecast and the ridge in the corresponding UK/UK forecast.

3. A transplant experiment

Comparison of the initial Meteorological Office and ECMWF analyses shows that there are significant differences between them. There are several regions where the 500 mb height differences are greater than 4 dam, but here consideration is given only to the differences over the Pacific Ocean and Alaska. Fig. 4 shows a widespread negative difference over much of this region; this is because the Meteorological Office model has a cold bias of about 1 dam relative to the ECMWF model. There are three areas where differences exceed 4 dam: Alaska, the Californian coast and mid Pacific. The mid-Pacific anomaly results from greater amplitude in the ECMWF analysis of a weak ridge following the major upper trough at 160° W. This anomaly was seen to grow and progress eastwards in the forecast difference fields. The difference progressed at a faster rate than the upper trough-ridge patterns. The initial anomaly resulted in a sharper upper trough which was further forward at 150° W in the EC/UK run at day 1, and this feature can be followed in the difference fields during the following days. The growth of the differences is initially quite slow, but becomes much more rapid after day 3 as the systems progress.

The significance of the Pacific analysis differences in explaining the difference in the operational forecasts can be investigated by carrying out a transplant experiment in which a portion of the ECMWF analysis from the Pacific region (20° N–65° N, 120° W–160° E) is inserted into the Meteorological Office analysis. Both the mass and wind field variables at all levels were transplanted and a smooth transition between the inner transplant area and the remainder of the field was achieved by merging the analyses over a three-grid-length boundary zone.

The effect of the transplant on the 5-day forecast is illustrated in Fig. 5(a). Note that compared with the original UK/UK forecast (Fig. 2(a)) the North Sea ridge becomes sharper and the low to the north-east of Iceland assumes a lesser significance with a centre now appearing to the south-west of Iceland. Also the flow over the mid and west Atlantic is 'flatter' with less pronounced troughs and ridges. The difference chart given in Fig. 5(b) shows a distribution of the low-high-low pattern similar to that in Fig. 3. The values of the negative differences in the Atlantic and northern North Sea are almost identical to those in Fig. 3; however, in the eastern Atlantic the positive difference of 16 dam compared to the 37 dam in Fig. 3 indicates that the transplant was only partly successful in improving the movement and depth of the trough. Several transplants were attempted, but this one produced the greatest improvement over the UK/UK operational forecast.

4. Tests with a revised Meteorological Office analysis scheme

The forecast was rerun using an analysis produced from the analysis correction scheme (Lorenc and Dumelow 1985). This revision to the repeated insertion analysis scheme used at the Meteorological Office is designed to combat some of the deficiencies in the operational scheme. It allows observations to influence the model over a much larger area and no selection is performed so that all observations with a significant weight within the sphere of influence of a model grid point are used. This approach provides a somewhat smoother increment field. The observations are also used in a more timely manner by inserting them into the model during a period around their validity time (particularly important for aircraft reports).

Comparison of the initial analysis fields between the operational analysis and the analysis correction scheme at 500 mb shows the largest differences over the Pacific and Alaska. The 500 mb forecast from the revised analysis scheme at day 5 is shown in Fig. 6(a). A direct comparison of this figure with the

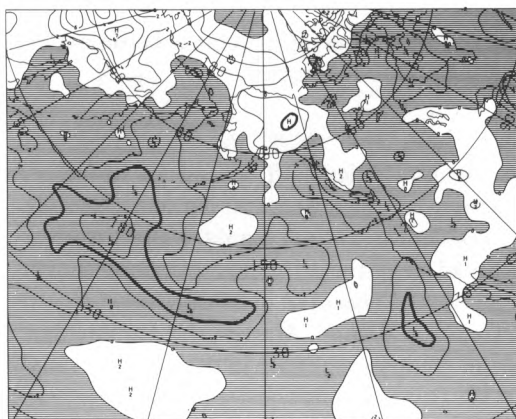


Figure 4. Difference between the Meteorological Office and ECMWF analyses of the 500 mb height (dam) at 12 GMT on 8 January 1986. Shaded areas indicate negative values. Heavy lines enclose areas where differences exceed 4 dam.

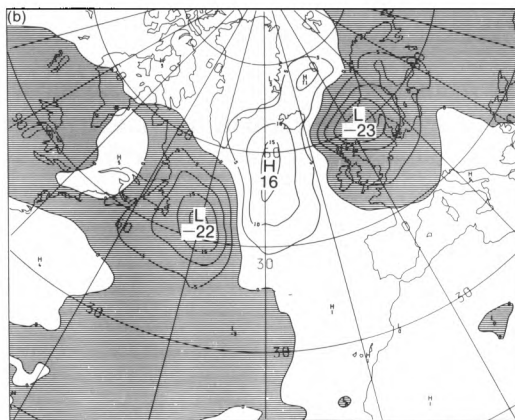
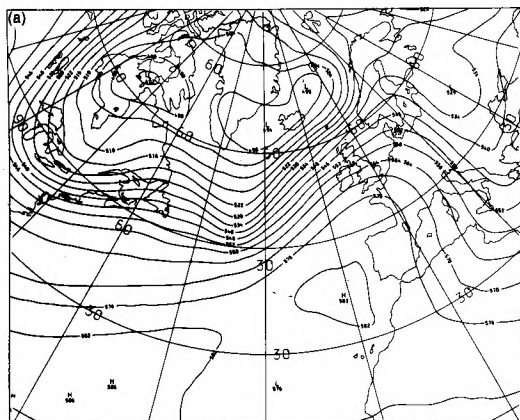


Figure 5. (a) The 5-day forecast from 12 GMT on 8 January 1986 of the 500 mb height (dam) using the Meteorological Office analysis with a portion of the ECMWF analysis (20° N–65° N, 120° W–160° E) transplanted into it, and (b) the corresponding difference from the UK/UK forecast given in Fig. 2(a). Shaded areas indicate negative values.

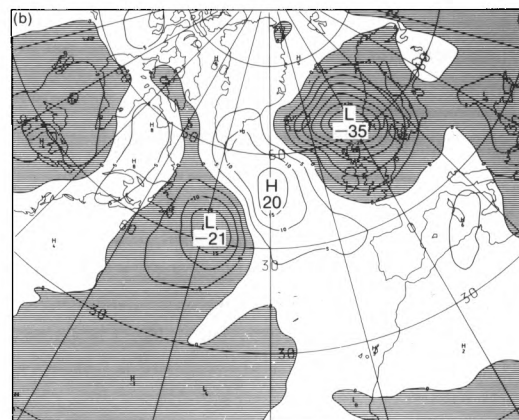
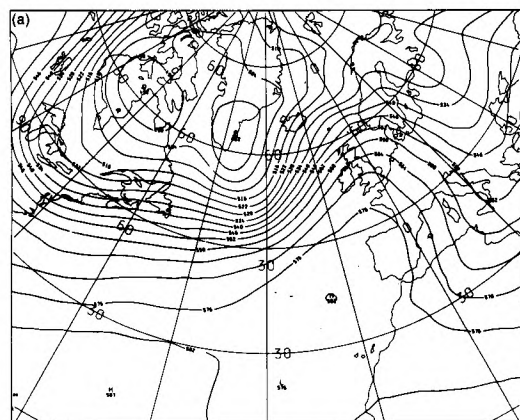


Figure 6. (a) The 5-day forecast from 12 GMT on 8 January 1986 of the 500 mb height (dam) using the analysis correction scheme, and (b) the corresponding difference from the UK/UK forecast given in Fig. 2(a). Shaded areas indicate negative values.

corresponding operational forecast (Fig. 2(a)) and an examination of the verification chart (Fig. 1(c)) show the improvement in the forecast using the analysis correction scheme. See also the differences given in Fig. 6(b) compared to those in Fig. 3.

Investigations of the data used in the analyses suggest that the ECMWF analysis scheme has made more effective use of the sparse volumes of data in the Pacific, particularly the single-level wind data. The improved analysis may be due to the larger sphere of influence given to the observations by the ECMWF scheme as this is a feature which has been incorporated into the analysis correction scheme.

5. Concluding remarks

It has been demonstrated that a poor Meteorological Office analysis was responsible for the poor medium-range forecast from 12 GMT on 8 January 1986. An ECMWF forecast run from this poor Meteorological Office analysis gave an evolution similar to the UK/UK operational forecast.

Difference charts were successful in tracing back the large 5-day difference in the east Atlantic to differences in the analyses in mid Pacific. By means of a transplant technique it has been shown that an analysis error in a relatively small section of the Pacific at upper levels contributed most to the subsequent forecast error. In this instance it seems that the Meteorological Office analysis scheme had difficulty in accepting single-level wind data from aircraft reports.

The new Meteorological Office analysis correction scheme, which is currently nearing operational implementation, provided a better analysis on this occasion, and the forecast from that analysis evolved correctly in most respects to give excellent guidance at day 5 (apart from a small timing error).

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Joint Centre for Mesoscale Meteorology

A.J. Thorpe

Department of Meteorology, University of Reading

The Joint Centre for Mesoscale Meteorology has recently been brought into existence as a collaborative venture between the Department of Meteorology of the University of Reading and the Meteorological Office.

The objective of the Centre is to promote research in mesoscale meteorology, in order to increase basic scientific understanding of, and improve the skill of forecasting mesoscale weather systems. This will be achieved by developing a focused research programme for the Centre with a balance of observation, modelling, and theory, and by fostering collaboration nationally and internationally.

Much of the significant weather within synoptic-scale systems is organized on the mesoscale; examples include rapidly developing cyclones, frontal phenomena, squall lines, mesoscale convective systems, cold-air vortices, polar lows and local orographic effects. As a consequence of their scale, mesoscale systems are not only inadequately observed by the present operational synoptic network but also poorly resolved by routine weather prediction models. World-wide developments in observational and computer technology will enable mesoscale weather systems to be better resolved leading to progress on their understanding and prediction.

The establishment of the Centre follows the recent example of collaboration in mesoscale meteorology — the Mesoscale Frontal Dynamics Project (MFDP); see Clough 1987*. That project arose from a desire to pool resources and expertise in the universities and the Meteorological Office to study a mesoscale phenomenon of both theoretical and practical interest. Active cold fronts were chosen for the variety of mesoscale structure they exhibit and for the important forecasting problem they represent. At the core of the planning of the MFDP were the mesoscale groups at the University of Reading and in the Meteorological Office. The project includes an important French contribution with a smaller German involvement. The field phase of the MFDP took place from October 1987 to January 1988 and the data look to be of the highest quality. It should be emphasized that such mesoscale data sets will take on a growing importance as numerical weather prediction model resolution increases. It is with the renewed realization engendered in the MFDP that the United Kingdom possesses considerable expertise in basic theory, modelling, and observations of mesoscale weather systems that the Centre was established.

The Centre is composed of three groups: the mesoscale dynamics group of the Department of Meteorology specializing in basic mesoscale research, the mesoscale group of the Cloud Physics Branch (Met O 15) of the Meteorological Office specializing in observations and diagnostics which is located in the Department of Meteorology, and a group in the Forecasting Research Branch specializing in mesoscale dynamics and forecast models which is located at Meteorological Office Headquarters, Bracknell. The move of the Met O 15 group to the university has involved four scientists occupying rooms in the Department of Meteorology. A direct computer link to Bracknell is being used by this group together with graphics, line printer, and PC facilities.

The participating groups in the Centre will be able to draw on a wide range of key research facilities. These include observational data from, for example, radar, satellites, meteorological research aircraft, and radiosoundings. Also, advanced numerical models are available using computers such as the Amdahl at Reading, the Cray-1S at London, the Cray-XMP machines at the Atlas Laboratory and at ECMWF, and the ETA 10 at the Meteorological Office.

A steering group determines the direction and monitors the progress of the Centre. This is currently composed of Dr K.A. Browning, Dr P.W. White and Dr P.R. Jonas from the Meteorological Office, and Professor R.P. Pearce, Professor B.J. Hoskins and Dr A.J. Thorpe from the Department of Meteorology. Further details of the organization and *raison d'être* of the Centre can be found in *Report No. 1* available from the address at the end of this article. The research which forms the Centre's activities is determined by the component groups and forms the basis of the Joint Research Programme of the Centre. This programme is agreed by the participating groups and published on an annual basis; see *Report No. 2* for 1988. The role of the Centre's Co-ordinator, Dr A.J. Thorpe, is to co-ordinate those efforts of individual scientists and groups where these contribute to the Centre's research programme and to foster progress by organizing national and international meetings.

Much of the first year's work of the Centre will involve the MFDP and in particular the analysis and diagnosis of the data in the light of the specific scientific hypotheses set out in the Project's plans. This

* Clough, S.A.; The mesoscale frontal dynamics project, *Meteorol Mag*, 116, 1987, 32–42.

will also involve using forecast and research models to simulate the observed frontal dynamics. The key issues include the dynamics of rainbands, the low-level jet, frontal collapse, frontal waves, upper tropospheric forcing, and the role of diabatic forcing by microphysical processes.

Plans for the future involve research requiring the development of new observational programmes and modelling efforts. Instrument developments, on a time-scale of about 5 years, which are likely to have an important impact on the work of the Centre include: the possible use of an advanced airborne Doppler radar capable of mapping mesoscale and convective-scale fields of motion over large areas, the development of surface-based remote profilers, the availability of Doppler data from some ground-based radars, the provision of high-resolution data from commercial aircraft in the Heathrow area, and the availability of improved sounding products from satellites. Future model developments include greater resolution and larger domain in the mesoscale model, use of non-hydrostatic research models using a variety of vertical coordinates, and exploitation of semi-geostrophic models in finite-difference and geometric-type formulations. The Centre will play an important role in the IAMAP 89 meeting to be held in Reading in August 1989. As well as presenting papers on the scientific results of the MFDP in the symposium on 'Mesoscale processes in extratropical cyclones', a workshop is being planned on the needs and opportunities for observational studies and numerical prediction models of mesoscale weather systems.

Enquiries concerning any aspect of the Centre's activities should be directed to Dr A.J. Thorpe, Joint Centre for Mesoscale Meteorology, Department of Meteorology, University of Reading, 2 Earley Gate, Whiteknights, P O Box 239, Reading RG6 2AU.

Notes and news

Retirement of Mr D.E. Jones

Mr D.E. Jones, MSc, DIC, ARCS, Assistant Director (Synoptic Climatology) retired from the Meteorological Office on 15 July. During a career of nearly 34 years he was involved in a wide range of work in the Office which included research, training, and forecasting at home and overseas.

David Jones was born in 1928 at Dowlais in Glamorgan. One consequence of his move to London (where he spent most of his childhood) about 5 years later was that he left his Welsh accent behind in his homeland, though his true origins are betrayed not just by his name but also by his active love for singing and his ability to become the life and soul of any party.

In 1946 he went up to Imperial College to read mathematics and graduated with a first class honours degree after only 2 years. College regulations demanded that he stay on an extra year and so, as he already had an interest in the weather, he attended courses in the Department of Meteorology which at that time was headed by Professor Sir David Brunt. He was duly awarded an MSc and a DIC at the end of the year. His academic abilities were recognized by an invitation by the Department to stay on for a further 2 years to do research under P.A. Sheppard. This must have been an exciting period to be a student at Imperial College. Rapid advances were being made in the science of meteorology and the Department was expanding with a new influx of enthusiastic young staff; E.T. Eady, F.H. Ludlam, B.J. Mason and R.S. Scorer all joined the Department during these early post-war years.

National Service was, of course, obligatory and David decided that the only way to stay in meteorology was to take a short service commission in the Royal Navy as an instructor lieutenant. It appears that his sea-legs were not unduly tested during his time in the Navy as his 'full sea-time was crossing the Gosport ferry in uniform'. After 6 months at Kete, Pembrokeshire, he spent 2½ years forecasting for RNVR training squadrons at the Royal Naval Air Station, Bramcote where Seafires

(Naval adaptations of Spitfires) were being flown from grass runways. It was during this period that he and Olive were married and their first son was born.

David joined the Meteorological Office in 1954. There were only four people on the Scientific Officers' course at the Training School at Stanmore that year; David is the only one who has remained in the Office until retirement. He didn't do the usual forecasting rounds after the course because of his Navy experience but instead was posted to what was then the Short-range Forecasting Research Branch. Later he helped with the development of the Sawyer–Bushby model and participated in trips to Manchester with Fred Bushby, Mavis Hinds, Janet Portnall and others to use the Ferranti Mark I computer (the joys of these trips have been fully documented by Mavis Hinds, together with a photograph of a youthful, broadly smiling David Jones at the controls of the computer*). In 1960 (after 2 years as an upper-air forecaster at Dunstable) he began a project in the Dynamical Research Branch to develop a model with an explicit tropopause level, and 3 years later he was promoted to Principal Scientific Officer.

In 1966 David successfully volunteered for a posting to Cyprus. One of his earliest tasks was to drive in a stake at the site chosen for the radar for the new radiosonde station to be established at Episkopi (the station was officially opened 3 years later, 1 week after David had left). He closed the station at Akrotiri, where the runway was cracking up, but otherwise his time in Cyprus was uneventful. It was a quiet period, politically, and the only moments of tension occurred when General Grivas returned and it was seriously thought that the Turkish forces would invade the island.

When David was asked at the end of his tour for his views on the future direction of his career, he stated that he didn't want to be a Senior Forecaster, to do research in objective analysis or to do long-range weather forecasting. The Postings Board, in its inscrutable wisdom, immediately posted him to the Central Forecasting Office to be a Senior Forecaster and, 2 years later, to the Forecasting Research Branch (Met O 11) to do research in objective analysis. David was given the task of developing an analysis scheme suitable for use in real-time tropical numerical forecasting during GATE (the GARP Atlantic Tropical Experiment) in 1974. Several novel problems were overcome, including those due to weak geostrophy and the need to analyse both geopotentials and winds. Not least of the difficulties was the impossibility, in the absence of the observational database, of testing the system adequately beforehand.

Promotion to Senior Principal Scientific Officer came shortly after a posting to the Meteorological Office College at Shinfield Park in 1974. There David undertook the task of completely revamping the Scientific Officers' course, especially the dynamics lectures which had remained largely unchanged for nearly a decade. In 1976 there was a move to become Head of Central Forecasting. David was the first occupant of this post with such widespread experience in numerical weather prediction. Even though model guidance had been used for over a decade, there were still ingrained attitudes to change. Long-standing mutual distrust between the Central Forecasting Branch and Met O 11 disappeared and resources were pooled to develop and implement the 15-level model. David was also responsible for redesigning the North Sea shipping forecast areas, including the naming of two new areas North Utsire and South Utsire (these were introduced operationally in the early 1980s).

In October 1980 David was invited to visit China with Sir John Mason, Professor J.T. Houghton and Professor J.L. Monteith. This was one of the earliest foreign scientific parties to go to the country after the death of Mao Tse Tung (they were referred to by some as the Gang of Four). David gave lectures on numerical weather prediction and operational forecasting and visited several scientific institutes in Beijing, Nanjing and Shanghai. In a display of exceptional thoroughness, David learnt enough Chinese to give several short speeches, something that greatly impressed both his hosts and his colleagues.

* Hinds, M.K.; Computer story, *Meteorol Mag*, 110, 1981, 69–81.

David's last posting, in 1981, was to become Head of the Synoptic Climatology Branch, responsible for long-range forecasting. Morale was at a low ebb in the Branch; for many years long-range forecasts had been oversold and it was felt by some that their lack of success was being viewed publicly as representative of the Office as a whole. The Branch became the first victim of the 'Thatcher cuts' in a well publicized decision to discontinue issuing long-range forecasts and to reduce its strength by seven posts. The period also coincided with the retirement of many of the 'old guard' and an influx of younger scientists. It was decided to continue long-range forecasting as a research exercise but to replace the 20 or so manpower-consuming forecasting methods by three highly computerized statistical techniques. Much greater emphasis was placed on research into the physical causes of climate fluctuations on time-scales from months to a few years and on the detection of climate change from quality-controlled observational databases. Long-range forecasting was considered from a world-wide perspective, and global numerical models were employed both for research and for experimental predictions. The success of the Branch over the last 7 years under David's leadership can be judged from the high international regard held for its research work and from its change from the Branch most people would like to avoid to one of the most popular choices for new-entrant Scientific Officers.

Both David and Olive have entered very fully into the social life of the Office despite having to bring up their now adult family of two sons and two daughters. David was Chairman of the Horticultural Society for 9 years and on several occasions Olive had to be on 'stand by' for the prize giving at the spring and autumn shows in case an invited dignitary failed to show up. David now plans an active retirement teaching English to foreign students. We wish both David and Olive a very happy future and trust that their decision to remain in Bracknell will mean that we will continue to see them on many occasions.

P.W. White

Review

Boundary layer climates, second edition, by T.R. Oke. 153 mm × 234 mm, pp. xxiv + 435, illus. London, New York, Methuen, 1987. Price £39.95 (hardback), £14.95 (paperback).

To be fair to the author of the above book the reviewer must open with a confession of only recently becoming involved in the atmospheric boundary layer. In view of this, it is not surprising that T.R. Oke is only familiar to him as the author of the volume in question.

The emphasis of most standard boundary layer texts appears to be on a rigorous mathematical approach rather than a conceptual or physical treatment. For a student it is the latter which, at least initially, is the most useful. *Boundary layer climates* attempts to fill this large gap.

There are three sections each containing several chapters. The first, 'Atmospheric systems', discusses the basic concepts of the boundary layer and the physics associated with it. 'Natural atmospheric environments' describes in detail the various budgets and balances of energy pertaining to several different types of underlying surface, including the climates associated with animals. The final section, 'Man-modified atmospheric environments', describes the effects, both good and bad, that man has on the climate and also any control he has on the weather.

The book is intended to appeal to two groups of readers. The first are those for whom meteorology is an important factor in their field and who require an introduction to its possible effects and applications. The second are students who require a practical supplement to other more theoretical texts.

Very little about either meteorology or mathematics is assumed and, indeed, little more than a rudimentary knowledge of differential calculus is called upon. However, much of the content is based on physical concepts. So, whilst the book does not contain anything particularly technical, a reasonable grounding in physics is an advantage.

Generally the text flows well. It contains discussions about various extremes of environment that the reader may well be unfamiliar with. This, coupled with lucid and rational explanations, invites further reading and suggests that the book is intended to be read from cover to cover. However, in chapters 3 and 4 of section 2 the author has deliberately followed a set pattern for each climate under consideration. Indeed, this makes for easy intercomparison but not for interesting, continuous reading and has more the approach of a reference book. The chapters are reasonably self-contained and there is very good cross-referencing throughout the book. This adds significantly to the ease of reading and allows the possibility of reading a section or even a chapter in isolation.

The general essence of *Boundary layer climates* is one of practicality. Where possible, actual values are put to otherwise abstract quantities. There is an appendix about methods of observing boundary layer parameters and profiles with some of the mathematics that these require. Also, a welcome addition to the first edition is the inclusion of some meteorological tables and physical constants.

A further supplement to the first edition is an appendix called 'Radiation geometry' with, among other things, a method for predicting the path of the sun, a discussion of shape factors and a section on diffuse radiation. Though very interesting and of some practical use, in the light of the general approach of the book it would appear out of place.

There is a detailed index, a large and useful list of symbols and a glossary which explains new terms (italicized) which are not fully explained in the text. There is a good bibliography, a list of authors and, perhaps more useful for the student, a section-by-section list of suggested further reading. The figures are plentiful and clear. The author often includes 'definition' diagrams which greatly aid the understanding of the text. Also, the figures are usually close to the relevant passage, avoiding constant thumbing back and forth.

As either a reference book or textbook *Boundary layer climates* is definitely written with a reader's wishes in mind. It is clear and well constructed and ably fills a much neglected gap in the literature of boundary layer meteorology and is a recommended purchase for newcomers to the subject and for those concerned with agricultural meteorology.

N. Wood

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Our drowning world, by A. Milne (Bridport, Dorset, Prism Press, 1988. £9.95) contains world-wide 'evidence' to support the author's thesis that approximately two thirds of the land surface of the earth could disappear under melted polar ice-cap water. Reasons why a catastrophe will not be averted are also examined.

Applications of thermal imaging, edited by S.G. Burnay, T.L. Williams and C.H.N. Jones (Bristol, Philadelphia, Adam Hilger, 1988. £45.00) aims to present a comprehensive introductory (only high-school physics required) treatment of the subject. The different areas of this multi-disciplinary subject are covered by relevant experts.

Topics in micrometeorology, edited by B.B. Hicks (Dordrecht, Boston, D. Reidel, 1988. £38.00, Dfl.125.00, US \$69.00) is a *Festschrift* to Dr A.J. ('Arch') Dyer, the distinguished Australian micrometeorologist. It consists of a collection of articles on the subject reprinted from *Boundary-layer meteorology*.

The little ice age, by J.M. Grove (London, New York, Methuen and Co. Ltd, 1988. £85.00) places an extensive body of material relating to Europe in the form of documentary evidence of the history of the glaciers within a global perspective. The book contains large numbers of maps, diagrams and photographs, many not published elsewhere.

Meteorology for seafarers, by R.M. Frampton and P.A. Uttridge (Glasgow, Brown, Son and Ferguson, 1988. £27.50) is a revised version of *Meteorology for seamen* and follows its predecessor in setting out to explain the complexities of the atmosphere to professional seafarers and the general reader alike.

Acta Meteorologica Sinica, edited by Chinese Meteorological Society (Chinese Meteorological Press, 1987. £230.00 (annual subscription for four)) provides a comprehensive coverage of Chinese studies and research on all aspects of atmospheric science. Also contained are reviews and information on symposia, and notes for timely reporting of recent significant findings.

Recent climatic change, edited by S. Gregory (London, New York, Belhaven Press, 1988. £33.00) addresses the scientific issues of the subject by researchers from more than a dozen countries. In the wide-ranging topics are included studies of the specific characteristics in particular regions of the globe.

Synoptic meteorology in China, edited by B. Chenglan (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. DM 128.00) is a summary of the complete meteorological research data of China. Verified methods and rules for weather prediction there are also given.

Tropospheric ozone, edited by I.S.A. Isaksen, (Dordrecht, Boston, Lancaster, Tokyo, D. Reidel, 1988. Dfl 190.00, US \$99.00, £58.00) contains the proceedings of a NATO Advanced Research Workshop. Transcriptions of the many presentations are included.

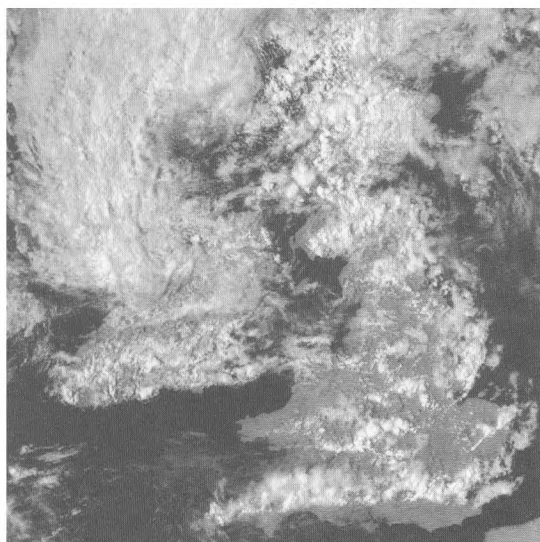
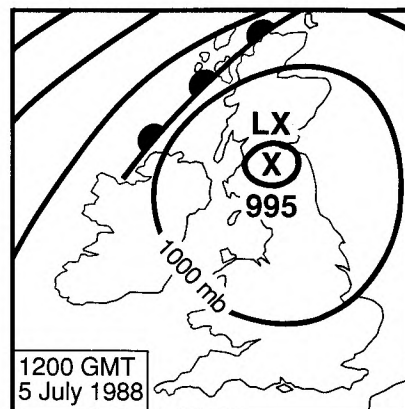
Proceedings of the second TORRO conference on tornadoes and storms, edited by G.T. Meaden and D.M. Elsom (Bradford-on-Avon, Arteteck Publishing Company, 1988) is a collection of papers from the conference. A variety of peripheral subjects with an international flavour are presented.

Correction

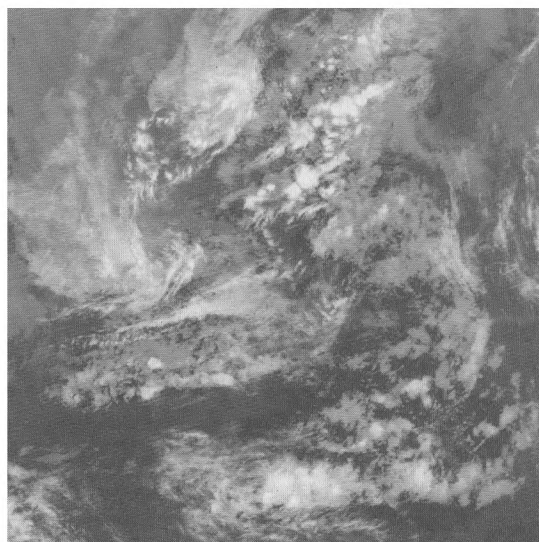
Meteorological Magazine, May 1988, p. 163, 27th line. Since this article was written the heavy falls of rain at Creebridge and Bargrennan have been amended to 51 mm and 44 mm respectively.

Satellite photographs — 5 July 1988 at 1542 GMT

The NOAA-9 visible and infra-red AVHRR images were taken on a day when an unstable returning polar maritime air mass covered the United Kingdom, in the circulation of a low centred over southern Scotland. In these unstable airstreams, convective cloud and showers often develop in bands dependent on topography and the low-level wind flow. The main feature on the images over southern England is the cloud band extending from Cornwall to Essex. The band originated during the morning within a zone of low-level convergence over the Cornish peninsula and its subsequent growth eastwards was assisted by convergence along sea-breeze fronts. Southern coastal areas remained largely cloud free. However, within the band, heavy showers and thunderstorms occurred (some with hail), causing localized flash flooding. Anvils from the cumulonimbi were blown northwards in the upper southerly flow. Less-marked convective cloud bands can be identified over Wales, north-west England and southern Ireland. Over central and south-west Scotland, near the low centre, numerous slow-moving cumulonimbus cells can be identified.



Visible



Infra-red

Photographs by courtesy of University of Dundee

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

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Closure of Binbrook

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The synoptic–dynamical evolution of the storm of 15/16 October 1987

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Summary

The synoptic–dynamical evolution of the intense depression which caused widespread damage across southern England during the night of 15/16 October 1987 is described using Petterssen's development equation and the omega equation in conjunction with a series of composite charts displaying selected diagnostic parameters from the Meteorological Office operational numerical weather prediction models. The evolution of the storm is shown to be consistent with expectations using the equations and, in particular, the intensification of surface-pressure gradients on the southern flank of the depression during the evening of the 15th is ascribed to a combination of strong cold advection and strong advection of negative vorticity on the cold side upstream of the jet-stream core.

1. Introduction

The meteorological events leading up to, and those obtained in association with, the intense depression that caused widespread damage across southern England during the night of 15/16 October 1987 have been described in comprehensive detail in the April issue of the *Meteorological Magazine* (Meteorological Office 1988); this was based on the official report produced by the Meteorological Office (Meteorological Office 1987). The depression was most notable for the intense winds on its southern and western flanks which developed during the evening of the 15th over Biscay and Finisterre. The development of the storm, not unnaturally, requires some explanation and forecasters need to know whether there were any clues which, even with the benefit of hindsight, could be exploited to advantage in the future.

The Meteorological Office report on the storm includes a series of mean-sea-level pressure (PMSL) analyses redrawn after the event by experienced forecasters in the Central Forecasting Office (CFO) at Bracknell. These analyses were based upon a fully integrated assessment of the data available (i.e. including upper-air data and satellite imagery for example) and must represent the best set of analyses that could be obtained. The paucity of surface observations over the oceans during the development phase of the storm means that alternative analyses, in some details, cannot be entirely rejected. Nevertheless, for present purposes the official analyses are considered to be essentially correct.

Use will be made of the routine output of analyses from the Meteorological Office operational numerical weather prediction (NWP) models (Meteorological Office 1985) to monitor the evolution and

development of the storm. NWP output has the great quality of internal consistency although phase errors in the location of systems can occur and careful subjective adjustments are required in such areas.

The period of study will be the 24 hours between 0000 GMT on 15 October and 0000 GMT on 16 October. The official report on the storm points out how sensitive the NWP forecasts were to variations in the analysis for 0000 GMT on the 15th. In particular, the differences between the operational fine-mesh model T+24-hour forecast and the same model forecast based upon an interpolated global model analysis (with later cut-off time for data) were startling, with the latter representing an excellent forecast by any standards. Nevertheless, the differences in the starting conditions for these model forecasts were not large and, realistically, no forecaster could be expected to spot these sort of deficiencies in the earlier analysis, even with access to satellite imagery, until the arrival of late data in the crucial areas. The aim of this paper is to demonstrate that forecasters can apply the fundamental dynamical principles that they are taught to use, in conjunction with the NWP output of diagnostic fields, to explain the broad-scale developments over the next 6 hours (exceptionally 12 hours) but not, realistically, any further ahead.

The information that the forecaster would seek to deduce on this occasion would be as follows:

- (a) Trends in level of PMSL in any part of the area under consideration.
- (b) Trends in direction of movement of the PMSL centres.
- (c) Trends in speed of movement of the PMSL centres.

For these purposes it is considered that the operational NWP analyses should be adequate unless significant errors can be detected from the imagery and other sources, e.g. aircraft reports. Analyses at 0000, 1200, and 1800 on the 15th and 0000 GMT on the 16th will be used in conjunction with Meteosat imagery and, where inconsistencies with the latter are apparent, arguments will be advanced for careful modification to the NWP diagnostic fields with the consequences for short-period trends in the evolution of the weather system.

2. Basic principles

It is useful to briefly outline the two fundamental equations governing the diagnosis of vertical motion and the production of sea-level (i.e. PMSL) vorticity.

2.1 The omega equation

The vertical motion may be derived from the well known omega equation which in simplified form may be expressed thus:

$$\nabla^2 \omega \approx \frac{\partial}{\partial p} \{ \mathbf{V} \cdot \nabla (\zeta + f) \} + \nabla^2 (\mathbf{V} \cdot \nabla T) \quad \dots \dots \dots (1)$$

where ω is the vertical motion in isobaric coordinates and the other symbols have their usual meaning. Large negative values of $\nabla^2 \omega$ imply that ω is positive (i.e. descending air) and positive values of $\nabla^2 \omega$ imply that ω is negative (i.e. ascending air). The omega equation is usually interpreted to infer that maximum values of ascending air in mid troposphere are associated with increasing (with height) positive advection of vorticity and also with maximum values of warm advection within the layer embracing the middle troposphere. Conversely, maximum values of descent are associated with upward-increasing negative advection of vorticity and maximum values of cold advection.

The practical usefulness of the omega equation lies in the fact that the two major forcing functions on the right-hand side of the equation are readily identifiable on standard working charts used by forecasters. Although current NWP models may not actually solve equation (1), the model vertical velocity fields can usually be interpreted from inspection of the omega equation (see, for example,

Morris 1986). It is worth noting, however, that there are areas of the chart where the two terms on the right-hand side of equation (1) are large and opposite in sign, making interpretation difficult without access to the NWP vertical velocity fields. In such cases the distribution of vertical velocity may be partitioned vertically or is generally small. However, Hoskins *et al.* (1978) have derived an equation which combines the two terms into one and this can provide useful additional information in these cases.

2.2 The equation for the PMSL vorticity

The equation governing the production of PMSL vorticity is derived very lucidly by Petterssen (1956) and may be stated as follows:

$$\begin{aligned} \frac{dQ_{1000}}{dt} = & \textcircled{A} \quad \textcircled{B} \\ & - (\mathbf{V}_{500} \cdot \nabla Q_{500} - \mathbf{V}_{1000} \cdot \nabla Q_{1000}) - \left(\omega \frac{\partial Q}{\partial p} - \frac{\partial \mathbf{V}}{\partial p} \times \nabla \omega \cdot \mathbf{k} + Q_{500} \nabla \cdot \mathbf{V}_{500} \right) - \\ & \textcircled{C} \\ & - \frac{R}{f} \nabla^2 \left(-\frac{g}{R} \mathbf{V}_{1000} \cdot \nabla h_{TT} + H + S \right) \dots \dots \dots (2) \end{aligned}$$

where Q is the absolute vorticity and h_{TT} is the 1000–500 mb thickness; the subscripts refer to the standard pressure levels. The adiabatic heating term, H , and the static stability term, S , are given by

$$H = \ln \left(\frac{1000}{500} \right) \frac{1}{C_p} \frac{dW}{dt} \quad S = \ln \left(\frac{1000}{500} \right) \overline{\omega(\Gamma_a - \Gamma)}$$

where Γ_a and Γ are the adiabatic and actual lapse rates in terms of pressure, and dW/dt is the heat, other than latent heat, supplied to or removed from unit mass in unit time.

In order to interpret equation (2) it is useful to invoke the geostrophic assumption which implies a relationship between local changes of vorticity and contour height. For example, increases in cyclonic vorticity are equivalent to local maxima of falling contour height. The terms in equation (2) may be combined into three groups.

(a) Group A represents the difference in quasi-horizontal advection of vorticity between 1000 and 500 mb. Usually, and unless a strong circulation is present at sea level, the 500 mb term dominates this group. This implies, for example, that if, on synoptic charts, a fall of 500 mb contour height is advected across a region and is not matched by a comparable fall of PMSL heights through advection then, assuming the other terms in equation (2) are negligible, there must be a net fall of PMSL heights to balance the difference between the advection terms.

(b) Group B is usually fairly small; the vertical advection term transports vorticity from one level to another whilst the twisting term effects a rotation of thermal wind into the mean vorticity of the layer and vice versa. The divergence term can be very significant as a source of vorticity when the thermal advection tends to dominate the omega equation but in cases of strong coupling between upper-tropospheric vorticity advection and the lower troposphere, divergence at 500 mb probably has an insignificant role in equation (2).

(c) Group C is concerned entirely with the evolution of the thermal (1000–500 mb thickness) pattern under the influence of quasi-horizontal advection, diabatic heat transfer (through convection and radiation) and adiabatic cooling/heating associated with (dynamical) vertical motion. Latent heat is important in the last term. Equation (2) implies that, ignoring other terms, a local heating or cooling maximum will necessarily be associated with a fall or rise of PMSL vorticity respectively. (A simple exercise of gridding 1000 mb, thickness and 500 mb fields will demonstrate this fact.)

Equation (2) may be simplified by omitting the 1000 mb vorticity advection and the B group of terms to give

$$\frac{dQ_{1000}}{dt} = -\mathbf{v}_{500} \cdot \nabla Q_{500} - \frac{R}{f} \nabla^2 \left(-\frac{g}{R} \mathbf{v}_{1000} \cdot \nabla h_{TT} + H + S \right). \quad \dots \dots \dots (3)$$

In principle, qualitatively at least, most if not all the terms in equation (3) can be identified on standard working charts used by forecasters.

2.3 Application of the diagnostic equations to some idealized situations

Fig. 1 illustrates some of the concepts described above which have a particular bearing on the development of the October 1987 storm. Fig. 1(a) depicts an idealized jet-stream core with 'entrance' and 'exit' regions. This contour-height field has exact mathematical form and it is easy to calculate the distribution of geostrophic vorticity. The pattern of vorticity advection is readily apparent and assuming this pattern dominates the upper troposphere with negligible advection in the lower troposphere then according to equation (1) there will be ascending air in mid troposphere beneath the cold exit and warm entrance regions and descending air beneath the cold entrance and warm exit regions. These relationships are confirmed by experience. It can also be seen (referring to equation (3)) that the jet stream propagates itself forward through the differential advection of vorticity at both exit and entrance regions. Neglecting the presence of significant thermal advection, the thermal field below the jet-stream level will, to a first approximation, advance closely in phase with the latter due to the adiabatic temperature changes associated with the vertical motion. Before considering how other terms in equation (2) cause phase adjustments between the contour and thermal fields to occur there is one other important aspect of the jet stream that needs to be pointed out. The entrance and exit regions have strong ageostrophic components of flow due to the acceleration and deceleration respectively of the air flowing through the pattern. Fig. 1(b) illustrates the relationship between the streamlines and contours in these regions of the jet stream. The whole of the upper-tropospheric air mass is descending in the confluence region and ascending in the diffluence region. The combined effects of Figs 1(a) and 1(b) are shown in schematic cross-section form in Fig. 1(c). It is not difficult to envisage how stratospheric air may be carried well into mid troposphere upwind and to the cold side of the jet-stream core.

The most common way in which sea-level vorticity develops through the mechanism of equation (3) is from the balance between upper-tropospheric vorticity advection and the static stability term (which controls the rate of heating and cooling in the presence of large-scale ascent or descent). Fig. 1(d) illustrates the development associated with an upper-tropospheric wave pattern in which the thermal pattern is initially in phase with the contour pattern (i.e. negligible thermal advection). It is assumed that the saturated air is characterized by an environmental lapse rate equal to the saturated adiabatic lapse rate and that the dry air is characterized by a lapse rate less than the dry adiabatic lapse rate. The contour wave pattern will progress in accordance with the quasi-horizontal advection of vorticity and there will be mid-tropospheric ascent ahead of the troughs and descent ahead of the ridges (equation (1), first term on the right-hand side). In the dry regions the static stability will be large and opposite in sign to the vorticity advection term (equation (2)) and this implies that the thermal pattern translates in close phase with the contour pattern. In the saturated regions the static stability term will be virtually zero implying (equation(3)) a net gain of vorticity in the PMSL field. This manifests itself as a retardation of the thermal pattern relative to the progression of the contour pattern, and a low-level circulation develops. Furthermore, it is readily apparent that if there is a source of diabatic heating, e.g. convection from a sea surface, in the area of ascending saturated air, the degree of cyclonic development will be much enhanced in the PMSL field.

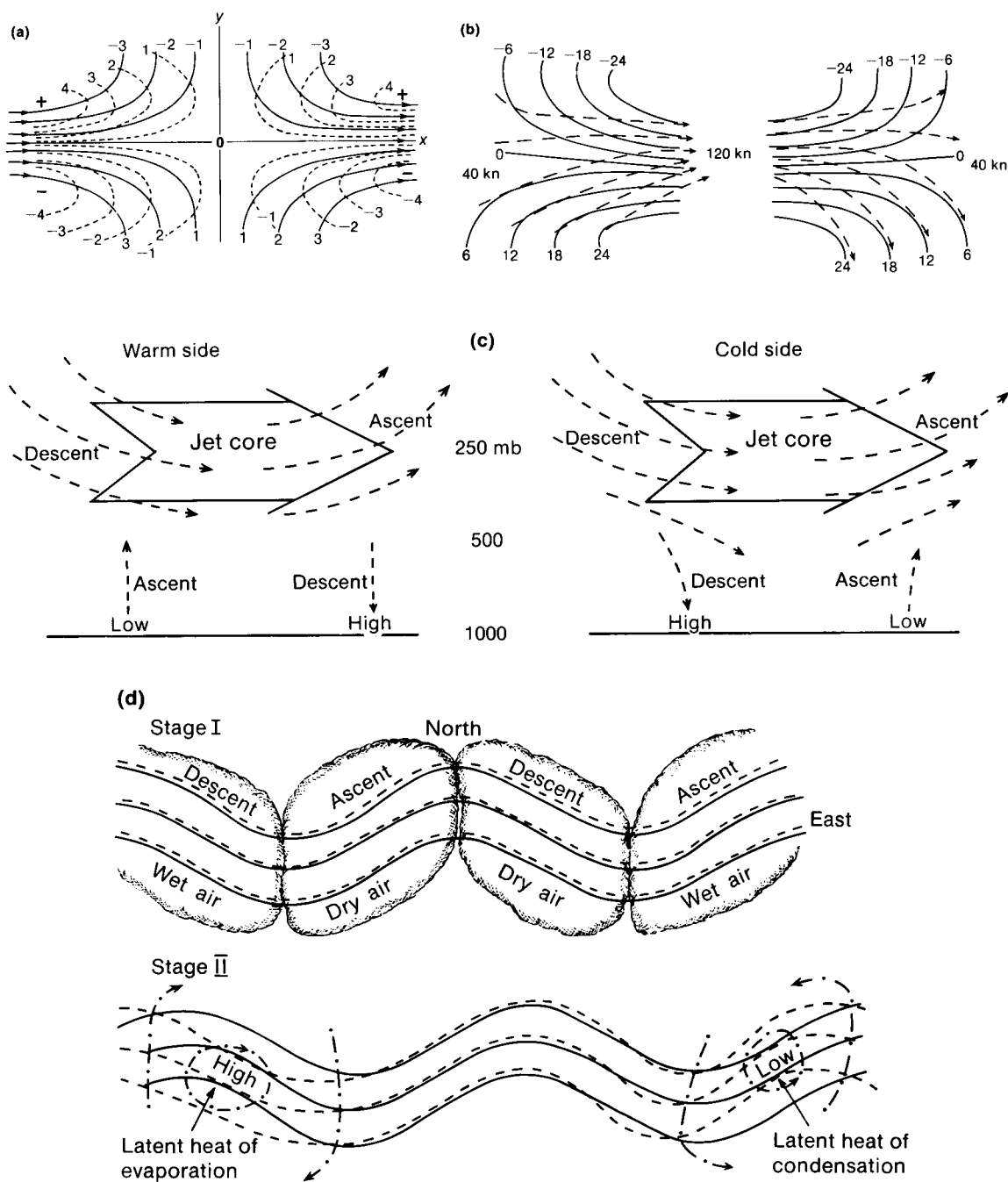


Figure 1. (a) Idealized geopotential height field at 500 mb (—) given by $h_{500} = \pm x \tan \theta y$ depicting jet-stream exit and entrance regions with associated geostrophic vorticity (---). (b) Streamlines (---) and contour field (—) at 250 mb indicating the ageostrophic motion. (c) Vertical profile of warm and cold sides of jet core showing ascent and descent regions. (d) Development of circulation in PMSL (---) due to relative motion of 500 mb field (—) and 1000-500 mb thickness (---) through the influence of latent heat. The isopleths in (a) and (b) have arbitrary units.

3. Diagnostic charts

Before the advent of powerful computers and sophisticated NWP models, forecasting the evolution of synoptic-scale systems was based on quasi-subjective calculations of terms such as those contained in equations (1) and (3). Whilst it is indisputable that modern NWP model forecasts are much superior to quasi-subjective methods the fact is that NWP forecasts can occasionally be seriously in error for a number of reasons. One of the primary tasks facing forecasters must be to anticipate potential major errors in NWP guidance, effectively adding value to the guidance in the so-called man-machine mix process. However, in order to carry out this task forecasters must have a thorough perception of the relative importance of those terms in the equations that they can identify on any occasion; in other words they must monitor the synoptic evolution very closely.

Most of the output from the Meteorological Office NWP model is produced for specific forecasting tasks (e.g. forecasting wind, temperature, cloud and precipitation) but some output is used for diagnostic purposes. The diagnostic parameters may be combined and two composite charts in particular can be very useful:

(a) A composite consisting of the upper-tropospheric jet-stream core (speed and direction), PMSL isobars and a selection of total thickness isopleths superimposed upon the 850–500 mb mean vertical velocity and thermal advection analysis. This composite is designed to display cause and effect in the distribution of vertical velocity and contains explicitly two of the terms in equation (1). The jet-stream core is displayed to infer the sign and relative magnitude of the first term on the right-hand side in equation (1) and also, by induction, the first term on the right-hand side in equation (3). The distribution of thermal advection with respect to the thermal pattern demonstrates whether translation or amplification of the pattern is more likely. The distribution of vertical velocity with respect to the PMSL and thermal pattern allows a direct evaluation of the terms in equation (3) although the humidity and static stability distribution are still required.

(b) A composite consisting of PMSL isobars, and frontal boundaries deduced from the 850 mb wet-bulb potential analysis superimposed upon the model distribution of cloud (cloud is defined as relative humidity greater than or equal to 96% at any model level). As the model also parametrizes convection it is possible to display areas of (model) convective cloud for specific depths and tops reached. The usefulness of this composite is readily apparent. It shows the location and instantaneous movement of the boundary-layer air masses and their characteristics. Used with composite (a) it is possible to make direct evaluation of the sign and relative magnitude of the terms in equation (3).

It is particularly useful to compare these composites with satellite imagery thereby revealing possible deficiencies in the NWP model analyses. A sequence of these composite diagnostic analyses is used to illustrate the broad-scale development and evolution of the storm. Another composite chart consisting of the relevant satellite imagery with superimposed manually fine-tuned PMSL isobars and any other fields as appropriate, e.g. jet-stream analysis, will also be used. Specifically most attention will be focused upon the vorticity production within the centre of the low pressure complex as it transferred from north-east of the Azores to south-west England during 15 October 1987.

4. 0000 GMT on 15 October

At 0000 GMT (Fig. 2(a)) an elongated trough of low pressure was located west of Corunna (north-west Spain) extending over some 600 miles. The broad surface trough was closely related to a very strong baroclinic zone which was present in the lower and middle troposphere. The main surface centre was estimated to be at 43° N, 19° W with pronounced cold advection in the north and west quadrants, and warm advection in the south and east quadrants; thus the translation component due to thermal advection was strong.

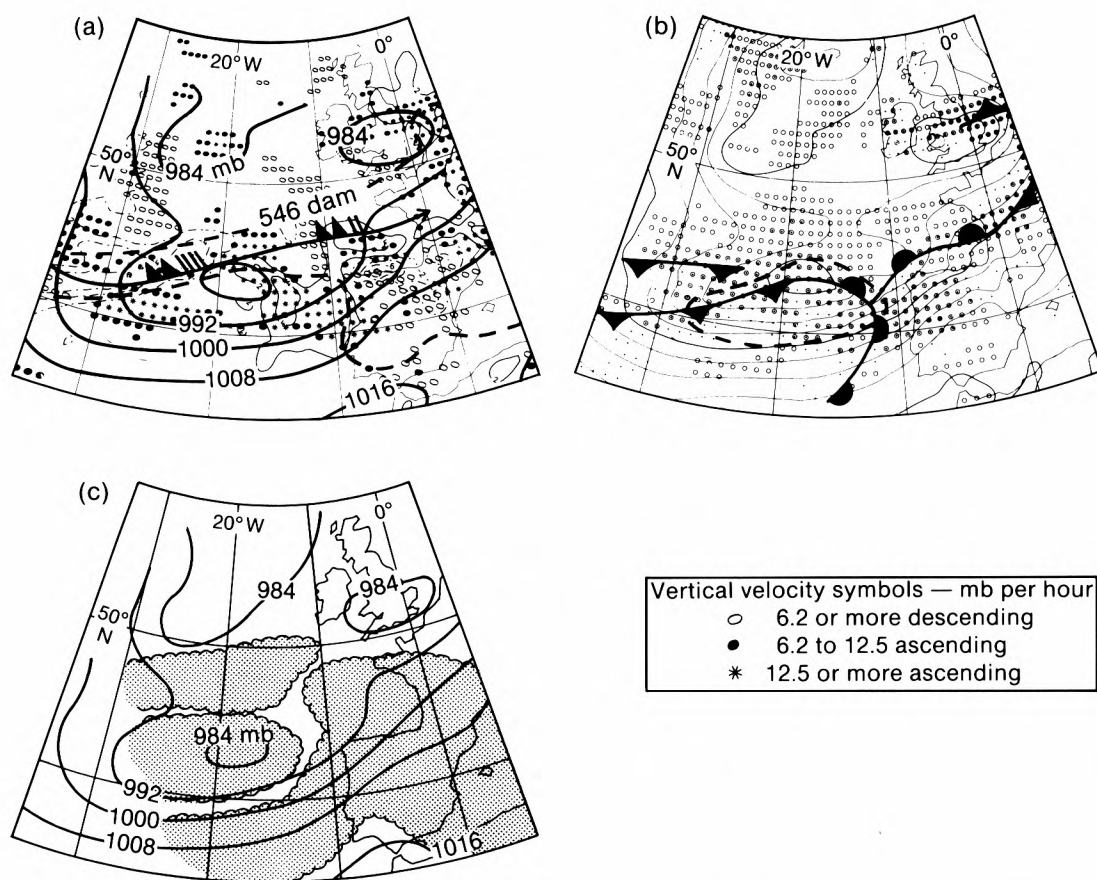


Figure 2. Charts for 0000 GMT on 15 October 1987: (a) composite fine-mesh model analysis showing jet-stream core (kn), 1000–500 mb thickness (---) and PMSL isobars (—) superimposed on the average (850–500 mb) fields of thermal advection (contours °C per 6 hours, solid lines warming, dashed lines cooling) and vertical velocity (see key), (b) composite fine-mesh model analyses of PMSL isobars (—), warm boundary of 850 mb wet-bulb potential temperature field (—) and areas of deep convection (---) superimposed upon fields of medium (○) and low (●) cloud (cloud is defined as relative humidity $\geq 96\%$ present at any model level — about four to choose from) and (c) manually fine-tuned PMSL isobars (—) and jet-stream core (kn) superimposed upon cloud areas obtained from satellite imagery (---).

The baroclinic zone was associated with a very strong jet core in the upper troposphere and at this time the core speed maximum was located well to the west near 40° W. The diagnostic vertical motion field indicated ascending air across the whole of the broad surface trough with strong ascent over and just east of the main centre. Ascent extended well to the rear of the trough despite the presence of cold advection and this ascent was almost certainly associated with the positive vorticity advection on the cold side of the advancing jet stream. Indeed, the whole area of ascent west of the main surface low pressure centre must have been due to the positive vorticity advection whilst the strong ascent ahead of the surface centre was probably largely due to warm advection.

It is interesting to compare the diagnostic cloud analysis (Fig. 2(b)) with the corresponding Meteosat imagery (Fig. 2(c)) and to note how well the detail north-west of Corunna is represented by the model. The model convective cloud parametrization indicated some very deep instability (tops up to FL450) just on the warm side of the baroclinic zone within the broad surface trough.

The composite charts may be interpreted with equations (1) and (3) to make the following deductions about the development and evolution of the system. The surface circulation centred on 43°N , 19°W is associated with a thermal ridge, and strong ascent is evident on the northern and eastern flanks of this small system. Warm advection east of the surface centre and cold advection to the west beneath the jet core will translate the thermal ridge eastwards. The ascent will tend to cool the air adiabatically, but noting the presence of cloudiness and deep convective activity it is most likely that the latent heat supported by diabatic heat will tend to maintain the intensity of the thermal ridge despite the presence of ascent. Thus, strong PMSL vorticity production could be expected east of the surface centre due to positive contributions from all three thermal terms on the right-hand side of equation (3). This will manifest itself on the charts as translation plus some intensification of the thermal ridge. There is little indication of any significant change of PMSL vorticity within and just west of this centre. However, there is very strong ascent further west centred near 41°N , 27°W with a marked PMSL trough. This region of ascent is clearly associated with vorticity advection ahead of the upper trough; inspection of the terms in equation (3) suggests that strong PMSL vorticity production is likely within this PMSL trough due to the combined effects of vorticity advection aloft, and latent and diabatic release. This implies that as upper-contour heights fall above the PMSL trough a corresponding fall of total thickness due to adiabatic cooling will be mitigated by the local heating terms. This results in an increase in cyclonic circulation at the surface. Further north-west, beneath the cold side of the jet core, despite the dominance of vorticity advection over cold advection, the air appears drier and less unstable so that PMSL vorticity production will be a limited process. At the same time the combination of horizontal advection and adiabatic cooling will tend to cause a relatively rapid fall of total thickness towards the east and south-east.

5. 1200 GMT on 15 October

By 1200 GMT (Fig. 3(a)) the elongated surface trough was centred north-west of Corunna. The baroclinicity was at least as strong as analysed earlier but no distortion had occurred (nor indeed was expected with the symmetrical thermal advection about the associated thermal ridge, implying emphasis on translation). The surface trough had deepened significantly over a broad area consistent with the expectations (Fig. 3(d)). It seems reasonable to suppose that the centre located near 43°N , 19°W at 0000 GMT had moved to the Brest peninsula whilst the developing centre near 41°N , 27°W at 0000 GMT had moved to be north-west of Corunna. The jet core located above the surface trough was about as strong as earlier (maximum speeds about 140 kn) and the diagnostic vertical velocity revealed strong ascent being maintained across the whole surface trough. The strongest ascent was associated with strong warm advection but ascent was present over the surface centre and to the rear despite cold advection in the lower troposphere. Upper vorticity advection was almost certainly the cause of ascent in the middle troposphere to the north-west of Corunna. However, it was noteworthy that the region of strong descent beneath the main (i.e. strongest) jet core and associated strong cold advection had advanced considerably relative to the surface low pressure centre.

Comparison of the diagnostic cloud analysis (Fig. 3(b)) with Meteosat imagery (Fig. 3(c)) reveals how well the model appears to fit reality; however, there is one area of significant difference. Satellite imagery reveals a small coherent cloud system resembling a positive vorticity advection maximum (PVA) just west of 20°W , north of 40°N . The model has not only poorly represented this feature but also diagnoses descent in the region. Furthermore the model apparently failed to assimilate an aircraft report of 175 kn near 40°N , 25°W at 0905 GMT so it would appear that the model speeds are up to 30 kn light at the base and rear of the upper trough near 25°W . By inference there is probably ascent occurring in mid troposphere at 20 – 25°W on the cold side of the jet core and this would account for the presence of the PVA in the imagery.

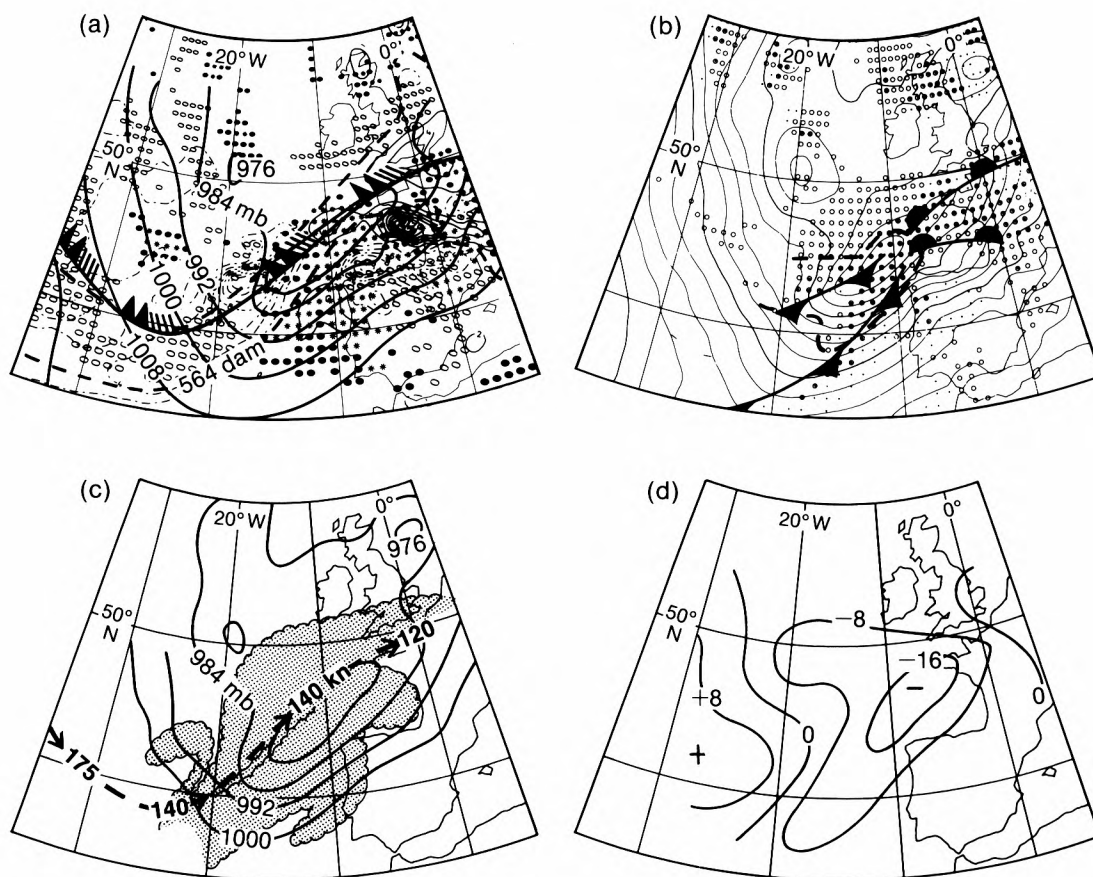


Figure 3. Charts for 1200 GMT on 15 October 1987: (a) to (c) as in Fig. 2 with (d) changes in PMSL (mb) during the previous 12 hours.

Despite the increase of circulation within the surface trough and strongly maintained ascent, 1000–500 mb total thickness values associated with the surface centre have remained virtually constant over the previous 12 hours. This indirectly reveals the combined effects of latent and diabatic heat transfer in the development process.

On the basis of the (modified) diagnostic analysis, further intensification of the surface pressure trough is to be expected. The main centre lies within a region of strong vorticity advection aloft, strong ascending air, a cloudy environment and associated convective activity; all factors combining to increase the PMSL cyclonic vorticity. At the same time the symmetry of thermal advection about the thermal ridge associated with the surface low pressure centre implies a strong element of translation being maintained. The magnitude of thermal advection had increased substantially over the past 12 hours especially in the regions flanking the main surface cyclonic centre and it was the cold advection that had increased the most.

Extrapolation of the above considerations leads to a possible conflict of developments. On the one hand the advancing west-north-west jet-stream core, with the associated PVA cloud cluster, may be expected to encroach even further upon the main surface trough causing more substantial cyclogenesis. On the other hand the region of strongest cold advection is now ahead of the west-north-west jet stream

and would be expected to oppose the effects of the latter especially if cyclogenesis continues as expected due to vorticity advection aloft already in the region of the broad surface trough north-west of Corunna.

Some reference should be made to the appearance of an apparent dry 'slot' in the satellite imagery. This feature appears to be closely related to the jet core itself and its existence is probably linked to the dynamics of the air motion through the jet-core axis, as illustrated in Fig. 1, for example. In other words the dry slot represents a tracer which can identify the position of a strong jet-stream core.

6. 1800 GMT on 15 October

By 1800 GMT further intensification and deepening had occurred within the broad surface trough with the main cyclonic centre now located north of Corunna (Fig. 4(c)). Late data reveals that the operational numerical analysis (Figs 4(a) and 4(b)) has placed the cyclonic centre too far north-east towards the Brest peninsula. The necessary modification to the model diagnostics therefore includes a phase shift of the thermal ridge axis and corresponding shifts in the location of thermal advection maxima. The jet-core speed is about right though. The flow appears to be marginally anticyclonic at jet-stream level but it is not clear whether the diagnosed presence of ascent above the surface cyclonic centre is due most to vorticity advection at middle or at higher tropospheric levels. The magnitude of cold advection is still dominant, centred just north-west of Corunna. Significantly the diagnostic vertical velocity analysis reveals that descent has spread across the whole south-west quadrant of the surface cyclonic centre, indicating the increased dominance of cold advection. The phase adjustments to the model analysis described above should not affect the vertical velocity analysis relative to the system except that, with the likelihood of cold advection north-west of Corunna being even stronger, descent was probably correspondingly stronger.

The satellite imagery revealed significant changes during the 6 hours preceding 1800 GMT. The PVA cloud cluster lost definition and the main cloud mass to the north-west of the surface trough was showing signs of breaking up, probably due to strong descent, whilst a tongue of the lower cloud began to move east within the circulation of the intensifying cyclonic centre. The jet-stream analysis for 1800 GMT was consistent with the evolution in the satellite imagery; the jet core was clearly broken near 20° W and considerably weaker than hitherto in this region. The maximum wind speeds now appeared to be close to the position of the surface cyclonic centre. This evolution in the jet-stream structure over the 6 hours was highly significant and had dramatic consequential effects upon the evolution in the PMSL vorticity production. There is no direct evidence to prove that the 175 kn jet core at 1200 GMT did not subsequently propagate forward and encroach upon the surface trough, but the sequence of satellite imagery suggests that it did not do so. The associated PVA cloud cluster was clearly losing definition by 1500 GMT and there was the first sign of break up appearing in the main cloud mass at this time also.

Extrapolation of developments forward from this time needs careful assessment as follows:

- (a) Although the areal extent of ascending air has been reduced considerably, ascent is still present above the surface cyclonic centre so that further deepening is to be expected. Whether the ascent is due to mid-tropospheric or upper-tropospheric vorticity advection, the direction of advection is towards the north-east so that the surface centre should be transferred north-east too.
- (b) The cold advection through the baroclinic zone south-west of the cyclonic centre is very strong and considerably stronger than the warm advection in the zone north-east of the centre. More significant, however, is the change in sign of upper-vorticity advection; the south-west jet is now a separate feature and with the strongest winds apparently located above the PMSL centre; the region south-west of this centre and to the cold side of the jet core is an area of negative vorticity advection (see Fig. 1 for an example). Hence the thermal advection and vorticity advection terms are combining

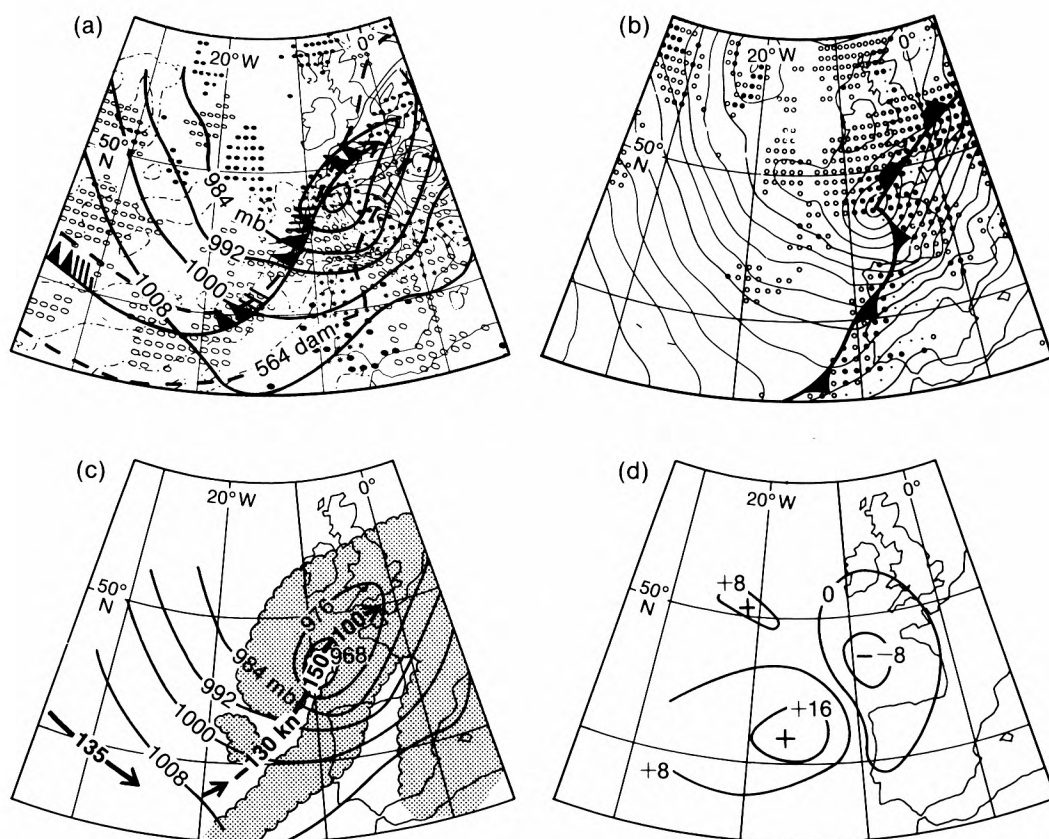


Figure 4. Charts for 1800 GMT on 15 October 1987: (a) to (c) as in Fig. 2 with (d) changes in PMSL (mb) during the previous 6 hours.

to produce strong descent and the production of anticyclonic vorticity in the PMSL field to the south-west of the surface centre. This manifests itself on the charts as a rise of upper-contour heights coupled to a fall of thickness values leading to a net strong rise of surface pressure. Thus, further deepening of the centre will lead to even stronger gradients in the south-west quadrant. Evidence that this evolution was already occurring at 1800 GMT is provided in Fig. 4(d) which illustrates the PMSL change over the preceding 6 hours.

7. 0000 GMT on 16 October

By 0000 GMT on the 16th the surface cyclonic centre had transferred north-east and deepened further, the deepening being more confined in areal extent than before, as expected. The surface gradients in the south-west quadrant had increased further, too, with very strong cold advection being maintained. Fig. 5(d) reveals in a spectacular fashion how the changing roles of the main dynamical forces created a substantial impact upon the PMSL. The 500 mb trough was almost vertically above the surface circulation and cyclonic vorticity was now present at 250 mb (not shown) directly above the surface system due presumably to deep upward penetration by the vertical transport of vorticity. The diagnostic vertical velocity (not shown) suggests that ascent was almost certainly confined to the north and descent confined to the south of the surface cyclonic centre so that further deepening was unlikely.

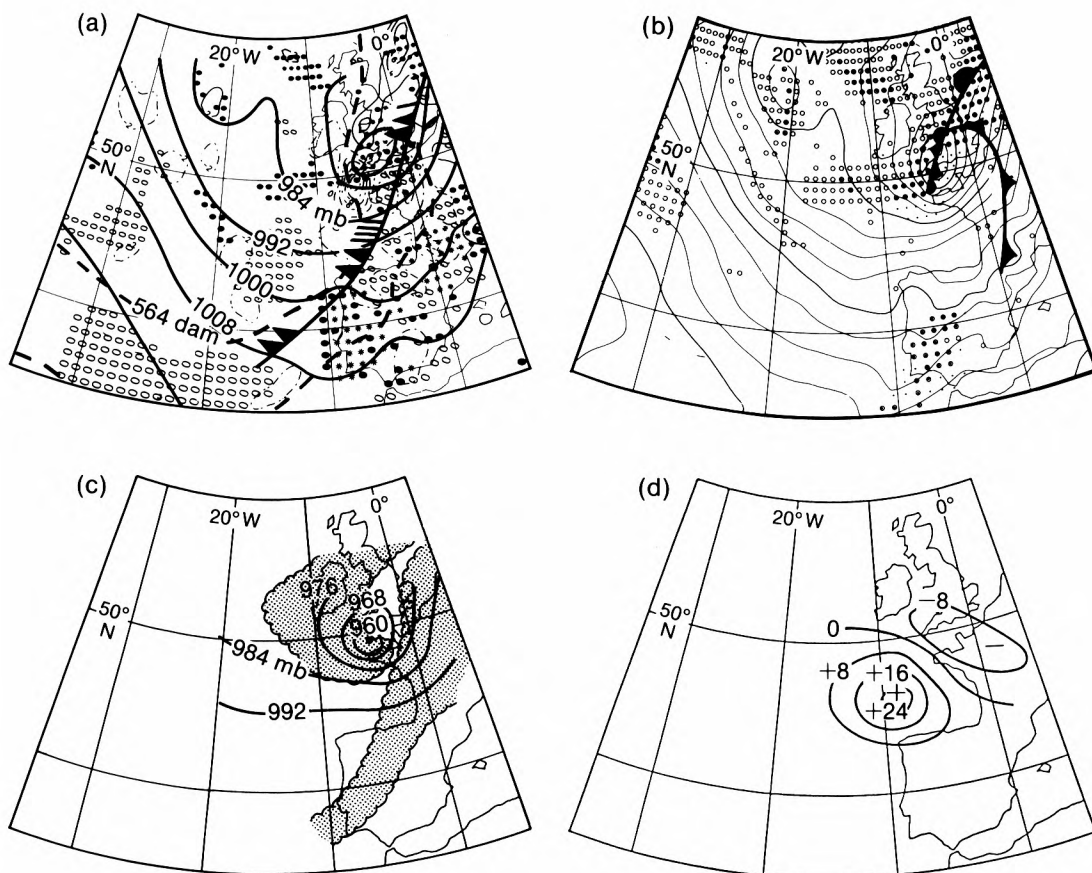


Figure 5. Charts for 0000 GMT on 16 October 1987: (a) to (c) as in Fig. 2 with (d) changes in PMSL (mb) during the previous 6 hours.

Significantly the baroclinicity has remained strong and undistorted so that the thermal advection fields, which were still symmetric about the thermal ridge axis, would combine directly with the vorticity advection fields to maintain rapid north-east movement beyond this time.

8. Concluding remarks

It has been demonstrated that the evolution of the intense depression which affected southern England during the night of 15/16 October 1987 can be explained, at least in qualitative terms, by reference to basic equations and using composite diagnostic analyses derived from the NWP model. This itself is of some comfort because if composite diagnostic analyses of the sort described in this paper can be made operationally available quick enough to be useful there is a good chance that the forecaster can make important decisions more quickly and more confidently than would otherwise be possible. In the case of the storm described in this paper, it was not until the 1800 GMT analysis was fully diagnosed that the exceptionally strong surface pressure gradients to the rear of the system could be anticipated with any real conviction. Under present operational conditions such deductions would be made between 2100 and 2200 GMT. In future, improvements in data processing should bring this period forward by an hour at least.

Finally it is interesting to compare the evolution of the maximum wind pattern as portrayed in the composite sequences in Figs 2 to 5 with the sequence of 250 mb wind forecasts from one of the rerun fine-mesh forecasts based upon the optimum analysis at 0000 GMT on the 15th. Two such fine-mesh forecasts are described in the official storm report (Meteorological Office 1987) and both produced excellent PMSL forecasts for successive stages in the development phases during the 15th. Fig. 6 is taken from the storm report. The most significant difference is at 1200 GMT in the position of the jet-stream maximum (compare Fig. 3(a) with T+12 in Fig. 6). If, as is suggested here, the PVA cloud cluster (as shown in Fig. 3(c)) identified the jet-stream cold exit position at 1200 GMT then the T+12 forecast in Fig. 6 is, strictly, incorrect in some detail. However, the T+18 forecast is reasonably consistent with Fig. 4(c) which could be interpreted as also supporting the suggestion here that the upstream jet-core

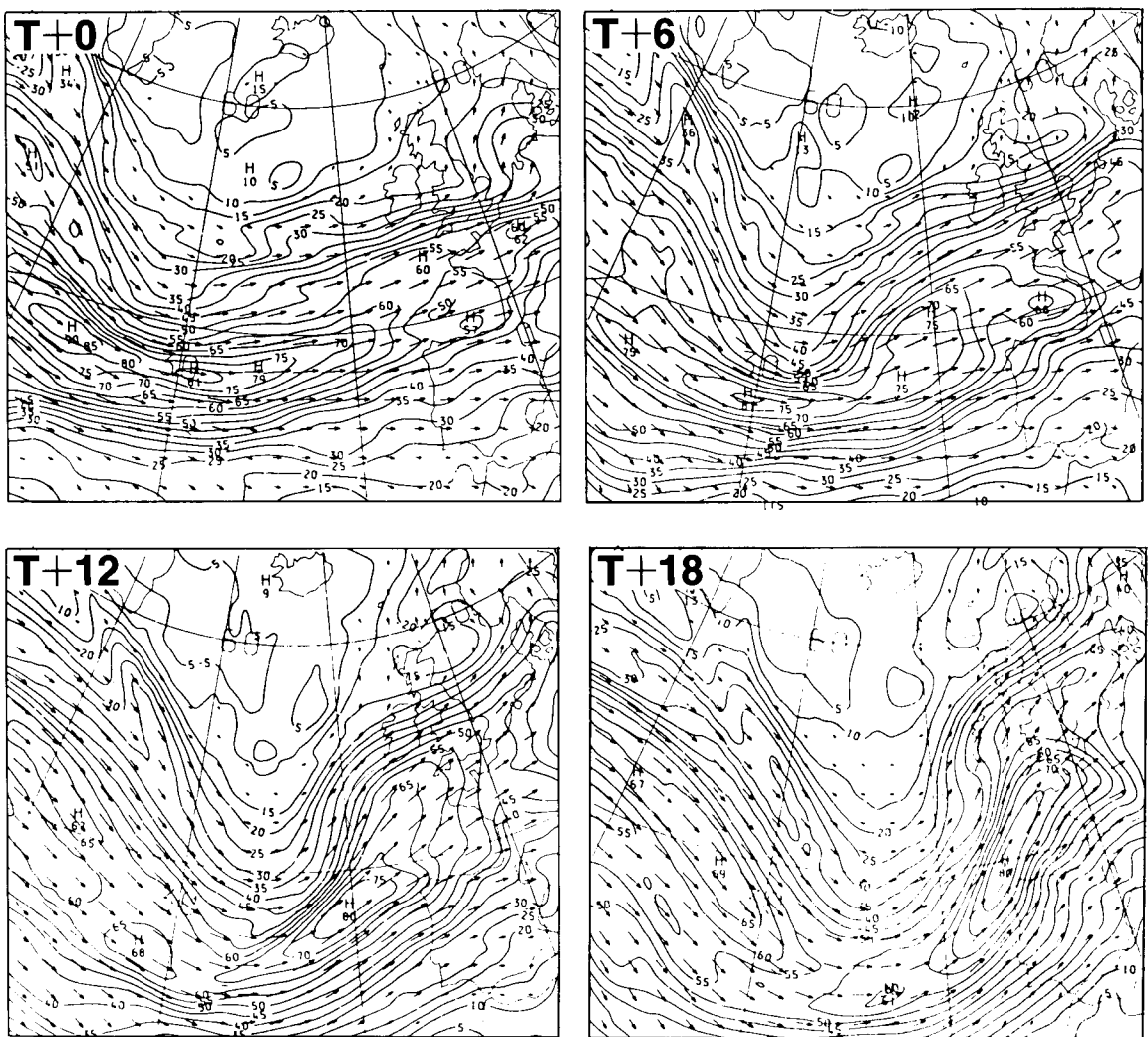


Figure 6. 250 mb winds (m s^{-1}) from a rerun fine-mesh forecast based upon the optimum analysis at 0000 GMT on 15 October 1987. Length of arrows is proportional to wind speed.

PVA cloud cluster became an irrelevance to the further development of the storm. Diabatic heating from the warm sea on the cold side of the baroclinic zone could possibly explain the weakening of the upstream jet maximum which probably occurred between 0900 and 1500 GMT with dramatic consequences for the dynamical evolution of the storm during the subsequent 9 hours.

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A large amplitude gravity wave detected by radiosonde*

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Summary

The routine operational radiosonde launched from Shanwell in Scotland at 2318 GMT on 12 December 1986 recorded very large variations in temperature in the lower stratosphere. These were accompanied by strong vertical shear in the horizontal wind and large variations in the rate of ascent of the balloon. There are indications that these disturbances were due to quasi-stationary gravity waves.

1. Introduction

The UK RS3 radiosonde system provides highly reproducible temperature measurements combined with a very fast time constant of response. Similarly, the operational Cossor radar is capable of resolving fine structure in the horizontal wind profiles on a vertical scale of a few hundred metres and amplitude of the order of 1 metre per second. Much of the detail in the operational radiosonde sounding is discarded when the TEMP messages are composed but is clearly of value in research projects.

Whilst it is widely recognized that the breaking of gravity waves exerts a powerful influence on the middle atmosphere circulation, only recently has the influence of inertia-gravity wave motion on tropospheric flow been considered seriously by numerical modellers. Unfortunately, the sort of information required by the modeller — large-scale, area-averaged vertical momentum fluxes — is not available. The case-study presented here deals with an extreme gravity wave event over mountains of modest stature and provides some insight into the kind of information about gravity waves that can be obtained from radiosonde data.

* An abridged version of a paper by Shutts, Kitchen and Hoare (1988) which appeared in the *Quarterly Journal of the Royal Meteorological Society*.

2. The observations

The routine radiosonde launched from Shanwell at 2318 GMT on 12 December 1986 recorded very large amplitude excursions in temperature in the lower stratosphere which were identified as being exceptional by the staff at the radiosonde station. The detailed profiles of temperature and wind derived from the RS3 radiosonde system fine-structure archive are given in Fig. 1. To put the ascent in context, the balloon trajectory is given in Fig. 2 and the synoptic situation is illustrated in Fig. 3.

Fig. 1 shows that between 15.5 and 22 km the radiosonde encountered strong vertical gradients in temperature and wind. In particular, at the stable layer around 15.7 km, the measured temperature increased by 9.9 °C for a change in computed geopotential height of only 134 m. This very stable layer was followed by an essentially isentropic layer about 2 km deep (see inset profile of potential temperature in Fig. 1(a)), and over this layer the total fall in temperature was 15.9 °C. Above 18 km another very stable layer was encountered, although not as pronounced as that at 15.7 km, followed by a deep layer with an average lapse rate of approximately 5 °C km⁻¹ but interrupted by three small inversions. The radiosonde balloon burst at an altitude of 24.1 km.

These large temperature variations were accompanied by strong vertical shear in the horizontal wind speed profile. The bases of the two stable layers identified above were both associated with local maxima in the wind speed profile (see Fig. 1(b)) and the isentropic layer was a region of much lighter wind. The transitions between the intense stable layers and the isentropic layer were marked by substantial changes in wind speed and direction.

The rate of ascent of the balloon computed from the change in radiosonde geopotential with time between adjacent data points in the fine-structure archive is plotted in Fig. 1(d). The mean rate of ascent of the balloon through the stratosphere was about 6 m s⁻¹ but superimposed on this mean value were variations of ±6 m s⁻¹. In the two stable layers bounding the isentropic layer the ascent rate was observed to fall to close to zero, whereas in the isentropic layer itself the ascent rate was enhanced by over 5 m s⁻¹. The close agreement between these rates of ascent and those computed from the data from the Cossor wind-finding radar prove that the variations in the rate of ascent were real.

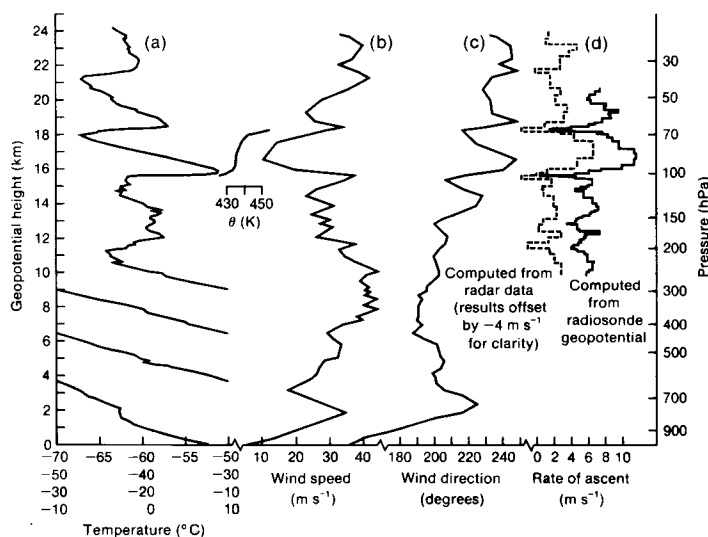


Figure 1. Profiles from the radiosonde launched at Shanwell at 2318 GMT on 12 December 1986 showing (a) temperature and potential temperature (θ), (b) wind speed, (c) wind direction and (d) rate of ascent computed from radar data and radiosonde geopotential.

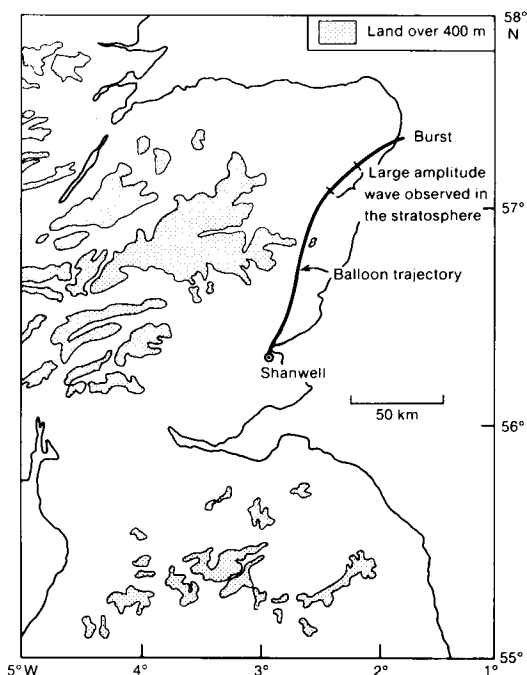


Figure 2. Balloon trajectory of the Shanwell ascent at 2318 GMT on 12 December 1986.

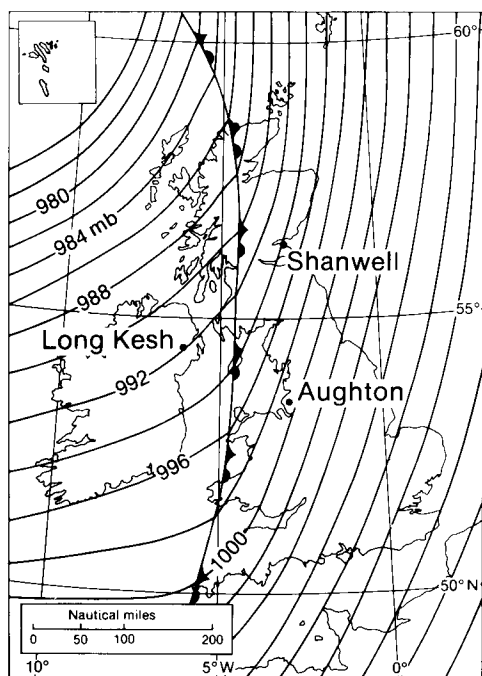


Figure 3. Synoptic situation at 0000 GMT on 13 December 1986 plus location of stations mentioned in the text.

Ascents from Shanwell at 1117 GMT on 12 December and 1118 GMT on 13 December show that the features in the stratospheric temperature and wind profiles shown in Fig. 1 were ephemeral. The geographical distribution of the fluctuations was investigated by examining the ascents from Aughton and Long Kesh. They also showed strong variations in temperature (10 °C over 2 km at Long Kesh) in the lower stratosphere but there were no obviously sympathetic fluctuations in wind speed and ascent rate.

3. Theoretical interpretation

A simple model of finite-amplitude gravity wave motion can be used to interpret the balloon observations.

For two-dimensional incompressible flow with constant wind speed and static stability it is possible to derive an expression for the streamlines of finite-amplitude gravity waves. From this the horizontal and vertical wind components can be derived.

A sinusoidal stationary wave solution may be used to model the ascent of an idealized radiosonde balloon through a uniform airstream with a gravity wave. It will be assumed that the balloon travels with the velocity of the ambient flow plus an upward component equal to the rate of ascent of the balloon in an atmosphere at rest. This allows the trajectory of the idealized balloon to be computed exactly and provides some simple mathematical expressions for the values of potential temperature which would be observed by the radiosonde (details are given in Shutts *et al.* 1988*).

Fig. 4 shows the profile of potential temperature measured vertically through a gravity wave and that seen by a balloon passing through the wave (various parameters derived from the Shanwell ascent have been used). The balloon perceives a markedly different 'vertical wavelength' as it samples phase variations in its horizontal as well as vertical motion fields. Where the downward motion of the air becomes comparable with the balloon's ascent, a marked fictitious inversion appears. For example, when the downward speed in the gravity wave exactly equals the 'still air' rate of ascent of the balloon, the balloon is no longer ascending yet it will still record a change in potential temperature as it moves horizontally through the stationary wave field.

Some of the features illustrated in Fig. 4 also appear in Fig. 1. For example, the marked inversion near 15.7 km in Fig. 1(a) is related to the decreased rate of ascent of the balloon to close to zero; even so a highly stable layer is still implied. In addition to shallow stable layers, there are layers which are nearly isentropic where the balloon travels upward at almost twice its 'still-air' ascent rate.

Determination of the vertical wavelength of the gravity wave is complicated by the slantwise ascent of the balloon: the apparent wavelength in Fig. 1(a) will be a mixture of horizontal and vertical phase variations, as in Fig. 4. However, the simple wave model provides strong evidence that the disturbance is a quasi-stationary gravity wave with horizontal and vertical wavelengths of about 16 and 6 km respectively, although there is some uncertainty about the actual phase speed.

The negative correlation between the fluctuations in the horizontal wind and vertical motion in the lower stratosphere (see Fig. 1) indicates that the gravity wave was accompanied by a downward momentum flux. Dr S. Mobbs and Ms J. Rees from the Mathematics Department of the University of Leeds have computed the momentum flux from the fine-structure data. They found that between 16 and 17 km, the downward momentum flux is approximately 3.3 N m^{-2} which is over ten times larger than the surface frictional drag expected in non-mountainous regions. Such a substantial flux of momentum implies a powerful influence on the lower stratospheric flow — albeit over a limited region.

* Shutts, G.J., Kitchen, M. and Hoare, P.H.; A large amplitude gravity wave in the lower stratosphere detected by radiosonde. *QJR Meteorol Soc*, 114, 1988, 579–594.

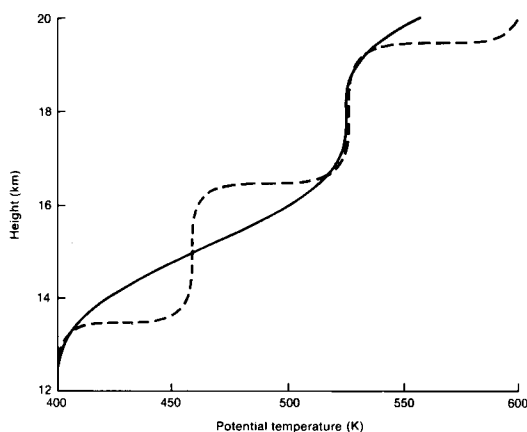


Figure 4. Potential temperature variation in a sinusoidal gravity wave measured vertically (solid line) and following an idealized radiosonde balloon (dashed line).

4. Conclusions

This study of the Shanwell ascent at 2318 GMT on 12 December 1986 demonstrates the potential of operational radiosonde soundings for analysing the structure of stationary, orographic gravity waves. Using a long period of routine radiosonde observations, it may be possible to build up a picture of the frequency and geographical distribution of gravity wave breaking in the lower stratosphere. This might be sufficient to permit the verification of gravity wave parametrization schemes now being used in operational weather prediction models.

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Lessons from the dispersion and deposition of debris from Chernobyl

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Summary

Radioactivity escaped from the wrecked reactor at Chernobyl for 10 days and spread over most of Europe. Part of the debris crossed Britain a week after it was emitted. Heavy thunderstorms and a northward-moving cold front washed out much of the radioactive iodine and caesium, especially on to the upland areas of North Wales, northern England, south-west Scotland, and Ulster. Several lessons have been learnt, including information on the dry and wet removal rates. These lessons are discussed in this paper.

1. The accident

The release of radioactive debris into the atmosphere from Reactor 4 at the nuclear power plant at Chernobyl in the Ukraine was the most serious in the history of the civil nuclear industry.

The disaster started in the early morning of 26 April 1986 during a rather special experiment. The aim was to test the safety of the reactor should two breakdowns occur simultaneously: firstly should the steam from the reactor suddenly fail to reach the great turbine generators and secondly should the

supply of electricity from the national grid to the turbines be cut off. The question then was: would the mechanical inertia of rotation of the turbines be sufficient to generate enough electricity to keep such vital components as the pumps working within the reactor for up to 50 seconds before stand-by diesel generators could be started and take over the necessary supply?

In fulfilment of this experiment the power of the reactor was brought to well below 20% of normal power in spite of the fact that the particular design of the reactor at Chernobyl was known to become potentially unstable at such low levels. At 0123 local time this instability was realized and the reactor accelerated from a small fraction of full power to 100 times full power in just 4 seconds, causing an explosive generation of steam and the rupturing of pipes and protective shielding. The core was now exposed to the air and rapid chemical reactions resulted causing a second explosion. The reactor building was destroyed and burning graphite and core debris were spewed out over the site and into the atmosphere.

The loss of radioactive material to the atmosphere persisted for nearly 10 days in spite of valiant efforts to seal the reactor with about 5000 tonnes of material dropped from helicopters. Roughly 2×10^{18} becquerels of activity were released into the air during this period, about a third of which went out in the first few hours. (A becquerel (Bq) represents one atomic disintegration per second.) Debris released in this early period was very hot and rose 1 or 2 kilometres into the atmosphere. Later emissions were much cooler and travelled largely within the boundary layer over long distances except when advected upwards at fronts or in large convective clouds.

2. The spread of debris over Europe

At the time of the explosion a ridge of high pressure was centred over north-west USSR (see Fig. 1(a)). The wind circulation associated with this ridge carried the upper part of the plume away towards the Baltic Sea and Scandinavia. Nearer the ground, the nocturnal clear skies had resulted in the development of a 500 m deep surface-based inversion. This inversion, whilst not preventing the sedimentation of the larger particles in the airborne debris, helped to insulate the local population from

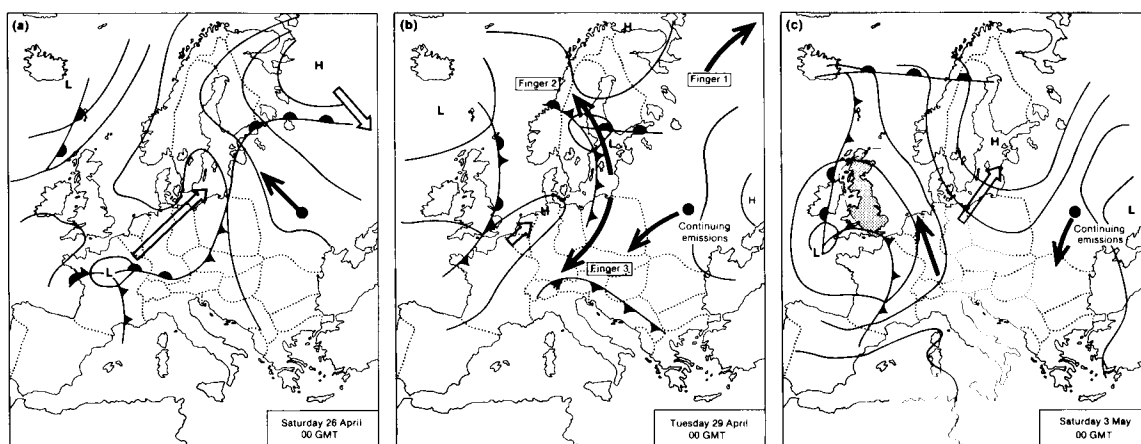


Figure 1. Schematic maps for (a) 0000 GMT on 26 April 1986, (b) 0000 GMT on 29 April 1986 and (c) 0000 GMT on 3 May 1986 showing how synoptic developments influenced the spread of radioactive debris from Chernobyl (●) in the days following the accident; \Rightarrow indicates movement of synoptic features, \longrightarrow movement of part of the Chernobyl cloud, and stippled area position of radioactive cloud over the United Kingdom.

the downward diffusion of the inhalable small particles which could have caused a great deal of damage within peoples' lungs.

Once the plume reached Scandinavia, it split into three 'fingers' (see Fig. 1(b)). One moved away to the east across northern parts of the USSR into Japan and China. A second finger, caused by a jet ahead of the cold front of an active depression, crossed central Norway and the Norwegian Sea and moved towards North America. Heavy rain which affected this finger on 28 April resulted in very large depositions of activity in central Scandinavia which contaminated the lichens and mosses, the main diet of the Lapp reindeer. A third finger moved south-westwards in response to a transient ridge of high pressure which followed the depression across north-west Europe. This finger moved across central Europe and the Alpine areas into France and then turned northwards, entering the United Kingdom in the early hours of Friday, 2 May (see Fig. 1(c)).

3. Passage over the United Kingdom

The passage of the debris over Britain makes an interesting story which can only be summarized here. A fuller description is given in Smith and Clark (n.d.). Beautiful warm spring weather on Friday, 2 May experienced over much of Britain was soon replaced by wet and stormy conditions on the Saturday and Sunday as a depression to the south-west of Cornwall deepened and an associated cold front moved into the country. Additionally, the warm air moving in from France ahead of the front became increasingly unstable and thunderstorms developed over the south-east of England in the early hours of Saturday; these moved fitfully north-westwards and caught up the main body of the cloud of debris over North Wales and northern England. The storms drew great quantities of contaminated low-level air into their systems causing considerable rainfall and heavy depositions, particularly in Snowdonia, the Skipton area of Yorkshire, Cumbria, the Isle of Man, Ulster and south-west Scotland. Parts of the radioactive cloud were drawn off to the west across Ireland by the circulation of the depression, but most of the debris continued to move northwards, the tail of the cloud eventually leaving the northernmost parts of Scotland by the end of Sunday. However, small traces of activity were detected later in the subsequent week as parts of the debris drawn off by the depression recrossed the country. Some of these features can be seen in Fig. 2.

4. Deposition of hazardous nuclides

The cloud of debris contained a host of different radio-nuclides originating from the reactor. From a health point of view the most important of these were iodine-131, a short-lived isotope which gets into milk and then into human thyroids, caesium-134 with a half-life of about 2 years, and caesium-137 with a half-life of 30 years. The caesium isotopes can accumulate in the human body and, like the iodine-131, can cause cancer. Nevertheless, the risk of this is very small indeed and, except in the most heavily contaminated areas around Chernobyl itself, increases in cancer incidence within the population are likely to prove undetectable. The main pathway for these isotopes into the body is through foodstuffs and not by direct inhalation. Consequently the activity has to be deposited first on the ground. This deposition arises not just from the 'cleansing' action of rain, a process generally termed 'wet deposition', but also from dry deposition — the combined effect of sedimentation of larger particles under gravity, impaction of particulates and aerosols on leaves etc., and absorption of reactive gases by the soil and vegetation.

Dry deposition depends on the product of the concentration, C , of the material close to the surface and a so-called 'deposition velocity', v_d :

$$\text{Dry deposition} = v_d C.$$

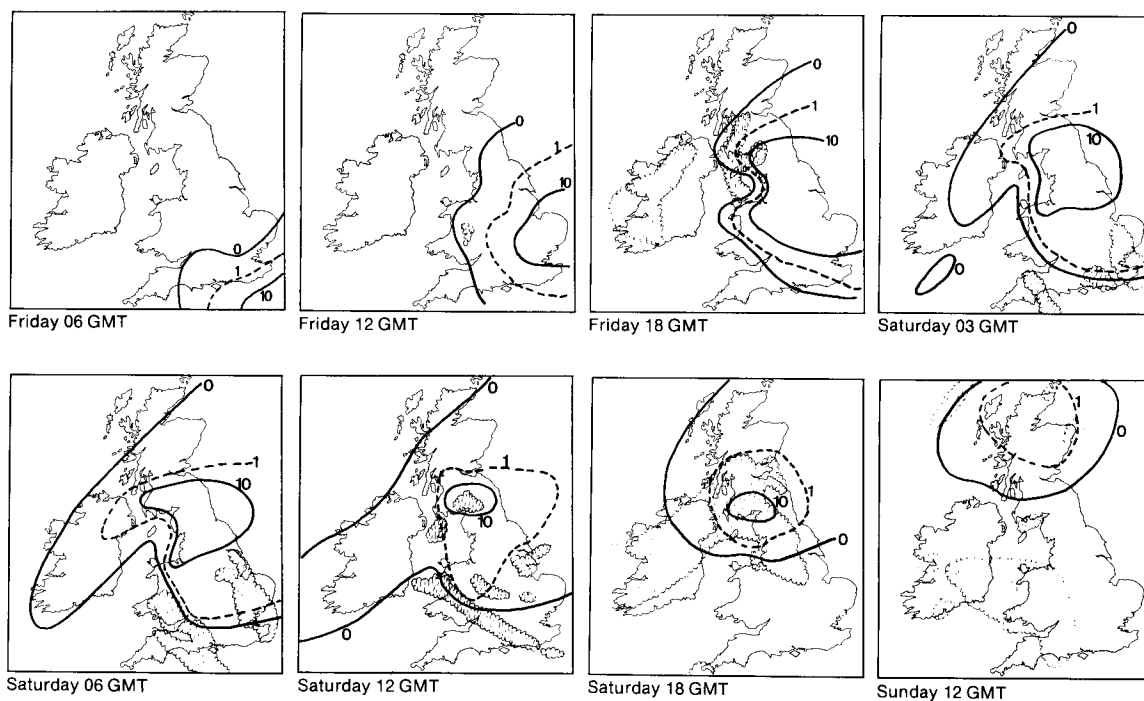


Figure 2. Position of radioactive cloud at various times as shown. Hatched areas indicate where some rainfall was reported and hence where significant wet deposition of radioactivity may have been occurring. Contours are in becquerels per cubic metre.

By comparison with wet deposition, dry deposition is rather slow — just 1 mm of rain can remove more material than can dry deposition operating over 24 hours. However, dry deposition is an almost continuous process whereas wet deposition is usually very intermittent. Consequently, in the deposition of acidifying species (in the acid rain problem) dry deposition is more important than wet deposition except in a few very wet areas of Europe like the Norwegian mountains.

In the Chernobyl debris, iodine-131 was partly gaseous in form and partly particulate. The gaseous component dry-deposited some eight times more rapidly than the particulate component. This can be inferred from the relative concentrations and depositions of both particulate caesium-137 and iodine in areas where no rain occurred (on the assumption that particulate iodine deposited as efficiently as the caesium).

The wet removal is assumed to follow the simplified expression:

$$\text{Wet deposition} = wCR$$

where C is the average concentration in the air during the rain, R is the rainfall expressed in millimetres and w is an empirically determined coefficient. Units of concentration are becquerels per cubic metre and units of deposition are becquerels per square metre. Based on measured depositions and air concentrations the following values of v_d and w have been inferred:

Iodine-131, gaseous: $v_d = 0.4 \text{ cm s}^{-1}$, $w = 490$,
 particulate: $v_d = 0.05 \text{ cm s}^{-1}$, $w = 650$.
 Caesium-137, particulate: $v_d = 0.05 \text{ cm s}^{-1}$, $w = 650$.

5. Rainfall over the United Kingdom

In the first few days and weeks following the passage of the Chernobyl debris over the United Kingdom the only rainfall data available in sufficient detail were from the weather radar output. Although the radar coverage at that time only covered England, Wales and the most southern parts of Scotland the picture provided was extremely useful and sufficiently accurate to pin-point the areas most likely to have been significantly contaminated by deposition. By July 1986 enough surface rain-gauge data had become available for a reasonable rainfall map for the whole of the United Kingdom to be drawn up, although it was not until late September that a complete quality-controlled map could be prepared. Fig. 3 shows this final rainfall picture. The values represent the rainfall which actually intercepted the radioactive cloud. Two points are of particular interest: firstly the convective storms resulted in narrow but very elongated 'footprints' of rainfall and secondly it is clear that the strength of the storms responded in a quite dramatic way to the nature of the terrain over which they were passing. Level uniform countryside tended to weaken the storms whereas large cities (e.g. London), mountains, and stretches of sea like the Solway Firth, rapidly strengthened them.

6. Total depositions

Fig. 4 gives the estimated deposition for caesium-137 over the United Kingdom using the deposition parameters given above in conjunction with the rainfall data implicit in Fig. 3 and the assessed concentrations of caesium-137 in the air. The levels of deposition vary enormously over the country and the highest values reflect the areas of heaviest rainfall. The maximum estimated deposition is in excess of $30\,000\text{ Bq m}^{-2}$ near Whithorn in Dumfries and Galloway. These depositions and the corresponding ones for iodine-131 can be integrated over the whole of the United Kingdom and compared with the estimated emissions from Chernobyl:

- Iodine-131: Total deposition on the United Kingdom = $2 \times 10^{15}\text{ Bq}$,
Deposition as a fraction of total emission = 0.7%,
Deposition as a fraction of first day's emission = 2%.
- Caesium-137: Total deposition on the United Kingdom = $3 \times 10^{14}\text{ Bq}$,
Deposition as a fraction of total emission = 0.8%,
Deposition as a fraction of first day's emission = 3%.

The depositions are compared with the emissions on the first day of the accident because trajectory analyses indicate that the debris that crossed the United Kingdom was emitted in a roughly 2-hour slot in the late morning of 26 April. It is interesting that a higher percentage of the caesium emission than of the iodine emission on that day was deposited on the United Kingdom; this can only be because the iodine, being partly gaseous, had lost more *en route* by dry deposition before reaching this country.

Caesium-134 is believed to have behaved in a very similar manner to caesium-137, and in fact was used to distinguish deposited caesium-137 arising from Chernobyl from that previously in the ground which had its origins in the weapons tests of the 1950s and 1960s. During the passage of the Chernobyl debris the concentration of caesium-134 was typically just over half that of the caesium-137. Consequently the total caesium-134 deposition on the United Kingdom is inferred to be about $1.5 \times 10^{14}\text{ Bq}$.

7. Agricultural effects

The consequences for agriculture in the United Kingdom were only of real significance in sheep farming. In all other aspects of agriculture the levels of activity were well below the emergency reference levels set by the Government (except for some game birds and freshwater fish in limited parts of

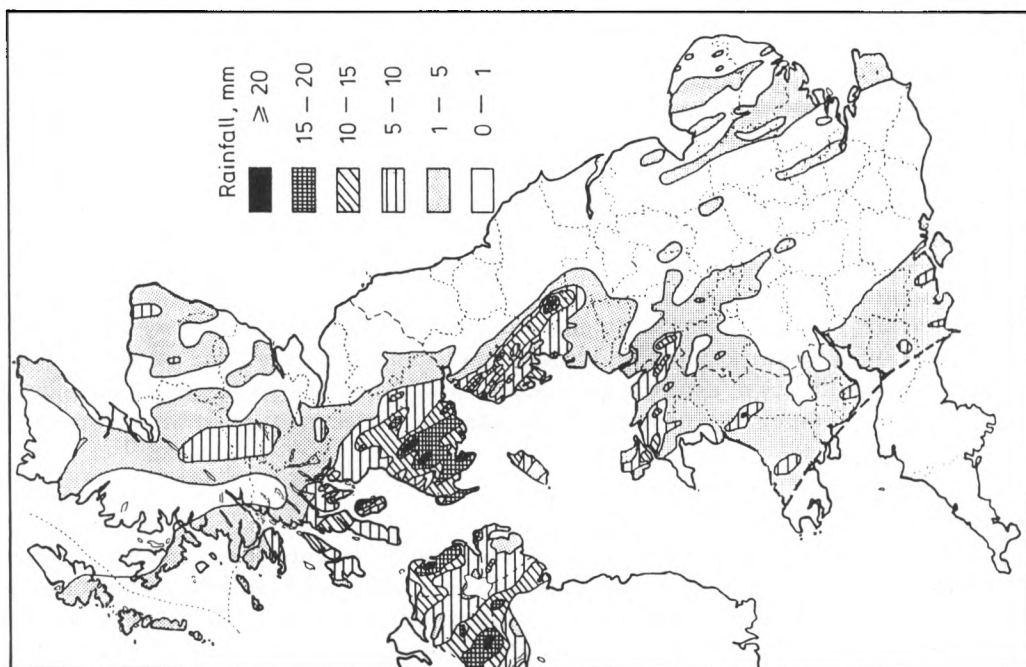


Figure 3. Rainfall, determined from over 4000 rain-gauge measurements, which intercepted the radioactive cloud. Rain which did not fall when the cloud was overhead is excluded. Dashed line indicates the south-western border of the debris.

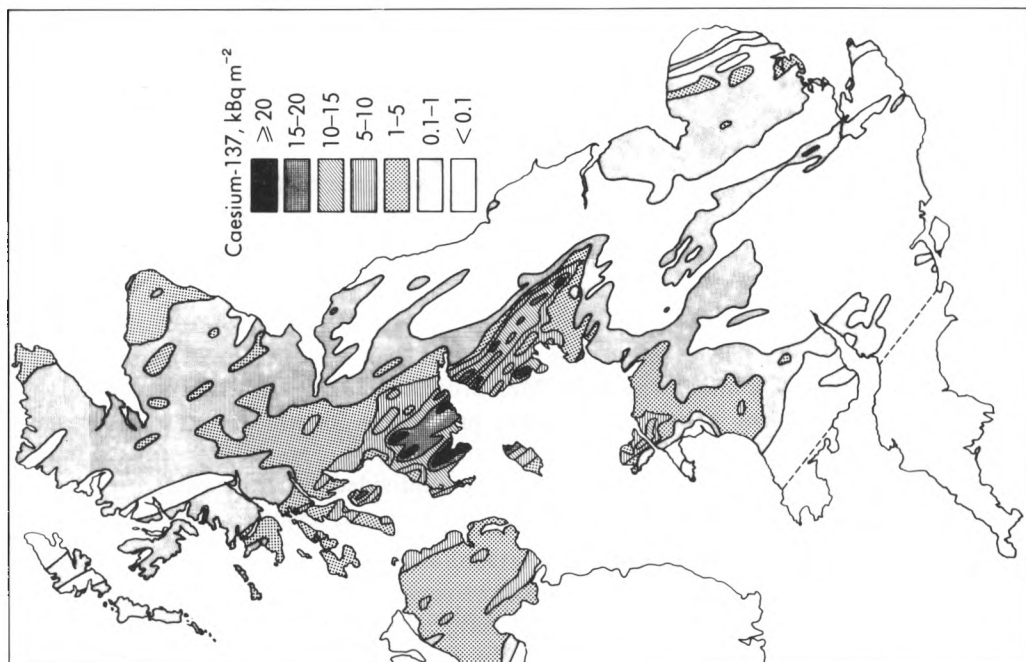


Figure 4. Empirically derived total depositions of caesium-137. Dashed line indicates the south-western border of the debris.

south-west Scotland). Unfortunately many upland sheep-farming areas were affected by relatively heavy depositions of caesium-137, and this led to restrictions on the movement and slaughter of sheep on farms where levels in the sheep in excess of 1000 Bq kg^{-1} have been recorded. To make matters worse, levels have changed only very slowly on some of these farms in contrast to the more rapid decline observed in many lowland areas. The important element appears to be the nature of the soil. Soils rich in clay minerals rapidly lock in the free caesium so that it becomes unavailable to the vegetation. Poor acidic soils typical of many upland areas are unable to do this and the caesium cycles through the uppermost humic layers of the soil and the vegetation so that its availability to grazing sheep falls off only very slowly.

8. Summary of the lessons of Chernobyl

A new perspective has been gained from the terrible accident at Chernobyl. This will be invaluable in the preparation of new models now under way in the Meteorological Office and elsewhere, and in the design and operation of monitoring networks and other procedures for use should another major accident ever occur. This perspective can be summarized through a listing of so-called 'lessons'. Limiting these to those with some meteorological interest, they may be subdivided into three categories: lessons regarding transport in the atmosphere, lessons regarding deposition and lessons for agriculture.

8.1 *Transport and dispersion*

(a) Synoptic-scale deformation: Close to the source, the plume probably behaved very much like a conventional plume from a factory chimney, growing under the action of three-dimensional turbulence in a quasi-conical manner. When the width of the plume exceeded 100 to 200 kilometres, the synoptic variations of velocity became dominant and the plume then grew through deformation as described by Gifford (1987).

(b) Wind shear in the vertical: Changes of wind speed and direction with height through the plume were principal factors in diluting the concentration within the plume, especially when deformation became dominant. Dilution occurs when shear is coupled with vertical mixing, either concurrently or successively through a diurnal cycle.

(c) Correction of trajectories using radiological data: Although it appears that most trajectory analyses carried out on the Chernobyl release have been reasonably successful in predicting the spread of the debris over Europe, it is almost certain that individual trajectories starting from Chernobyl at the same time differed significantly at long range and the apparent overall success simply reflects the very variable meteorological situation during the whole release. In other circumstances, differences might be more obvious. Radiological reports of activity would then be invaluable in optimizing the information that models are capable of giving. Fig. 5 shows the output of the Meteorological Office's basic Monte Carlo model simulation of the Chernobyl accident at four different times; these results are in apparent good accord with the known movement of the debris. This agreement has been optimized to some extent by judiciously selecting the best wind level in the light of radiological data.

8.2 *Deposition*

(a) Atmospheric stability at the source: Large releases will usually be hot releases and much of the airborne debris will rise away from the surface. How far it rises will depend critically on the stability of the air, and this will have consequences for the subsequent transport and deposition of the material. As seen earlier, a stable surface layer can protect the local population from much of the small inhalable particles and radioactive gases.

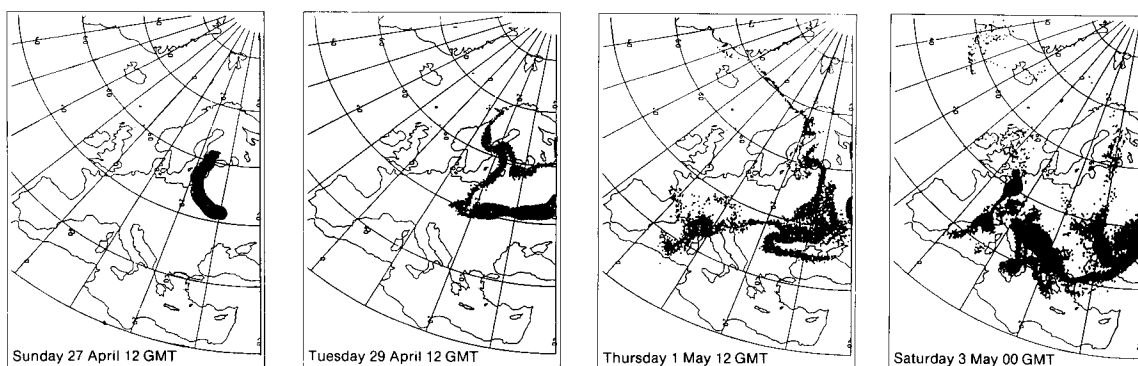


Figure 5. Simulation of the movement of debris from Chernobyl using a two-dimensional Monte Carlo model.

(b) Deposition rates for differing species: Washout rates and dry deposition velocities will differ significantly from one species to another, and these need to be well known in advance of any accident if model output is to be of real value.

(c) Convective rainfall and deposition shows banded structure: As evident in Figs 3 and 4, rainfall and deposition resulting from the thunderstorms during the passage of the Chernobyl debris over the United Kingdom were banded in narrow elongated 'footprints'. Interpolation between measurements of caesium-137 (for example) on grass or in soil should therefore be carried out with strong along-wind weighting and not with simple circular weighting.

8.3 Agriculture

(a) The importance of wet deposition: The Chernobyl accident has emphasized how much more efficient wet deposition is compared with dry deposition whenever rain occurs. Agriculturists wishing to monitor levels of deposition rapidly should therefore concentrate initially on areas where significant rain intercepted the debris. Quick help for this can be obtained from operational weather radar as long as the debris' movement is roughly known from models or from monitors in the field.

(b) Retention on vegetation: In areas where little or no rain occurred most of the deposition was through dry deposition and a high percentage was retained on the vegetation available to grazing animals. In areas of significant rain the total deposition may have been much higher but retention on the vegetation appeared to have been only some 10–25% of the deposited particulates, and very small indeed for the gases. This effect was very evident in the levels of iodine-131 in milk: levels in comparatively dry areas were not dramatically smaller than in wet areas for these reasons (Clark and Smith 1988).

(c) The influence of soil type on long-term effects: As seen from the aftermath of Chernobyl, soil type can critically influence the duration of the continued contamination of foodstuffs and grazing animals.

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551.501.9:358.4(425)

Closure of Meteorological Office at Royal Air Force Binbrook

J.G. Leslie

Meteorological Office, Royal Air Force Binbrook

The decision by the Royal Air Force to close their Strike Command airfield at Binbrook, Lincolnshire will terminate a Meteorological Office association with the locality dating back to the early years of the last war.

Meteorological Office staff, in uniform, were first drafted into Binbrook in 1940. Initially they supported Fairey Battle squadrons, then Wellingtons, and later, 460 Squadron of the Royal Australian Air Force flying Lancasters.

After the war the airfield remained active, but with observers and forecasters moving back into mufti. The first jet aircraft to arrive were Canberra bombers in 1951, which generated a need for meteorological information up to the low stratosphere on a regular basis. In 1960 staff were dispersed as the airfield came under Fighter Command, and an extensive reconstruction and runway lengthening programme was undertaken. Javelin squadrons were the first to arrive on reopening in 1962, but it was in 1965 that the aircraft arrived that were to have the longest and best known connection with Binbrook — the Lightnings. These supersonic air defence fighters of Numbers 5 and 11 Squadrons have remained until the present day, often on 24-hour alert against possible intruders from eastern airspace. New standards of vigilance in observing and short-term forecasting were demanded by the weather sensitivity and short endurance of these aircraft. However, judging by the lack of weather-related accidents in the last twenty-odd years, one may claim that the requirements have been well met.

It has not always been a comfortable life at Binbrook. In the fifties and sixties the office was accommodated in prefabricated huts which shook and whistled in the wind. Telephone calls were made from acoustic booths in which one bellowed against the roar of nearby jet engines. In 1968 peace and



quiet arrived in the form of a first-floor sound-proofed office, with a magnificent panoramic view over the airfield and surrounding areas — a great improvement.

Being sited on a ridge, atop the Lincolnshire Wolds, Binbrook has been famous for its exposed position. Nicknamed 'Windy Hill' by generations of airmen, as they were forced to adopt an almost permanent list from leaning into gusts around the hangars, it has generally lived up to its name. (A frequent, but discrete, source of amusement for hardened resident staff has been to watch occasional visitors as their eyes water and ears turn blue!) Records support the popular conception, with calculated mean wind speeds of 13 to 14 knots in the winter months, falling only a little to a mean of 9 to 10 knots in the summer. The maximum speed recorded was 50 knots with gusts to 78 knots in the winter gale of January 1976.

The hilly site has at least prevented any great extremes of temperature, with a maximum of 32.1 °C and a minimum of -12.6 °C being recorded in July 1969 and February 1986 respectively.

In winter any substantial fall of snow could be guaranteed to block access to the camp, as drifting from the large Lincolnshire fields filled in around the roadside hedges. The most notable occurrence of this was in February 1979 when a period of snow followed by frequent snow showers, together with north-easterly winds gusting to 45 knots, caused drifts 1 metre deep on the open airfield and in excess of 5 metres on some nearby roads. The snow was far too deep to be ploughed and eventually had to be dug out. The station was cut off for 5 days, with the staff 'trapped' on duty making round-the-clock observations and living from tins! Seldom has a winter passed without a similar occurrence, albeit not so severe.

For all that, though, the area is generally very pleasant, with a rather quiet, rural way of life and the complete absence of urban stresses. Many of the staff have, on a fortuitous posting, chosen to settle down and raise their families in this peaceful corner, contentment overcoming their ambitions.

In addition to the upheaval for the present staff, it is certain that Binbrook's closure will also create a significant gap in the observing network. With the lack of detailed information from the coastal strip, easterly winds have always brought problems for eastern England; Binbrook has acted as an outpost, warning of low cloud and sea fog for stations further inland. Will automatic stations fill the need?



Award

The Buchan Prize of the Royal Meteorological Society was received jointly by Dr G.J. Shutts (Forecasting Research Branch of the Meteorological Office) and Dr T.N. Palmer (at ECMWF on special leave from the Meteorological Office). It was presented for Dr Shutts' work on the forcing of blocking anticyclones by transient eddies, for Dr Palmer's work (with Dr S. Zhaobo) on the effect of North Atlantic sea surface temperature anomalies on the general circulation, and for their collaborative work (with R. Swinbank) on the parametrization of gravity-wave drag in numerical weather prediction models.

Dr Shutts' paper on blocking showed how synoptic systems approaching a split jet-stream pattern became elongated in the meridional direction and, under certain conditions, give up their energy so as to reinforce the blocking pattern.

Dr Palmer and Dr Zhaobo used a general circulation model to show that sea surface temperature anomalies in the north-west Atlantic give a statistically significant downstream response. The resulting 500 mb height anomalies were supported by an observation study using two independent 30-year periods of data.

The work of Dr Shutts, Dr Palmer and Mr Swinbank on gravity-wave drag gave convincing evidence, both theoretical and observational, that small gravity waves should exert a powerful drag force in the lower troposphere and lower stratosphere. In a study using a general circulation model, they demonstrated that a known systematic westerly bias in the wind direction could be removed by parametrizing the drag force due to breaking gravity waves. Similar parametrization schemes are now being used in most operational weather forecasting models.

Notes and news

Retirement of Dr W.T. Roach

Dr W.T. Roach, Assistant Director (Meteorological Research Flight) retired from the Meteorological Office on 5 August. He first joined the Office in 1953 as a Temporary Scientific Officer at Kew Observatory following a period in the Royal Electrical and Mechanical Engineers doing military service and at Imperial College where he obtained a BSc in physics and an MSc in meteorology. A year later he returned to Imperial College where he obtained a PhD on solar and infra-red emission spectra through the atmospheric window. This research brought him into early contact with the water vapour continuum, a topic which is of continuing interest to his group at the Meteorological Research Flight.

When, as a Senior Scientific Officer, Dr Roach returned to the Office in 1958 his first posting was in fact to the Meteorological Research Flight at Farnborough where he worked for Bob Murgatroyd on ozone and humidity measurements from aircraft. This was a time when the tropopause fold was coming into fashion and some of his studies were concerned with water vapour and ozone in this region. He also carried out some of the first measurements showing the large amount of absorption of solar radiation by pollution. After four years at Farnborough he moved to London/Heathrow Airport, where he spent a couple of years as a forecaster on the upper-air bench, before in 1964 going to Met O 15, the then Atmospheric Physics Branch, at Bracknell.

For Dr Roach the year 1964 marked the beginning of his studies of atmospheric structure as it affects the operation and safety of aircraft. It was shortly after this that I first met Bill Roach while we were both studying severe thunderstorms in Oklahoma. His subsequent study of photographs from high-flying U2

aircraft provided the first direct evidence of storm tops penetrating 20 000 ft above the tropopause. He deduced that such penetrations implied updraughts as strong as 100 m s^{-1} with extremely low temperatures within their upper parts. In recognition of the special importance of these studies for planning the operation of supersonic aircraft, Dr Roach was awarded the L.G. Groves Memorial Prize for Meteorology in 1967. Soon after his promotion to Principal Scientific Officer, in 1966 he moved to the Special Investigations Branch where he continued his work on aircraft hazards, studying clear air turbulence and giving advice on extremes to Concorde.

A new phase of work began in 1971 when Dr Roach moved back to Met O 15 which by then had become the Cloud Physics Branch. Apart from a short spell at the Meteorological Research Unit at Malvern in 1975, he remained in Met O 15 until 1977 carrying out a variety of studies, ranging from analysis of mesoscale wind fields in Project Scillonian to the effect of radiation on droplet growth. Using data gathered at the Meteorological Research Unit at Cardington he developed a better understanding of radiation fog. By explicitly modelling the details of the fog microphysics he and his colleagues demonstrated the importance of gravitational settling of fog droplets.

On promotion to Senior Principal Scientific Officer in 1977 Dr Roach became Assistant Director of the Special Investigations Branch. During the period to 1985 he was involved in a wide variety of work, including the forecasting of wind shear and severe storms, the automation of significant weather charts, the future use of aircraft wind and temperature data obtained via Data Link, and also the analysis of the spread and deposition of material from Australian nuclear tests. During the last three years, as Assistant Director at the Meteorological Research Flight (MRF), he has again had the opportunity to apply his years of experience in atmospheric radiation and cloud physics to the use of the Hercules aircraft. This has been an exciting period at MRF, with the modernization of the aircraft facilities and involvement in three major international experiments, HEXOS, FIRE and the Mesoscale Frontal Dynamics Project.

In retirement, Bill Roach intends to maintain his links with meteorology through his own personal research and through his membership of the Royal Meteorological Society and as its Treasurer. He and his wife Delia intend to remain for some time in the area and we wish them well over the coming years.

K.A. Browning

Restructuring of Branches within the Meteorological Office

Boundary Layer and Atmospheric Chemistry Branch (Met O 14)

The present role of Met O 14 in dealing with boundary layer research and the meteorological aspects of the release of material into the atmosphere will continue, but the Branch will take on additional responsibility for atmospheric chemistry. To this end the Atmospheric Chemistry Group from the old Cloud Physics Branch (Met O 15) has been transferred to Met O 14.

Meteorological Research Flight (Met O 15)

Research into radiation, cloud physics, and observational aspects of mesoscale and convective scale systems will be concentrated into a new Branch. Staff from the Cumulus and Stratocumulus Studies Group and the observational and technical groups within the old Met O 15 at Bracknell will join the Meteorological Research Flight (MRF) staff already at RAE Farnborough to strengthen the acquisition and analysis of data from the MRF aircraft. The Mesoscale and Convective Scale Research Group, although within the new Branch, is located at the University of Reading as part of the recently formed Joint Centre for Mesoscale Meteorology.

Remote Sensing Instrumentation Branch (Met O 19)

The Remote Sensing Instrumentation Branch will be formed from part of the old Satellite Meteorology Branch (Met O 19). It will work on advanced remote sensing instrument development, and deal with space-based, ground-based and airborne systems. The main activity of the Branch will be located at RAE Farnborough because of the need for easy access to the RAE/BNSC space test facility and the MRF aircraft. The Satellite Data Interpretation Techniques Group within the Hooke Institute at the University of Oxford will remain within this Branch for the time being.

Nowcasting and Satellite Applications Branch (Met O 24)

The new Branch will be concerned with the improved exploitation of remote sensing products in weather forecasting. It will consist of four groups dealing with:

- (a) the manipulation and application of digital satellite data (work previously carried out in Met O 19),
- (b) the interpretation of weather phenomena as aided by satellite and radar imagery (work previously done by the Satellite and Radar Studies Group in Met O 15),
- (c) the development of FRONTIERS (work previously done by two groups in Met O 19), and
- (d) the development and testing of very-short-range forecasting procedures and associated interactive work stations which will integrate remote sensing and numerical weather prediction products, and use expert system techniques as appropriate.

Forecasting Products Branch (Met O 8)

The Central Forecasting Branch (Met O 2) of the Meteorological Office had two main parts to it—the Central Forecasting Office (Met O 2a), concerned with producing operational analyses and forecasts, and Met O 2b, involved in the management and development of operational weather prediction facilities. In recognition of the wider support role which Met O 2b had acquired with the spread of automation throughout the Forecasting Services Directorate and with the provision of tailored model output directly to some commercial users, Met O 2b has been redesignated the Forecasting Products Branch and allocated the vacant Branch number Met O 8.

Fluid Dynamics Laboratory (Met O 21)

It is intended that a nucleus of the Fluid Dynamics Laboratory will be transferred to the Hooke Institute at the University of Oxford when arrangements with the University are finalized.

Review

Atmosphere, weather and climate, fifth edition, by R.G. Barry and R.J. Chorley. 156 mm × 234 mm, pp. xxii+460, illus. London, New York, Methuen, 1987. Price £30.00 (hardback), £10.95 (paperback).

The first edition (1968) of this book was judged as 'remarkably up to date' in an earlier *Meteorological Magazine* review. The fifth edition might be similarly described. It is aimed at geographers studying weather and climate in colleges, universities and sixth forms. Its aim is to impart an understanding of atmospheric processes, weather systems, climate (macro and micro), and climate change. As far as one who has neither taught nor studied geography can judge, the book is likely to meet these objectives. The authors are certainly eminently well qualified for the task, both being professors of geography.

The content is wide-ranging. The early chapters deal with atmospheric composition and structure, the effects of radiation, and the role of moisture. The central section explains atmospheric dynamics and the global circulation and goes on to discuss the weather and climate of temperate and tropical latitudes. Finally there is a chapter on small-scale climates — in plant canopies and cities — and one on climate variability and change. The scope is impressive and up to date. Numerical weather prediction and nowcasting are discussed as are climate models of various types. The El Niño Southern Oscillation phenomenon is described, so is the Sahel drought. The radiative effects of increasing CO₂ and other minor constituents of the atmosphere are discussed, and so are the effects of chlorofluorocarbons and oxides of nitrogen on atmospheric ozone. There is no reference to the relationship between sea surface temperature anomalies and Sahel rainfall nor any mention of the ozone hole. No doubt the sixth edition will rectify these omissions. The authors have also omitted any reference to 'nuclear winter'. Their restraint in not jumping on the bandwagon is commendable but a brief mention of the controversy should probably have been made. The section on observational data for weather forecasting is rather brief. More discussion of remote sensing would be worthwhile. The section on the tropics is a very good overview — one of the best modern introductions to tropical meteorology.

On the whole, the book is well written and readable. The text is clear, as are the diagrams, though one or two are a little dated. The book is well indexed and each chapter has plenty of references. Although the authors stated intention was to produce a 'non-technical' account they have included enough equations and explanation of physical processes to make the book useful to a wider audience than students of geography. Anyone teaching introductory courses in meteorology might well find the book sufficiently useful to buy it — I have already found it so, I keep my copy on my desk!

Professional meteorologists also, including forecasters, could usefully read it; they would gain a wider understanding of the topics covered outside their own specialism.

R. Kershaw

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Solar energy applications to buildings and solar radiation data, edited by T.C. Steemers (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.125.00, US\$69.00, £39.00) contains the proceedings of the second EC Contractors' Meeting held in Brussels in 1987, and is the fourth volume in the Solar Energy Development — Third Programme series. The reports presented give a full account of the current activities of the researchers and their co-operation in a European context.

Environmental meteorology, edited by K. Grefen and J. Löbel (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.280.00, US\$149.00, £84.00) contains the proceedings of an International Symposium held in Würzburg in 1987, which is intended to be the first in a series of symposia on the subject. Essentially, the many papers are concerned with the way meteorology acts as the link between emission and deposition of atmospheric pollutants.

Multiprocessing in meteorological models, edited by G.-R. Hoffmann and D.F. Snelling (Berlin, Heidelberg, New York, London, Paris, Tokyo, Springer-Verlag, 1988. DM 118.00) is a collection of papers presented at two workshops held at ECMWF. Trends to the migration to massive parallel systems in the near future are included.

Satellite and radar photographs — 28 July 1988

Fig. 1 shows a satellite image of a deepening depression which crossed the British Isles from the south-west giving 25 mm of rain in 24 hours over a wide swath across Ireland, North Wales and northern England. The well defined cloud bands had important repercussions on the rainfall distribution (Fig. 2) and the surface analysis.

A broad envelope of cloud associated with an old frontal zone extended from south-west to north-east across southern Britain and northern France. This was related to a gently ascending warm conveyor belt, W1 (see Fig. 3), whose northern limit was delineated by a band of cirrus, UU, marking the upper-level jet axis. Along the north coast of France, heavy rain occurred beneath a narrow band of warmer cloud tops, FF, lying along the surface front. Central and southern England were overlain by a layer of dry mid-level air beneath W1, and consequently the weather remained dry for much of the day.

The separate cloud canopy over Ireland and northern Britain originated from a secondary warm conveyor belt, W2, which emerged from beneath W1 and ascended rapidly over a warm frontal zone. This ascent, coupled with potential instability release within W2 (shown by the lumpy cloud structure over south-east Ireland), led to widespread heavy rain with rates widely exceeding 10 mm h^{-1} .

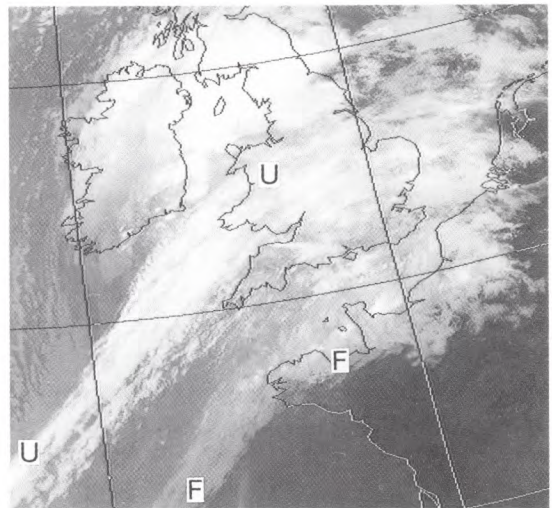


Figure 1.

Photograph by courtesy of University of Dundee

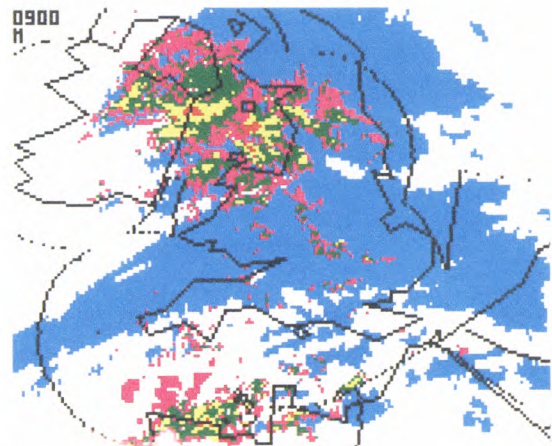


Figure 2.

Figure 1. NOAA-10 infra-red image for 0800 GMT.

Figure 2. Meteosat-derived infra-red cloud-top temperatures for 0900 GMT, light blue colder than -15°C . Radar rainfall intensity (mm h^{-1}): pink <1 , green $1-3$, yellow $3-10$, red >10 . Coastlines, national boundaries and radar network boundaries are shown in black.

Figure 3. Location at 0900 GMT of the depression, surface fronts, and warm conveyor belts W1 and W2 referred to in the text. The area of heavy rain originating from W2 is stippled.

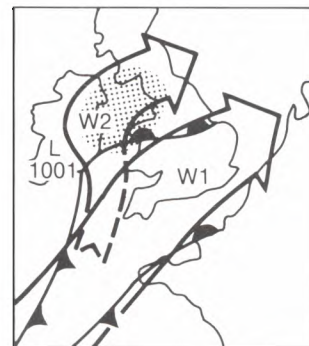


Figure 3.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

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Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

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THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

Instant occlusions
Management of meteorological data
Winter of 1987/88
A forecaster's storm

November 1988

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THE METEOROLOGICAL MAGAZINE

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The development of instant occlusions in the North Atlantic

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Meteorological Office, Bracknell

Summary

The evolution of the traditionally interpreted 'instant occlusion' is explained using satellite and radar imagery, synoptic observations and numerical-model diagnostics. An alternative analysis scheme is proposed for the cases studied in this paper. The main physical processes are described in the form of simple airflow models. Finally, forecasting guidelines are presented.

1. Introduction

In the North Atlantic, it is often necessary to predict the synoptic evolution and resulting weather distribution during interaction between a front and an approaching cold-air vortex or polar trough. The two features, both of which are readily identified on infra-red satellite imagery, may remain separate or merge. Where merging occurs it is conventional (Anderson *et al.* 1969) to place an 'instant occlusion' along the cloud band originally associated with the polar vortex since the cloud pattern resembles a classical occlusion, although its evolution and structure differ (see Fig. 1).

Locatelli *et al.* (1982) studied a number of cold-air vortices interacting with a polar front and proposed the analysis scheme reproduced in Fig. 2. Upon merging, the low-pressure centre and the main transition to cold air were associated with a cold-air vortex rather than the polar front.

For the cases presented in this paper, an analysis scheme adopting the same principle as Locatelli *et al.* (1982) is proposed, with the cold-air vortex being treated as a separate baroclinic disturbance which interacts with the polar front. The revised analysis is shown to be consistent with the thermal gradients which develop around the cold-air system and describes the synoptic evolution and associated weather more realistically than the traditional 'instant occlusion'. Browning and Hill (1985) studied a similar type of system and derived the simple conceptual model shown in Fig. 3(a), relating the principal cloud-features to ascending airflows or conveyor belts. In the cases studied in this paper, the cloud band of the cold-air vortex corresponds to a warm conveyor belt (labelled W in Fig. 3(b)) derived from a

* Now at Meteorological Office, Bracknell.

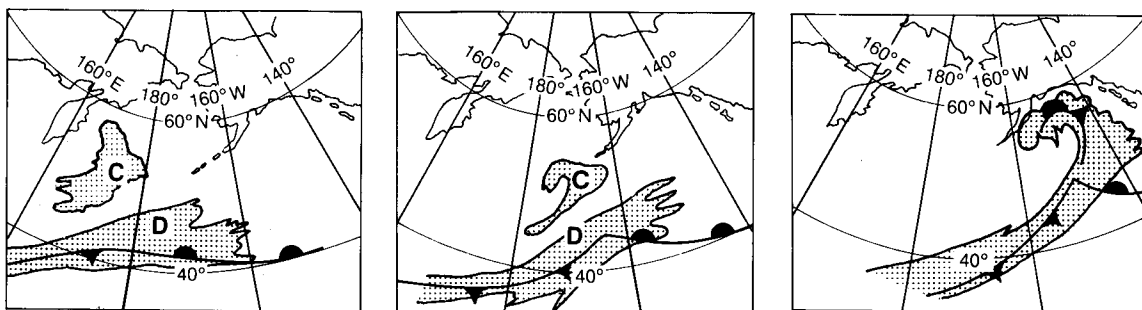


Figure 1. Evolution of cloud features resembling the instant occlusion as portrayed by Anderson *et al.* (1969), stippling representing the main cloud areas. Cloud labelled C is associated with the polar vortex, and D with the polar front.

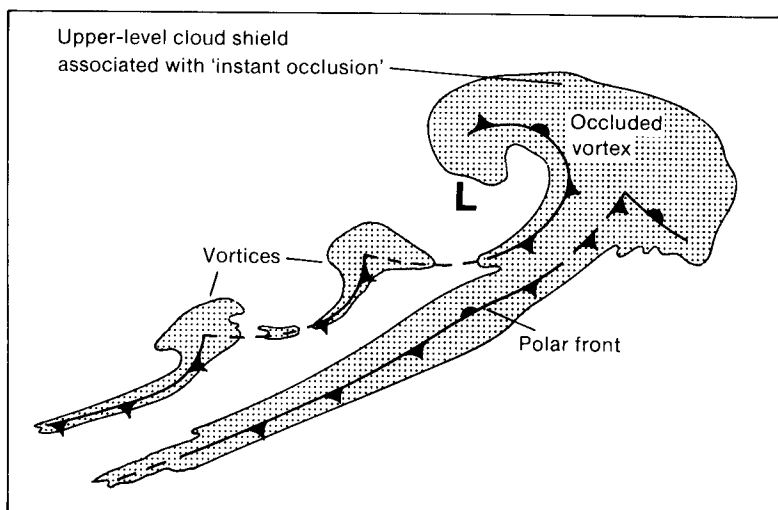


Figure 2. Schematic representation of polar vortex/polar front interaction reproduced from Locatelli *et al.* (1982).

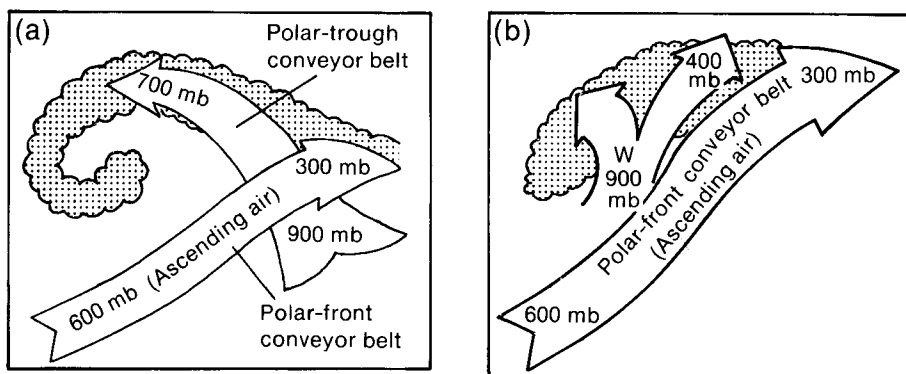


Figure 3. Airflows relative to the motion of the cloud band of the cold-air vortex in the systems described (a) by Browning and Hill (1985), and (b) in this paper. In (b) W is the conveyor belt referred to in the text.

shallow layer of moist air behind the band rather than a flow orientated along its axis as in Fig. 3(a). The difference between the two flow regimes appears related to whether the cold-air feature possessed baroclinicity prior to interaction with the polar front.

The study is based mainly on the case of 7–10 February 1987 and is supported by evidence from two other similar cases. We seek to

- (a) describe the synoptic-scale evolution by relating the features on the imagery to the surface and upper-air analyses and the main dynamical processes,
- (b) describe the sequence of surface weather,
- (c) suggest a simple model of the principal airflows during the interaction and merging of the two cloud features, and
- (d) provide guidelines for the prediction of the development sequence.

2. The sequence from satellite imagery and surface analysis

Fig. 4 shows the sequence of events between 7 and 10 February 1987 as seen from NOAA satellite imagery. On the 7th (Fig. 4(a)) the significant features prior to interaction were

- (a) cold front F which is referred to in this paper as the forward cold front, and
- (b) two areas of enhanced convection A and C in the polar air which were accompanied by surface troughs (Fig. 5(a)).

Examination of earlier satellite imagery and synoptic charts revealed that C originated from a front which had moved east over Canada. It then became engaged into a western Atlantic upper trough as a weak surface feature retaining some baroclinicity. Thus C inherited a gradient of wet-bulb potential temperature (WBPT) as shown in Fig. 5(a) and is therefore analysed as a cold front; this is referred to as the rearward cold front in this paper. In contrast, A had much less baroclinicity. A and C resemble the vortices shown in Fig. 2 which are detached from the polar front.

Area A moved quickly north-east (Figs 4(a) to 4(d)) accompanied by its surface trough which eventually came to lie close to the occluded front north of the British Isles where it lost its identity as a separate feature. The criterion that the polar vortex should approach the front to within 350 n mile to initiate interaction (Marshall 1982) was found not to be satisfied. In this case an instant occlusion did not form.

By the early morning of the 8th, C had moved north-east, approximately parallel to the north-western edge of F, and evolved into two distinct clumps C1 and C2 (Fig. 4(b)). The leading clump, C1, contained much layered cloud (with embedded convection) whilst C2 had more broken cloud. An indication of baroclinicity can be inferred from satellite imagery if the cold-air feature contains dense layered cloud which can sometimes be leaf-shaped (Weldon 1979), instead of being a small convective comma, characteristic of a positive vorticity advection (PVA) maximum.

During the morning, new cloud G formed between C1 and F (Fig. 4(c)). By 1200 GMT, a minor wave had formed on the forward cold front (Fig. 5(b)). A new low of 1011 mb had developed at the northern end of the rearward cold front. (A more detailed surface analysis is presented by McGinnigle *et al.* (1988).) Tightening of the 850 mb WBPT gradient north of this new low suggests that warm frontogenesis was taking place. By the afternoon, the tops of G had grown to form a nearly continuous cloud mass between C1 and F (Fig. 4(d)). The upper cloud appeared to rotate cyclonically to form hook H (Fig. 4(e)) which advanced ahead of the rearward cold front. Meanwhile the originally well defined southern tail of C1 became increasingly fragmented (Fig. 4(c)) and difficult to identify. G and H together gave the appearance of an 'instant occlusion' linked to a wave (see Fig. 1).

On the 9th (Fig. 4(e)), the wave and hook remained identifiable but the frontal cloud to the south narrowed and became more fragmented. By 1200 GMT on the 9th, the frontal wave had moved quickly

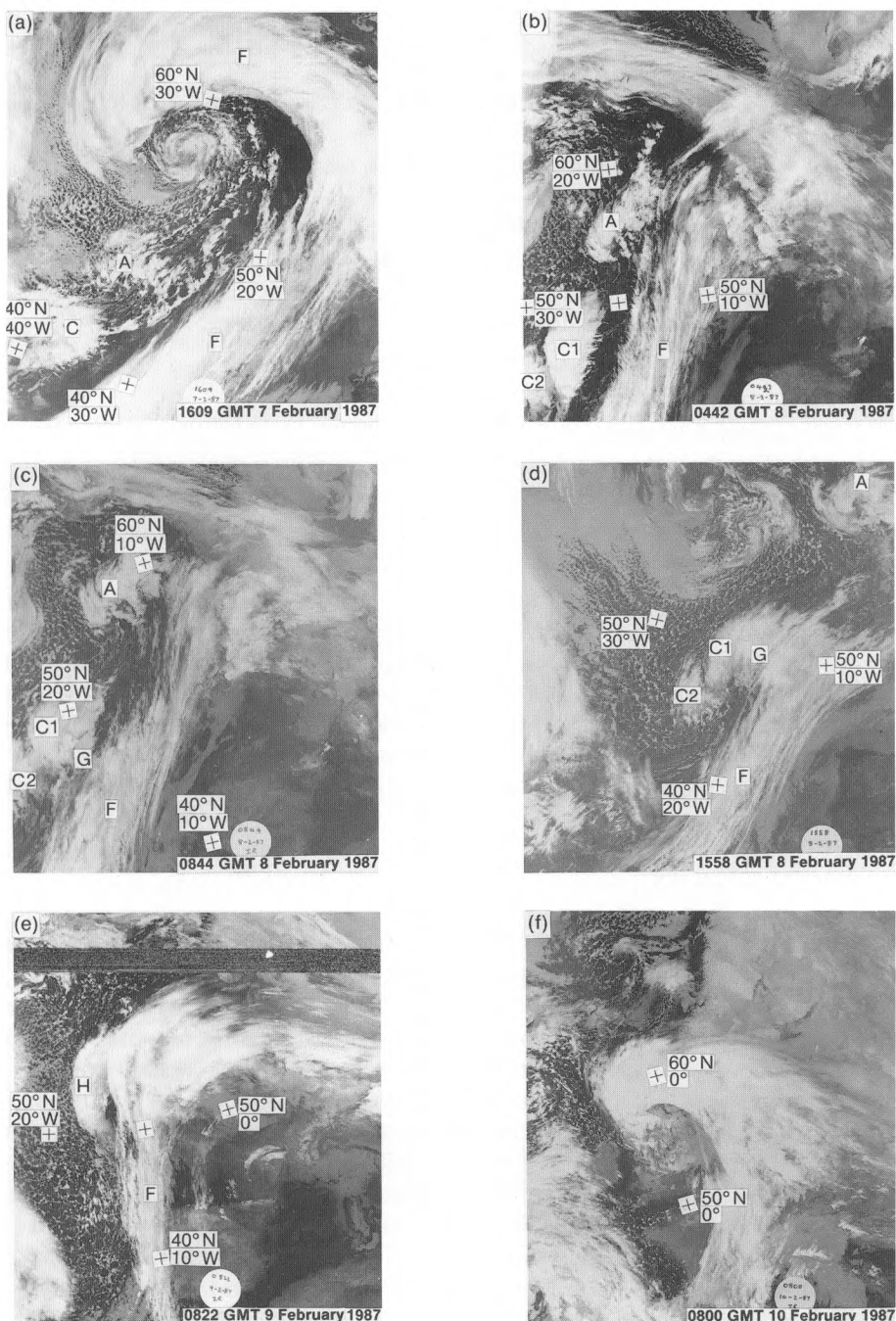


Figure 4. NOAA infra-red imagery for 7–10 February 1987. (a) 1609 GMT on the 7th, (b) 0442 GMT on the 8th, (c) 0844 GMT on the 8th, (d) 1558 GMT on the 8th, (e) 0822 GMT on the 9th, and (f) 0800 GMT on the 10th. All times are equator crossing times. Cloud areas A, C, C1, C2, F, G and H are referred to in the text. Selected latitude/longitude intersections are shown by a cross. (Photographs by courtesy of University of Dundee.)

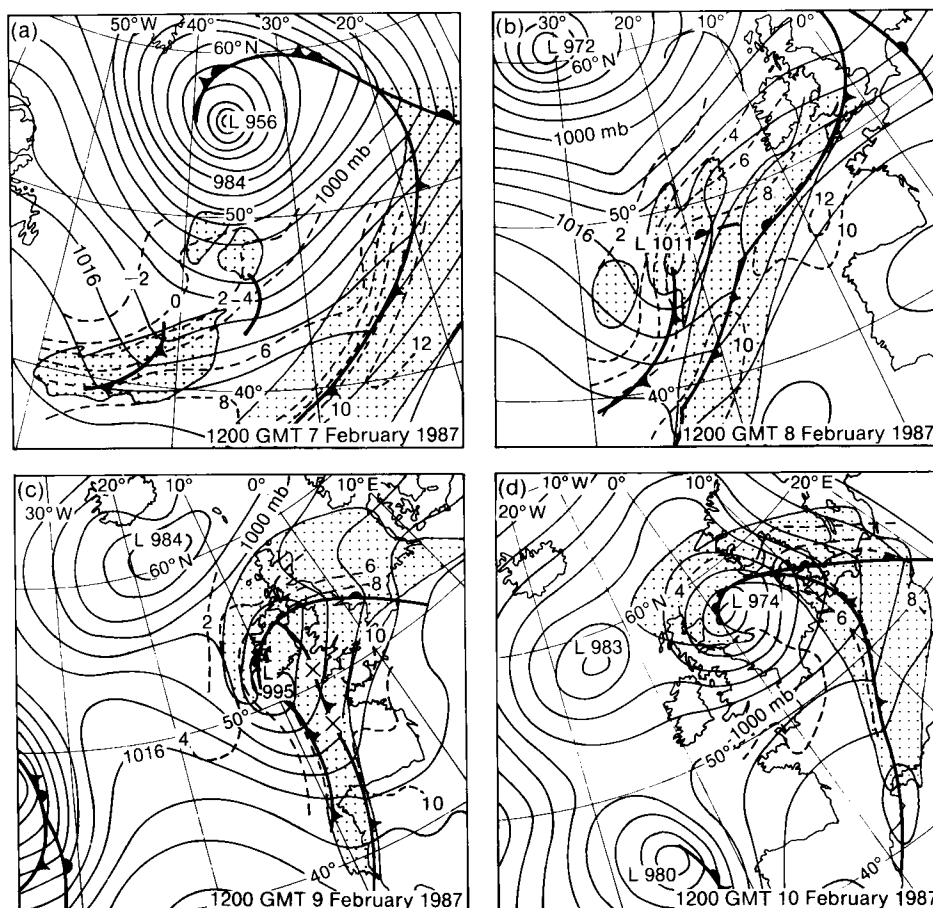


Figure 5. Analyses of sea-level pressure and frontal positions, model-analysed 850 mb WBPT ($^{\circ}\text{C}$) (dashed lines), and upper-cloud areas (stippled) derived from available NOAA and Meteosat imagery for 1200 GMT on (a) 7, (b) 8, (c) 9, and (d) 10 February 1987. The bold line on (a) at approximately 45°N , 34°W is a surface trough.

north-east to Northern Ireland (Fig. 5(c)) deepening to 996 mb while the cold-air low had deepened to 995 mb. This low became co-located with the cloud-free slot near south-west Ireland (Fig. 4(e)) whilst the forward cold front progressively lost its identity. As the complex low-pressure area over the British Isles transferred eastwards it steadily deepened, consolidating into one centre forward of the cold-air low which soon lost its identity.

3. Upper-air and dynamical considerations

The 300 mb winds and contours for 1200 GMT on 7, 8 and 9 February 1987 are presented in Figs 6(a), 6(c) and 6(e) respectively. Areas of ascent, descent and thermal advection analysed by the Meteorological Office fine-mesh model (Gadd 1985) are shown in Figs 6(b), 6(d) and 6(f) for the same times. The main cloud areas derived from satellite imagery are superimposed on all the fields. The model can be used to explain the dynamics because its cloud and humidity fields were consistent with the satellite imagery over the area of interest even though analysis of the cloud-free slot and hook at 1200 GMT on 9 February was a little too far east.

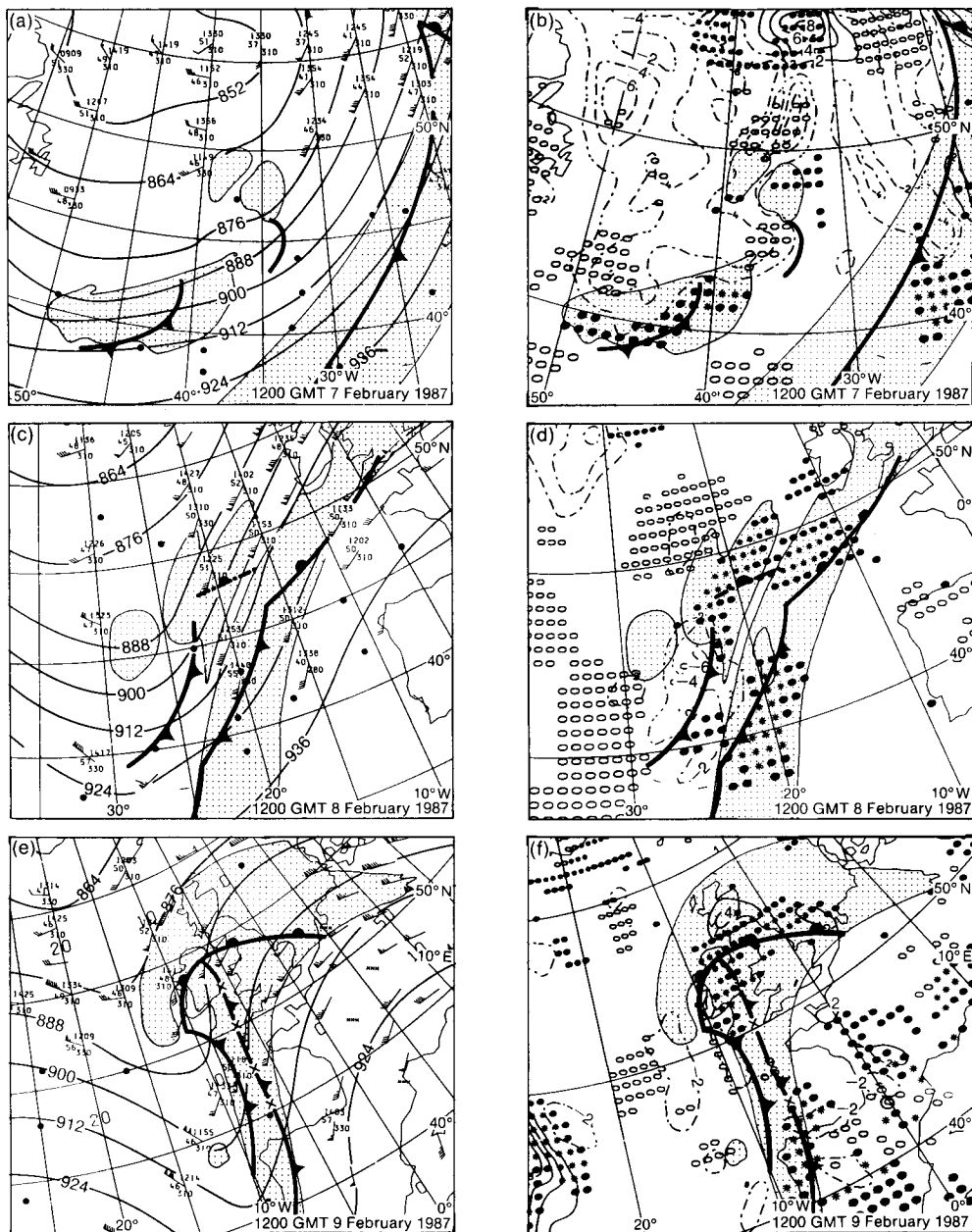


Figure 6. Upper-air pattern, model diagnostics and upper-cloud areas for 7–9 February 1987. (a) and (b) 1200 GMT on the 7th, (c) and (d) 1200 GMT on the 8th and (e) and (f) 1200 GMT on the 9th. Surface fronts are shown conventionally and troughs are shown as bold lines. In (a), (c) and (e) upper-cloud areas (stippled) are deduced from Meteosat imagery. Wind reports at 300 mb and from aircraft near that level are shown. Contours are in decametres for the 300 mb level. Other observation locations are marked by a dot. (b), (d) and (f) show upper-level cloud areas (stippled) and fronts superimposed on fine-mesh model analyses of vertical velocity (\circ 6.2 mb h^{-1} or more descending, \bullet 6.2–12.5 mb h^{-1} ascending and $*$ 12.5 mb h^{-1} or more ascending), and thermal advection ($^{\circ}\text{C}/6\text{h}$) averaged over the 850–500 mb layer (solid contours indicate warming, dash-dot contours cooling).

At 1200 GMT on the 7th, cloud areas A and C were situated on the forward side of broad upper troughing covering the western half of the North Atlantic and were co-located with ascent in the lower and middle troposphere (Fig. 6(b)). This ascent resulted from PVA induced by short-wave troughs within the flow. Area A did not develop because it did not lie in a favourable part of the upper-air pattern.

By 1200 GMT on the 8th, the main troughing had moved east (Fig. 6(c)), and C1 remained within a PVA maximum ahead of the trough. C2, near the base of the trough, moved quickly towards Iberia and the cloud became broken (see Fig. 4(d)). Meanwhile ascent was co-located with C1; this expanded, intensified and extended towards the forward frontal cloud to the east. The region of ascending motion between the two cloud areas corresponded to the right entrance region of the jet, inferred from the upper-level wind observations on Fig. 6(c). Very little WBPT contrast now remained on the forward cold front due to advection of high WBPT between C and F. (On the forward side of the extending upper trough, another wave was carried eastwards towards Iberia, embedded in the large area of ascent (Fig. 6(d)), along with the remnants of C2.)

Following merging of C and F after 1200 GMT on 8 February, the upper trough continued eastwards (Fig. 6(e)) and a large area of warm advection giving ascent resulted in the cloud over the north of the British Isles (Fig. 6(f)). Within the frontal cloud to the south and near the hook, there was slight descent (Figs 4(d) and 4(e)) giving thinning and warming of the cloud tops.

This case is one of several in which the relationship between the imagery, upper-air pattern, and surface analyses were similar. For instance, Fig. 7 shows analyses of 500 mb height and 1000–500 mb thickness with added major cloud areas derived from imagery for the present case, 10–11 November 1986 and 7–8 December 1986. In each case, the cloud system in the polar air was embedded in a strong upper flow that carried it towards the forward front. Any earlier cyclogenesis in the cold air upstream which distorts the flow would prevent interaction between the two systems. Later in this paper, the implications of the similarities are exploited to produce general forecasting guidelines.

4. Mesoscale weather distribution

The features on the imagery can be related in more detail to the frontal analysis as they crossed the British Isles on 9 February, soon after the NOAA image in Fig. 4(e). More frequent imagery from Meteosat and the UK weather radar network is presented in false colour in Figs 8(a) to 8(f).

The main features in the Meteosat infra-red image for 1100 GMT (Fig. 8(a)) have already been identified in section 2 except for some convective cloud, labelled T, over the south-west tip of Ireland in the originally cloud-free slot between the decaying forward cold front and the hook. This convection developed rapidly under a tongue of dry air aloft, clearly shown on the water vapour imagery (Fig. 8(b)) which depicts the distribution of moisture at about 400 mb (Eyre 1981). The dry air was observed above 470 mb in the radiosonde sounding from Valentia in south-west Ireland; the air was also unstable and, according to the numerical-model diagnostics (Fig. 6(f)), was rising ahead of the surface low near south-west Ireland (allowing for the slight longitudinal phase error in the model's analysis). Fig. 8(e) shows convection having closed the gap between the hook and forward cold front.

Other features of interest from the satellite and radar imagery are as follows:

- (a) There was a narrow band of rain to the west of England and Wales, associated with the forward cold front (Fig. 8(c)). This corresponded with the band of thicker cloud in the visible image (Fig. 8(d)). The rain gradually decayed as it moved east, especially over the southern half of the United Kingdom (Figs 8(c) and 8(f)). The band of heavy rain over the Irish Sea and North Wales is thought to have resulted from mid-level convection which had developed earlier behind the forward cold front.

(b) The thicker cloud on the eastern side of the hook shown in the visible image (Fig. 8(d)) corresponded to warmer tops in the infra-red image. Rainfall here was probably heavier and more widespread than further west where the cloud was thinner. Cloud warmed and decayed in the southern tip of the hook (Figs 8(a) and 8(e)).

(c) The area of rain over northern England was associated with ascent due mainly to warm-air advection (Fig. 6(f)) north of the warm front.

(d) The rearward cold front was difficult to identify from the visible and infra-red imagery.

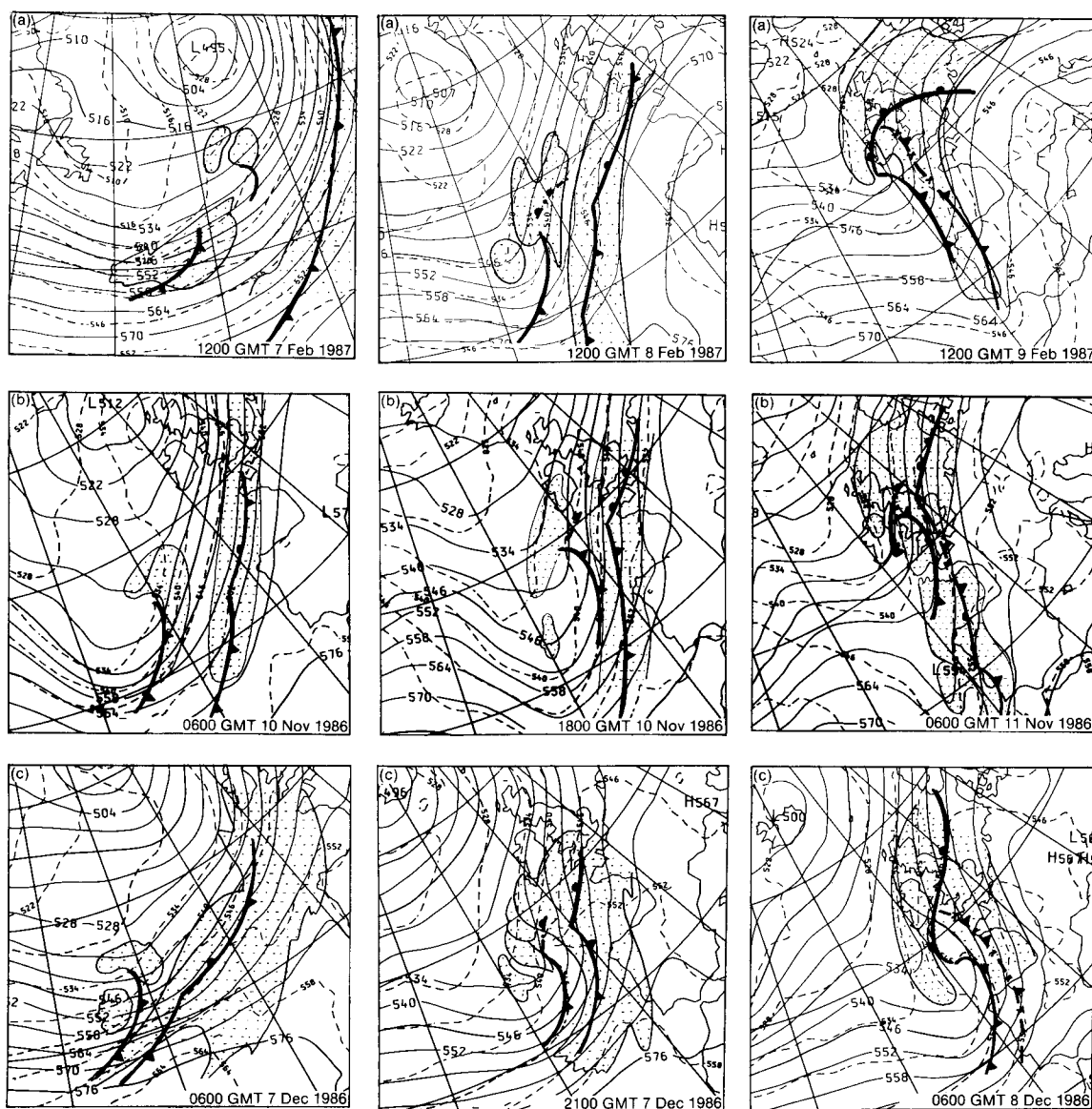


Figure 7. Sequences of upper-air analyses derived from the fine-mesh model for (a) 7-9 February 1987, (b) 10-11 November 1986, and (c) 7-8 December 1986. Continuous lines are 500 mb heights and dashed lines are 1000-500 mb thicknesses both in decametres. Upper-cloud areas are stippled.

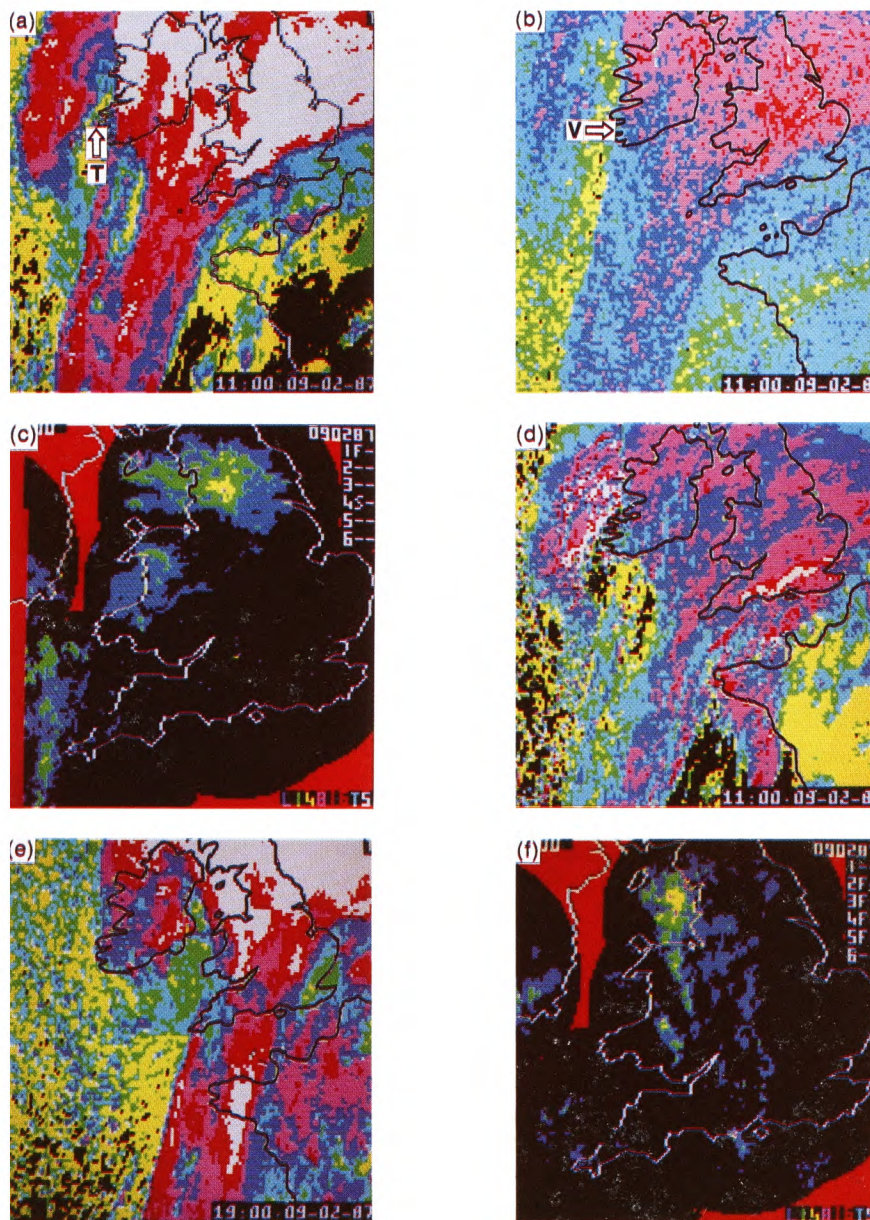


Figure 8. False-colour Meteosat and radar imagery for 9 February 1987. (a) Infra-red image for 1100 GMT. The colour scheme represents temperature slicing as follows: white, colder than -40°C , red -40 to -30°C , mauve -30 to -20°C , dark blue -20 to -10°C , light blue -10 to 0°C , green 0 to 5°C , yellow 5 to 10°C , and black warmer than 10°C . T is an area of growing convection referred to in the text. (b) Water vapour image for 1100 GMT. This shows the amount of moisture in the mid and upper troposphere, centred around 400 mb (Eyre 1981). The colour sequence is as in (a) and represents increasing dryness of the air, red being moistest, yellow being driest. V marks the location of Valentia. (c) Radar network imagery for 1100 GMT. Blue represents rainfall rate of $< 1 \text{ mm h}^{-1}$, green $1\text{--}4 \text{ mm h}^{-1}$, and yellow $> 4 \text{ mm h}^{-1}$. The apparent gap over south-west Wales is due to the radars not seeing rainfall at long range. (d) Visible image for 1100 GMT. The colour sequence is as in (a) representing decreasing reflectivity, white being the densest, most reflective cloud. Yellow and black are predominantly cloud-free areas. (e) Infra-red image for 1900 GMT. Colour slicing as in (a). (f) Radar network imagery for 1900 GMT. Colour slicing as in (c).

The surface analysis corresponding to the time of the imagery in Figs 8(e) and 8(f) is shown in Fig. 9. The forward cold front has been drawn through the line of patchy rain which could be followed on radar imagery, but there was little change of wind or dew-point across it. The thunderstorm reported over Ireland was within the region of convective activity identified in Fig. 8(e). The main air-mass change was at the rearward cold front where the dew-point fell significantly and the cloud base lifted but only patchy rain occurred. Fig. 10 is a time sequence of hourly observations from two stations in southern England, one coastal (Culdrose) and one inland (Gatwick), showing that the basic characteristics of the two fronts were preserved whilst crossing southern England. The warm front in Fig. 9 has been analysed along the warm side of the surface wet-bulb temperature gradient.

This case is one of several in which the evolution was similar. For example on 8 December 1986 (Fig. 11), as on 9 February 1987, there was deep convection immediately north of the cold-air vortex and lower dew-points followed the rearward cold front. The forward cold front was marked by a progressively weakening rain band. A schematic diagram showing cloud outlines, frontal analysis and weather is presented in Fig. 12, which will be used in section 6 for forecasting guidelines. The area bounded by the forward and rearward cold fronts and the hook is characterized by moist air near the surface and extensive low cloud, giving showery outbreaks of rain, and drizzle. Within the colder, drier air west of the rearward cold front, cloud becomes more broken and convective. Deep convection may develop between the hook and the forward frontal band.

The subsequent behaviour of the system following the stage depicted in Fig. 12 is governed by the large-scale upper-flow pattern. The cold-air surface vortex will, in most cases, be situated so near the upper-trough axis (Fig. 7) that it will undergo little further development and will soon begin to fill. The most favourable development area is found several degrees forward of the upper trough (i.e. well ahead of the original cold-air vortex) and this is where any further cyclogenesis would occur.

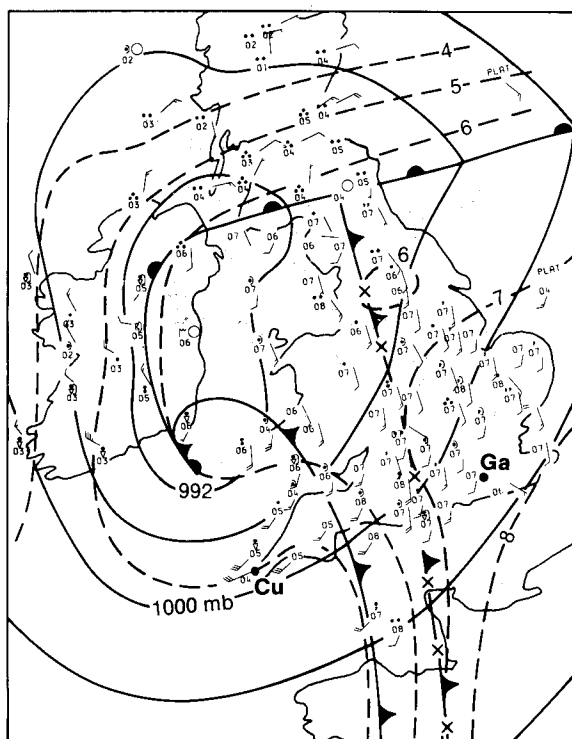


Figure 9. Surface synoptic analysis for 1900 GMT on 9 February 1987. Plotted observations show present weather, wind, and dew-point ($^{\circ}\text{C}$). The locations of Gatwick and Culdrose are shown as Ga and Cu respectively. 850 mb WBPT isopleths ($^{\circ}\text{C}$) derived from a model analysis at 1800 GMT are shown as dashed lines.

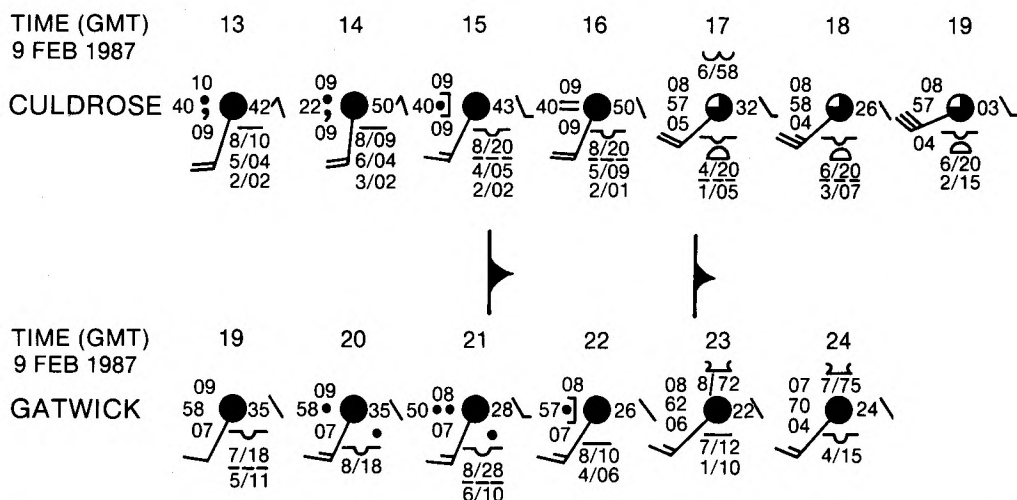


Figure 10. Sequence of hourly surface observations from Culdrose and Gatwick (labelled Cu and Ga respectively in Fig. 9) between 1300 and 2400 GMT on 9 February 1987. The cold front symbols are marked adjacent to the time of passage across both stations.

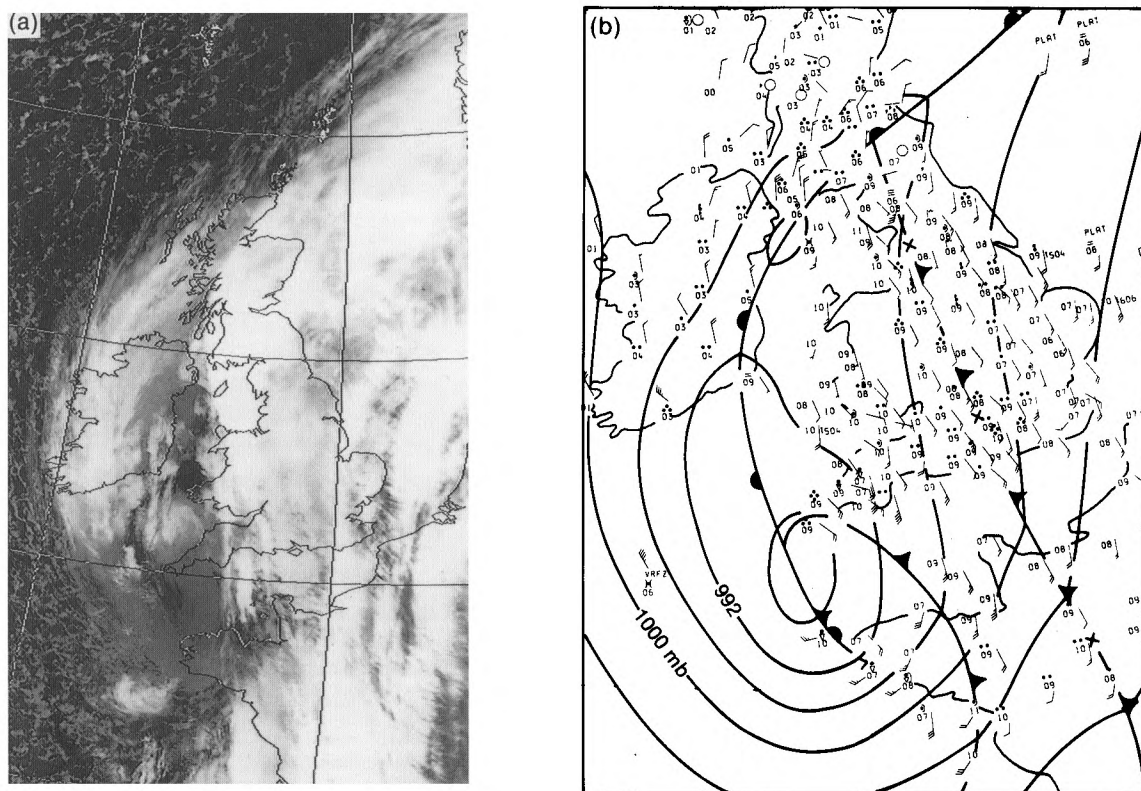


Figure 11. (a) NOAA-9 infra-red imagery and (b) surface analysis for 1500 GMT on 8 December 1986. The symbols on the surface analysis are as in Fig. 9. (Photograph by courtesy of University of Dundee.)

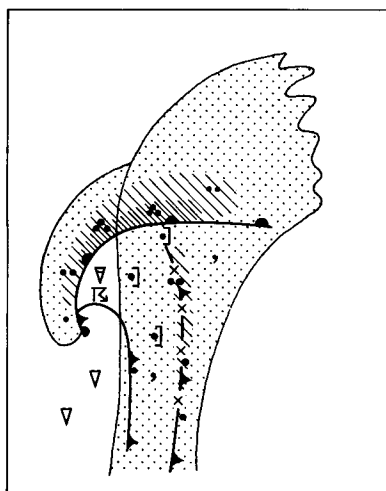


Figure 12. Schematic representation of upper-level cloud, and rainfall in the mature system as it crossed the British Isles. Current-weather symbols are used to depict observations characteristic of various parts of the system. Stippling represents upper-cloud areas, light hatching areas of light rain and dense hatching areas of moderate or heavy rain.

5. Conceptual model

Of the three cases already presented, that of 10–11 November 1986 provides the best opportunity of detailed understanding of the merging process since this took place in a data-rich area over the British Isles. Fig. 13 shows the merging of the two systems using a sequence of 3-hourly Meteosat infra-red and water vapour images. The cooling of the cloud tops can be seen in the former gap between the cold-air vortex and the forward frontal band with rapid moistening at upper levels. The pockets of locally heavy rain over the Irish Sea, labelled R in the radar image, occurred within this area of cloud growth, and amalgamated into an area of heavy rain over northern England shortly afterwards.

The hook consisted of three separate mesoscale convective elements labelled X, Y and Z. Region X expanded as it moved north-east whilst Y and Z dissipated and warmed. The differential motion of X, Y and Z produced the apparent rotation of the cloud envelope associated with the cold-air vortex.

Vertical velocities derived from fine-mesh analyses are also shown in Figs 13(a) and 13(c). Prior to merging, a band of upward motion extended across from the cold-air vortex to the forward frontal cloud with a separate maximum on each, then consolidated into a single region of ascent by 0000 GMT on 11 November. Following examination of the fine-mesh model analysis, it was found that the air immediately upwind of the region of rapid cloud growth was potentially unstable (McGinnigle *et al.* 1988). Therefore, merging appears to have been a response to large-scale forcing within a potentially unstable environment.

The airflow model presented in Fig. 14 proposes to account for merging of the cold-air vortex and frontal cloud band, formation and maintenance of WBPT gradients and the precipitation distribution. The model has been derived using rapid movie-loop sequences of half-hourly Meteosat images, along with fine-mesh model diagnostics (isentropic analysis, vertical velocities and 850 mb WBPT). The evolution is described in three separate stages.

Stage 1 (Pre-merging stage)

The cold-air feature C, coincident with a PVA maximum, approaches a cold frontal zone F. At this stage C is composed of a series of convective cells generated at its rear edge, with anvils combining to

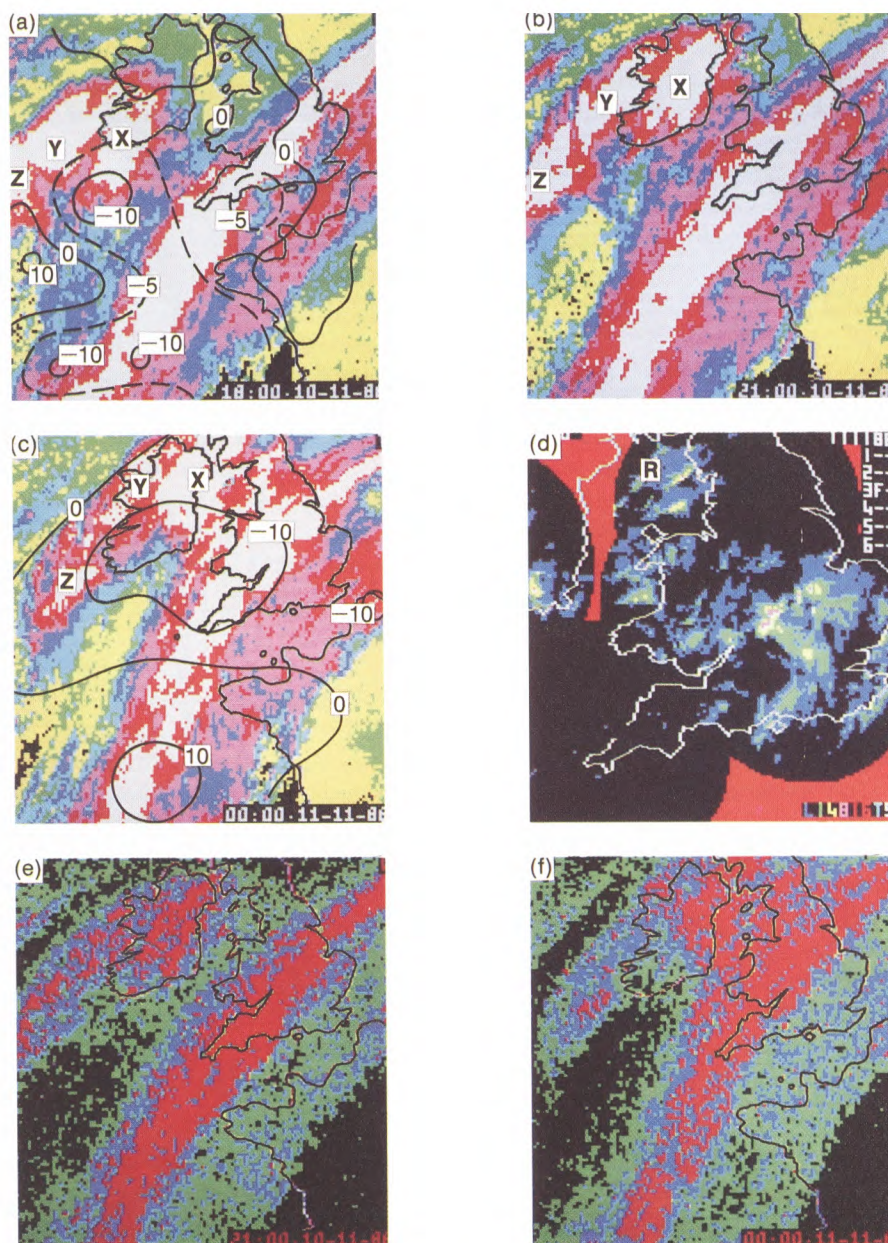


Figure 13. Sequence of Meteosat and radar images for 10–11 November 1986 showing merging of a cold-air vortex and frontal cloud band over the British Isles. Infra-red images are shown for (a) 1800 GMT and (b) 2100 GMT on 10 November, and (c) 0000 GMT on 11 November, the colour scheme being white, colder than -40°C , red -40 to -30°C , mauve -30 to -20°C , dark blue -20 to -10°C , light blue -10 to 0°C , green 0 to 10°C , yellow 10 to 15°C and black warmer than 15°C . Isopleths of vertical velocity (mb h^{-1}) at 600 mb derived from model analyses are superimposed on (a) and (c), negative values representing upward motion. The letters X, Y and Z mark the convective elements referred to in the text. (d) Radar-network image for 0000 GMT on 11 November, the colours as in Fig. 8(c). R is the rainfall area referred to in the text. (e) and (f) are water vapour images for 2100 GMT on 10 November and 0000 GMT on 11 November respectively, black representing driest upper-tropospheric air, and green, blue and red successively moister air.

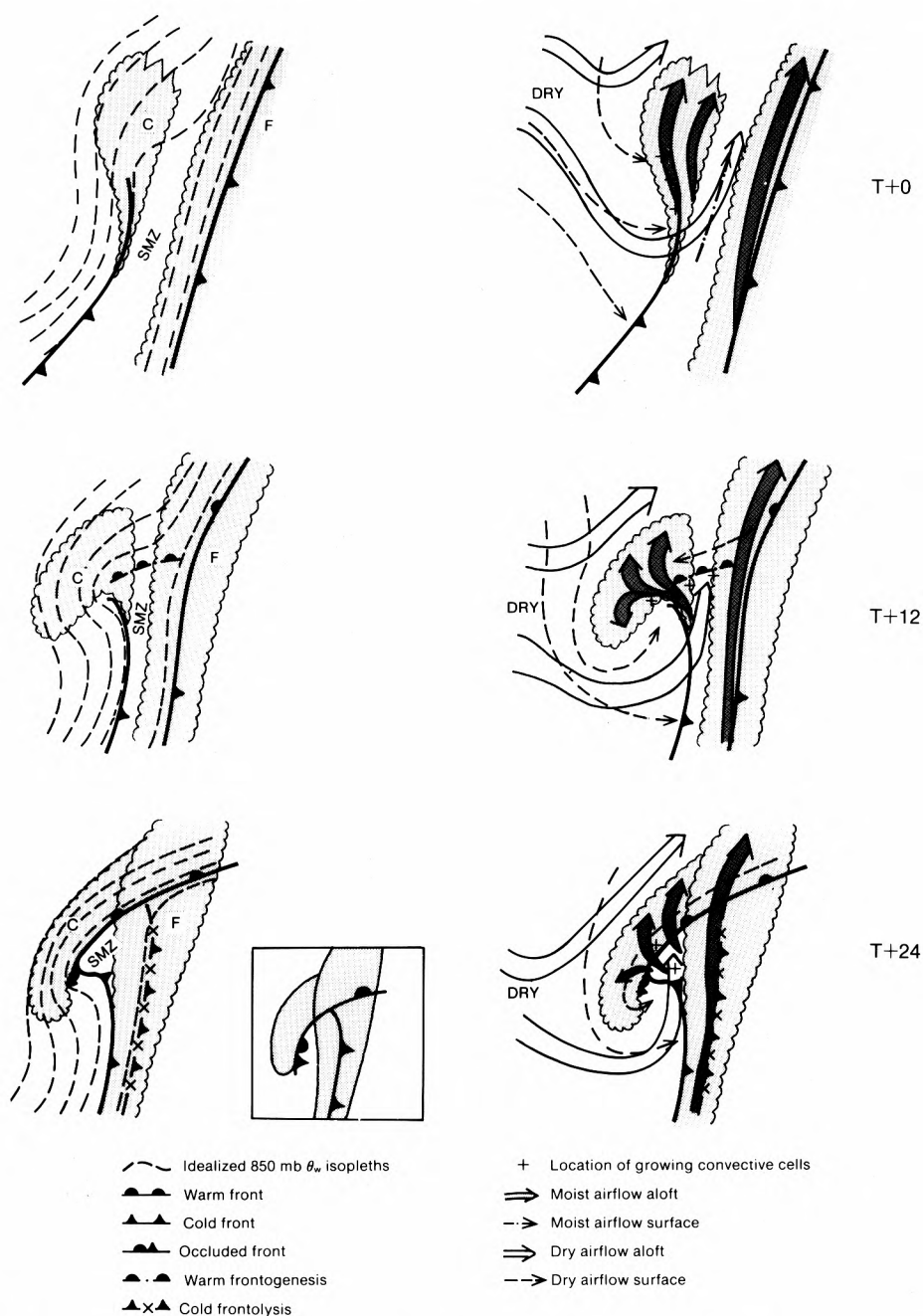


Figure 14. Life-cycle model showing the interaction between a polar air cloud feature, C, and polar frontal cloud, F, at approximately 12-hourly intervals. Such an interaction is conventionally interpreted as an 'instant occlusion' but a revised frontal analysis is presented here. Stippling denotes upper cloud. The figures in the left-hand column show idealized thermal structure superimposed on schematic upper-cloud outlines. In the right-hand column airflows relative to the system's movement are superimposed, broadening and narrowing arrows showing ascending and descending air respectively. SMZ denotes shallow moist zone. Inset shows the conventional analysis corresponding to stage 3.

produce the upper-cloud shield. At low levels, air of low WBPT follows the cold front at the rear of C. At middle and upper levels, dry air moves around the base of the trough within the strong upper flow, overrunning the tail of C, then travelling parallel to the sharp edge of F. At low levels, warm, moist air is advected ahead of C, weakening the thermal contrast associated with F and generating potential instability within a new shallow moist zone (SMZ) between C and F. This contrasts with the case of Browning and Hill (1985) in which the cold-air feature possessed little baroclinicity and so the thermal gradient was retained on the polar front. (In such cases, any new cyclogenesis would occur on the forward front rather than on the rearward frontal zone and the cold-air feature would remain separate from the main frontal cloud canopy, e.g. Browning *et al.* 1987.)

Stage 2 (The merging stage)

C appears to rotate rapidly leaving behind a trailing low-level WBPT boundary. Convective cells continue to be generated at the southern rear edge of C, with a series of anvils carried forward, and dissipating upon encountering the dry air to the rear of F. The potential instability already created between C and F may then be released as ascending motion is imposed upon this region by a combination of warm-air advection and PVA. Rapid cloud growth then proceeds in the gap. Warm advection ahead of C generates a thermal gradient on its northern side and a low-level flow (similar to the cold conveyor belt described by Carlson 1980) is established from F towards C ahead of this nascent frontal zone.

Stage 3 (The mature stage)

C and F have linked, thus completing the instant occlusion process as traditionally interpreted. The new front has been placed along the inside edge of the hook-shaped cloud, C, on the warm side of the 850 mb WBPT gradient. The edge of the cold-frontal cloud band may still be apparent above the hook and normally corresponds to the upper-level jet axis. (Since the temperature gradient along the rearward cold front occupies a shallow layer, the jet axis will normally remain ahead of it, tied to the forward front which, at upper levels, retains some thermal structure.) C becomes aligned with the upper trough (Fig. 6(e)) and, having stopped rotating, may appear unchanged for many hours. Warm, moist boundary-layer air from the SMZ ascends along the new frontal slope, producing a band of rain along the inside of the hook-shaped cloud C. Since this region is overrun by dry, low-WBPT air, some convection cells will also be generated. Continued but less rapid ascent associated with the newly-formed baroclinic zone produces progressively colder cloud tops towards the outside of the hook but with lighter rainfall. Deep convection may occur anywhere within the SMZ, but is most likely to become concentrated just ahead of the cold-air low where strong PVA is acting upon an environment that is destabilizing due to cold advection aloft.

The mature system corresponding to stage 3 differs from Browning and Hill (1985) in that cloud band C is fed by air with high WBPT from an SMZ behind it instead of a flow predominantly along its axis. The presence of this flow originating from a potentially unstable SMZ is crucial in determining whether new cloud growth and possibly heavy rain will occur within the previously cloud-free gap. Conversely, in cases where this flow is absent, (e.g. in Fig. 3(a)), precipitation intensity is suppressed near the intersection of the two cloud bands.

The analysis shown in Fig. 14 reflects the thermal and weather distributions more realistically than the commonly used 'instant occlusion' analysis, which is shown in the inset of the figure for comparison. The overall shape of the system corresponding to stage 3 resembles the 'cloud head' frequently observed prior to explosive cyclogenesis (Böttger *et al.* 1975, Monk and Bader 1988). Indeed, an analysis scheme by Monk (personal communication) similar to that proposed in Fig. 14 probably also applies in such cases.

A vertical section across the two cold fronts in stages 2 and 3 of Fig. 14 is similar to the split-front model (e.g. Browning *et al.* 1987). The weakening forward front acts as the 'upper cold-front' as it still possesses an upper-level moisture boundary despite very little surface temperature contrast. Meanwhile, the rearward front acts as the surface cold front.

6. Forecasting guidelines

In this section, forecasting guidelines are presented which are based on the foregoing case-studies.

(a) An 'instant occlusion' of the type described in Fig. 14 may form if all the criteria (i) to (iii) below are satisfied:

- (i) A cold-air cloud cluster, which may be leaf-shaped, contains dense layered cloud.
- (ii) Surface observations or numerical-model diagnostics (e.g. 850 mb WBPT) show that a thermal gradient is associated with this cloud.
- (iii) The cloud is embedded in a strong upper flow that will carry it to within 350 n mile of the polar front (Marshall 1982).

(b) Having satisfied the criteria in (a), and if the cold-air cluster rotates (indicating cyclogenesis), merging of the cold-air cluster and the polar-frontal cloud band normally follows.

(c) During 'merging', cloud develops rapidly ahead of the rearward cold front producing rain which may be heavy. This front trails behind its original upper cloud. The resulting hook-shaped cloud canopy then moves parallel to the orientation of the forward cold front.

(d) After merging (see Fig. 12) the following occurs:

- (i) The heaviest rain falls at the inside of the hook.
- (ii) The main air-mass boundary is along the rearward cold front, the forward cold front becoming difficult to identify at the surface.
- (iii) Convection may develop anywhere between the hook and the forward cold front, but is particularly likely to be deep (perhaps with thunder) immediately ahead of the cold-air surface low.
- (iv) As the cold-air surface low occludes and starts to fill, any further cyclogenesis will take place on its forward side.

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Acquisition, checking and management of meteorological data

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Summary

The basic system for acquiring, checking and managing meteorological data used at the Geophysical Experimental Observatory at Macerata, Italy is presented. The system uses a data logger and a personal computer.

1. Introduction

During the last ten years the development of technology used in meteorological research has led to the application of systems which acquire and check numerical information about ambient atmospheric parameters. Therefore it is now possible to automate totally the acquisition and processing of data.

In the Geophysical Experimental Observatory at Macerata (approximately 43° 17'N, 13° 25'E and 303 m above sea level) in Italy there is a trend towards the total automation of the system for acquiring meteorological data. The system described here has been used for various applications and it has proved to be particularly versatile and easy to use.

2. The meteorological data acquisition system

The basic acquisition system is shown in Fig. 1. An integral part of the system is a planning data logger (Campbell Inc. model CR7) which is capable of carrying out mathematical and statistical operations. The sensors connected to the data logger are listed below.

- (a) Platinum-resistance thermometers with a resolution of 0.2 °C (dry- and wet-bulb).
- (b) Sensor with a chemical element for measuring relative humidity with a resolution of 1%.
- (c) Heated rain-gauge with a resolution of 0.2 mm.
- (d) Impulse sunshine recorder with a minimum threshold of 0.147 cal cm⁻² min⁻¹.
- (e) Tachometric anemometer with a minimum threshold of 0.25 m s⁻¹.
- (f) Potentiometric sensor for the wind direction with a resolution of 1°.
- (g) Potentiometric barometer with a resolution of 0.5 mb.
- (h) Nine Moll thermopiles — one for global solar radiation (direct plus diffuse radiation), one for diffuse solar radiation (including the Schuepp band), and others with optical filters for specific spectral bands of the global solar radiation (the total spectrum covers 300 to 2800 nm).

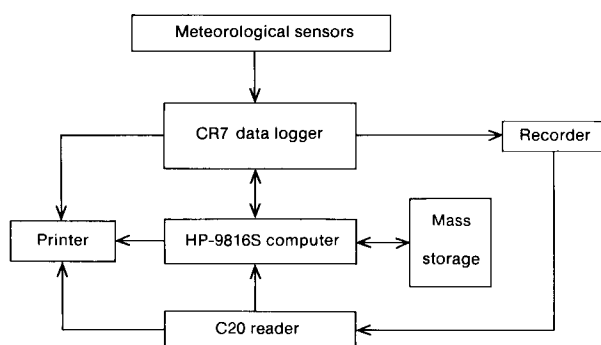


Figure 1. Data acquisition system.

Platinum-resistance thermometers to measure soil temperature and an instrument to measure evaporation are planned to be installed in the near future.

For each meteorological parameter there is a specific sampling and data-processing program which allows various mathematical manipulations to be carried out — these include addition, multiplication by a constant, varying offset, fitting of polynomials of up to degree five and the computation of trigonometric expressions. The operator of the system sets the sampling time and derives the meteorological parameters from the information collected by the sensors using two principal programs, both of which provide hourly values of various parameters.

The first program uses data collected every 3 seconds to provide the following hourly information.

- (a) Total global radiation and total diffuse radiation.
- (b) Total sunshine.
- (c) Total rainfall.
- (d) Mean wind speed and direction, mean vector wind, standard deviation of wind speed and direction, and maximum wind speed and the hour in which it occurred.

Additionally, every 24 hours, information about global solar radiation in various spectral bands is available.

The second program allows the processing of temperature (wet- and dry-bulb), relative humidity and pressure using a scanning period of 30 seconds. Each hour the following information is available.

- (a) Instantaneous temperature (dry-bulb), mean and standard deviation of the temperature, and the maximum and minimum hourly temperature and the hours in which they occurred.
- (b) Instantaneous relative humidity, and the mean and standard deviations of the relative humidity.
- (c) Instantaneous pressure.

There is no processing of the wet-bulb temperature, but this temperature is used to check the relative humidity sensor and, indirectly, the air-temperature sensor.

The data logger stores the hourly data in ASCII code, and after about nine days (the period depending on the rate at which data is stored in the CR7) an overwrite process is started. Periodically all the data are stored on tape using a recorder (each tape holds about 180 000 pieces of data). At any time it is possible to act manually on the CR7 system to obtain tabulations and to monitor the quantities being displayed; this can be done without altering the execution of the program. When there are incorrect readings because of interference, special codes are displayed. However, the system is completely protected from variations in the power supply system and also from electromagnetic interference on the external sensors. A buffer battery system allows the system to continue working when the mains electricity supply fails.

The data stored on the tapes are periodically tabulated using a C20 reader connected to a printer. This reader is also connected to a Hewlett Packard HP-9816S series 200 computer by means of an RS232 serial interface. The transmission of data processed by the CR7 system to the computer takes place by means of definite hardware protocol and by software which has about ten instructions. The meteorological parameters are passed in a sequence fixed by the program. This ensures a homogeneous sampling of the sensors.

3. Checking the meteorological data

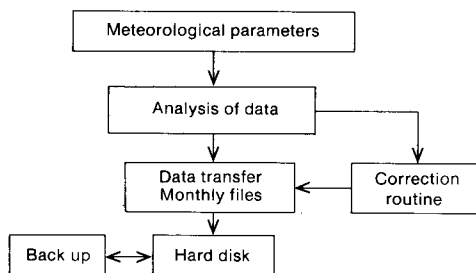


Figure 2. Checking procedure for meteorological data.

Fig. 2 illustrates the checking procedure used for the data. All the meteorological parameters are analysed using suitable software — there is no manual quality control. The checking is carried out by means of various calculations which should identify unreliable data; this is done before parameters are stored as monthly files. The most important of these checks are listed below.

- (a) Global radiation (G) and diffuse radiation (D) must be positive and satisfy $0.25 \leq D/G \leq 1.0$ and $0 \leq G/G_0 \leq 0.7$ where G_0 is the amount of radiation from the sun on a horizontal surface at the top of the atmosphere (depends upon time of day, time of year and latitude as well as other astronomical parameters; see Appendix).
- (b) Sunshine given by the sensor (E_E) and that from the Campbell–Stokes recorder (E_C) which is keyed into the system must satisfy $(E_E - E_C) \leq 0.15$ hours and $E_E < E_0$ where E_0 is the theoretical amount of sunshine (see Appendix).
- (c) Precipitation must be less than 50 mm h^{-1} (Allen 1972, Shearman 1975).
- (d) Maximum gust speeds must be less than 50 m s^{-1} and more than the mean wind speed; the standard deviations of the wind speed and direction must be less than 10 m s^{-1} and 81° respectively (Bryant 1979a, 1979b).
- (e) Air temperature, mean temperature, and maximum and minimum temperatures must be within their climatological extremes for the month.
- (f) Relative humidity and mean relative humidity must lie between 0 and 100%, and the standard deviation of the humidity must be less than 12%.
- (g) Atmospheric pressure must lie between 950 and 1000 mb.
- (h) Global radiation in various spectral bands must be less than values based on experiment (Kondratyev 1969).

These checks are based on the meteorological conditions at Macerata so that if the system is used at a location where the conditions are significantly different the numerical limits in the checks would have to be changed (Mammarella 1986, Cerquetti and Cruciani 1987, Ricketts 1980).

With the checking program it is possible to act on ‘wrong’ data using a correction subroutine. By means of a series of checks made with suitable laboratory instruments, it is possible to test the sensors’

efficiency and also to estimate if an event is exceptional. In the case of wrong data it is possible either to interpolate a value or give it a numerical code which indicates a missing value (Worthing and Geffner 1965). The program stores each parameter in monthly files on logical records with immediate access. The final step of the checking program is to transfer all files to the hard disk and the back-up.

Through a software process of continuous monitoring of all sensors, it has been possible to make further checks of the values. This monitoring program uses a direct link between the computer and the CR7, and allows the CR7 readings to be monitored without altering the continuous data processing. This procedure aims at identifying incorrect readings due to a malfunction of a sensor or incorrect data processing. The checks on the reliability of a value are the same as those for each meteorological parameter. There are also other relationships that, for example, make it possible to check the correct working of the relative humidity sensor and the air thermometer. They make use of the temperature of the wet-bulb thermometer whose value is measured every 30 seconds. By making use of psychrometric formulae (see Appendix) it is possible to calculate the value of the relative humidity and make a comparison with the value given by the sensor. The difference between the two values must be less than 6% to ensure good estimates of dew-point temperature, saturation vapour pressure and absolute humidity. When the difference is greater than 6% it is necessary to check the sensors against suitable calibration instruments.

4. Meteorological data management

Fig. 3 shows the procedure for the standard daily management of all available observations. The data acquired through the sensors are augmented by synoptic information (e.g. clouds and visibility) inserted into the system by the operator via a keyboard. The synoptic observations are processed, in accordance with international regulations, at 08.00, 14.00 and 19.00 hours local time.

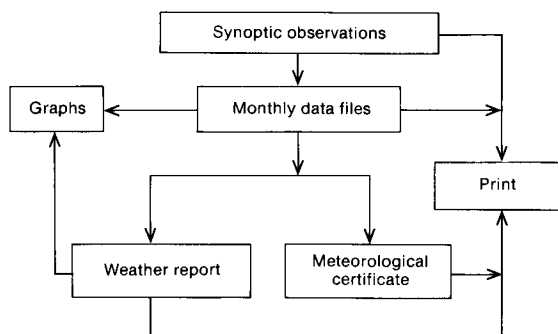


Figure 3. Meteorological data management.

Every month, data files are prepared which contain the data averages and general summaries. This information can be displayed as diagrams or tables (referred to as 'weather report' in Fig. 3). Generally the software allows random access to all data, with the ability to perform mathematical/statistical analysis. Moreover, when meteorological information is requested by public bodies, corporations and industry, the system can provide tabulations of the required data (referred to as 'meteorological certificate' in Fig. 3).

5. Conclusions

The system for acquiring, checking and managing the meteorological information is very effective in providing information for the Meteorology and Climatology Department of the Geophysical

Experimental Observatory (Osservatorio Geofisico Sperimentale 1957–86). The system has considerably reduced the time taken to analyse data and to carry out research — it has also made it easier to check and file data. In spite of this, procedures are still being improved in order to eliminate errors and to increase the versatility of the system.

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Appendix — Some formulae used in the data-checking program

Direct solar radiation

Hourly values of the extra-atmospheric radiation on a horizontal surface (G_o) are given by integrating the following equation

$$dG_o/dt = KI_o \cos Z$$

with the reduction factor for the earth–sun distance (K), the solar constant $I_o = 1.94 \text{ cal cm}^{-2} \text{ min}^{-1}$, solar zenith angle (Z) and the solar declination (δ) given by

$$K = 1 - 0.034 \sin\{(360/365)(i - 94)\}$$

$$\cos Z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h$$

$$\sin \delta = 0.4 \sin\{(360/365)(i - 80)\}$$

where t is the time in minutes, ϕ is the geographical latitude, h is the hour angle of the sun and $i = 1, 2, \dots, 365$ is the Julian day (Smithsonian Institution 1958, Coulson 1975).

Theoretical sunshine

The theoretical amount of sunshine (E_o) is given by

$$E_o = (2/15)\cos^{-1}(-\tan\phi\tan\delta)$$

where ϕ and δ are the latitude and the solar declination respectively.

Psychrometric formulae

From the dry- and wet-bulb temperatures (T_A and T_B) the saturation vapour pressures at the dry- and wet-bulb temperatures (E_A and E_B) and the vapour pressure (P_v) are computed using

$$E_A = 6.1 \times 10^{\{7.5T_A/(237.3 + T_A)\}}$$

$$E_B = 6.1 \times 10^{\{7.5T_B/(237.3 + T_B)\}}$$

$$P_v = E_B - 0.65(T_A - T_B).$$

From these the relative humidity (U), absolute humidity (U_A) and dew-point (T_R) are derived from

$$U = P_v(100/E_A)$$

$$U_A = (U/100)(0.795066E_A)/(1 + 0.00366T_A)$$

$$7.5T_R/(237.3 + T_R) = \log_{10}(P_v/6.1).$$

Wind

The hourly values of the scalar (\bar{S}) and vector mean (\bar{V}) speeds (Brooks and Carruthers 1953) are given by

$$\bar{S} = \frac{1}{n} \sum_i (N_i + E_i)^{1/2}$$

$$\bar{V} = \frac{1}{n} (\sum_i N_i^2 + \sum_i E_i^2)^{1/2}$$

where $N_i = V_i \cos\alpha_i$ and $E_i = V_i \sin\alpha_i$ are the north-south and east-west components of the wind (where α_i is the wind direction and V_i is the magnitude of the vector wind), and n is the number of samples.

The standard deviation of the wind direction is

$$SD(\alpha) = 81(1 - \bar{V}/\bar{S})^{1/2}.$$

The winter of 1987/88 in the United Kingdom

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Summary

The winter was very mild, especially in eastern and central areas of England and Wales, and generally wet. After a dull December most places in England and Wales had above-average sunshine, February being particularly sunny; Scotland, however, had a generally dull winter.

1. The winter as a whole

Mean temperatures over the winter (December 1987–February 1988) were above normal nearly everywhere, apart from some places in western Scotland, and ranged from about normal in western Scotland to nearly 2 °C above normal on the east coast of England. Ashover, Derbyshire reported that only the winter of 1974/75 was warmer at the station since records began there in 1967. It was wet in most places. Rainfall amounts ranged from 85% of normal in Northamptonshire and Grampian Region to 157% of normal in parts of the Lake District. Sunshine amounts were above normal in all parts of England and Wales, but below normal in Scotland, and ranged from 47% in north-west Scotland to 166% in the north Midlands.

Information about the temperature, rainfall and sunshine during the period from December 1987 to February 1988 is given in Fig. 1 and Table I.

2. The individual months

December. Mean monthly temperatures were above normal nearly everywhere in the United Kingdom, ranging from about normal in the south-west to more than 2 °C above normal in north-east England. Monthly rainfall amounts were below normal in all areas except southern Scotland, ranging from less than half the normal in south-east England and part of eastern Scotland to just above normal in southern Scotland and South Wales. Monthly sunshine amounts were generally below average except in north-west Scotland and Northern Ireland, ranging from 53% of average at Wattisham, Suffolk to 169% at Stornoway, Western Isles. It was the dullest December at Sheffield, Weston Park, South Yorkshire since 1958 and at Coventry (Bablake), Warwickshire since 1964.

January. Mean monthly temperatures were above normal nearly everywhere but near normal in north-west Scotland, ranging from 0.1 °C below the average at Tiree, Strathclyde to 2.4 °C above average at Gatwick, West Sussex. Mean monthly rainfall amounts were above normal everywhere except Shetland and the far north of Scotland, ranging from about 80% of average in Shetland to over 250% in parts of East Anglia. It was a very wet month with record amounts of rainfall in parts of southern England and the east coast of Scotland; it was the wettest January in England and Wales since 1948, the wettest at Hampstead, Greater London since records began there in 1909 and one of the wettest months on record with more than 100 mm falling in central London, the most since the London Weather Centre started records in 1940, according to provisional figures. Sunshine amounts were average or above average everywhere except parts of southern Scotland and some eastern areas of England, ranging from 55% of the average at Eskdalemuir, Dumfries and Galloway to 143% in north-east Scotland.

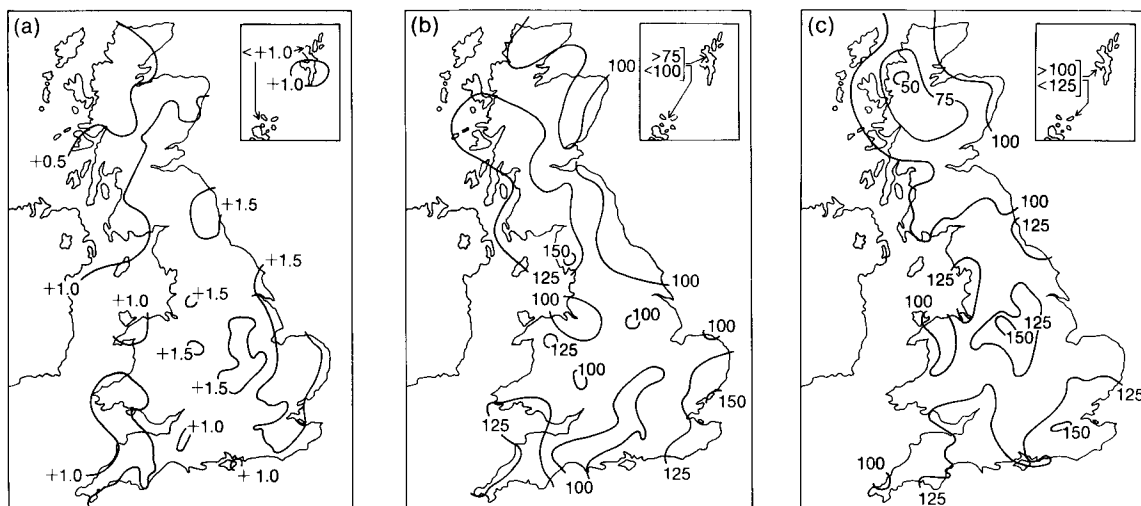


Figure 1. Values of (a) mean temperature difference, (b) rainfall percentage and (c) sunshine percentage for winter 1987/88 (Dec-Feb), relative to 1951-80 averages.

Table 1. District values for the winter months, December 1987-February 1988, relative to 1951-80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.6	+5	119	103
Eastern Scotland	+1.0	+4	113	95
Eastern and north-east England	+1.5	+4	107	108
East Anglia	+1.5	+3	117	113
Midland counties	+1.5	+1	107	117
South-east and central southern England	+1.3	-5	118	123
Western Scotland	+0.9	+5	130	100
North-west England and North Wales	+1.1	+3	124	108
South-west England and South Wales	+0.9	+7	118	116
Northern Ireland	+0.7	+6	124	104
Scotland	+0.8	+5	121	99
England and Wales	+1.3	+2	115	114

Highest maximum: 15.2 °C in the Midlands in December.

Lowest minimum: -9.8 °C in eastern Scotland in December.

February. Mean monthly temperatures were above normal everywhere and ranged from 0.1 °C above normal in north-west Scotland to 1.5 °C above normal in parts of eastern Scotland and northern England. Sheffield, Weston Park reported the highest February mean temperature at the station since 1980. Monthly rainfall totals were generally above normal in Scotland and Northern Ireland but below normal in England and Wales, ranging from just over 170% of normal at Tiree, Strathclyde to just over half the normal in central London. Monthly sunshine totals were generally above normal everywhere except north-west Scotland, ranging from 56% at Cape Wrath, Highland Region to about twice the normal in some parts of the Midlands and East Anglia. It was a very sunny month, with many places in

central and southern areas in particular having the highest February sunshine total since records began. Five places measured about 144 hours: Brighton, East Sussex, Bognor Regis, West Sussex, Swanage, Dorset, Teignmouth, Devon and Torbay, Devon. Among others it was the sunniest February on record in Coventry (Bablake), Warwickshire in a record going back to 1895, and Sheffield, Weston Park reported the sunniest February since 1949.

3. The weather month by month

December. The month started cold but mainly dry over most parts of the United Kingdom. There was extensive and persistent fog in north-east Scotland for the first few days of the month, where temperatures stayed below freezing all day on the 3rd. Outbreaks of rain reached south-western areas on the 3rd, giving some snow over the moors. This was followed by 10 days of cold settled weather, but with overnight fog forming, mainly over England. Rain came to nearly all parts except the far north and brought milder weather to parts of southern England, Northern Ireland and Wales on the 16th. The weather in the second half of the month remained unsettled with frontal systems moving in from the Atlantic, bringing cloud and rain, but also staying mild or very mild. Although there was frost early on the 25th, it was generally a very mild day with some dense fog at first in southern England. Thunder was heard in Shetland on the 22nd and at several places in northern or western Scotland on the 29th and 30th. Hailstones between 10 mm and 20 mm in diameter were reported at Colonsay, Strathclyde on the 29th. Most of the area south of a line from Torbay, Devon to The Wash was rather dry, with only about half the average rainfall. Brooms Barn, Suffolk reported the driest December since 1963; it was the driest December at Hampstead, Greater London since 1963, at Sheffield, Weston Park, South Yorkshire, since 1971 and over Northern Ireland as a whole since 1975.

January. The month started with fronts bringing heavy rain and some exceptionally mild conditions to England, Wales and Northern Ireland. On the 2nd heavy rain caused a landslide on the road between Bideford and Torrington, Devon. By the 4th rain moved north-east across England and Wales, with some fairly heavy snow on the Pennines. On the 4th gusts to 68 kn and 63 kn were measured at Aberporth and Brawdy, Dyfed; a 13 800 tonne tanker was reported to have been blown away from its moorings at Milford Haven by very strong winds. In Cardiff three women were injured when winds sent glass roof panels crashing down on shoppers and stallholders at the Central Market, and a double-decker bus was blown into a wall injuring the driver and two passengers. On the 6th gales caused the closure of the Severn Bridge for the third time in its history when gusts overturned a high-sided lorry. A mean wind of 41 kn and gust of 64 kn was measured at Rhoose, South Glamorgan. In west Oxfordshire a motorcyclist was killed and his pillion passenger badly injured when a gust of wind blew them into a tree. Showers were widespread on the 10th, with sleet and snow over higher ground. On the 14th there was a little sunshine nearly everywhere; many eastern and south-eastern areas stayed dull and cold on the 15th. Heavy rain fell on north-western parts of the United Kingdom on the 17th; there was a return to cold weather on the 18th, and on the 20th and 21st it was very sunny. On the 29th torrential rain fell in southern parts of England and Wales causing flooding as far apart as Gloucestershire and Wiltshire in the west and Essex and Kent in the east. The month ended with further heavy rain. Thunder and hail were reported on 6 days, notably over England and Wales on the 4th and 6th; on the 5th about 20 people escaped injury when lightning demolished the steeple of a Swansea chapel, hurling masonry blocks into nearby houses.

February. February was a month of contrasts. The month began generally unsettled, with showers or longer periods of rain. Snow, sleet or hail occurred widely, especially in northern and western areas. It

remained unsettled until the 15th when high pressure brought more settled conditions to southern areas, although showers of rain or hail continued to affect Scotland and Northern Ireland, but with some sunny spells in between. Thunder was widely reported, notably on the 1st, 9th and 13th. Hail was widespread and frequent during the first half of the month. Gales or severe gales were widespread across England and Wales on the 1st: gusts of more than 50 kn were widely reported, and gusts to over 70 kn near exposed western and south-western coasts. Strong winds continued to affect many areas on the 2nd with gales in places; there were several gusts between 60 kn and 75 kn at exposed places in the south and west at about midday. Further gales and storm force winds came to many parts of Great Britain on the 9th. There was a gust of 96 kn during the afternoon at Gwennap Head, Cornwall, a record February gust for England and Wales and in many places, especially in the west, gusts of more than 70 kn were recorded. Plymouth, Devon reported a gust of 72 kn, the highest February value on record there. The wind slowly moderated on the 10th. Strong cross winds in Devon and Cornwall brought down trees and disrupted traffic. North-west England suffered the worst damage, however, with structural damage to buildings, including the roof of the Town Hall at Bury, Greater Manchester and disruption of road and rail traffic.

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The great storm of 16 October 1987 — a forecaster's story

G.M. Capstick

London Weather Centre

Summary

One wet day this summer whilst reading yet another article about the great storm of October 1987 I realized that perhaps I should tell the story of one forecaster on duty at the time. The following is my personal account of the events that night as seen through the eyes of an offshore forecaster at London Weather Centre.

As the first anniversary of the storm of 16 October 1987 passes, it is interesting to look back on that night. The storm of Friday 16 October 1987 will be remembered by the staff at London Weather Centre for many years to come, and those who were on duty that day will remember it for the rest of their lives. I was on duty that night having started a run of shifts on Monday the 12th prior to going on holiday in Yorkshire. Thus I was able to follow events fairly closely, from being aware on Monday that a major low was likely to be near the United Kingdom towards the end of the week, to being aware on Thursday night that the event was actually happening.

My job was to forecast the winds and waves for the rigs and platforms in the North Sea. With a major new contract starting at midnight on Thursday a decision was made as early as Tuesday between myself and the Commercial Manager that, in view of the situation, it would be advisable to send the new customer an update on the weather situation as soon as possible after midnight on Thursday. The night duty begins at 1900 GMT and my first task was to look at the situation and to consider whether the previous forecast was adequate or whether it needed amending. In order to do this it is normal procedure to analyse the 1800 GMT wind and sea data. After drawing up the relevant charts it became evident that a major weather event could take place overnight and that the forecast winds from the previous issue could be too low, even though gusts over 60 kn were forecast. The main problem was threefold; (a) when would the event take place, (b) how windy would it be, and (c) where would the strongest winds occur?

At this time severe gale force 9 warnings were in force for most of the relevant sea areas. After analysing the charts I rang the Central Forecasting Office (CFO) at Bracknell to tell them that I thought the winds would be stronger than force 9, but I decided that the situation was still uncertain and would wait until the 2100 GMT data had been seen before making any major amendments. At this stage a certain amount of planning was being done for the morning forecasts but time did not allow as much planning as normal.

The 2100 GMT chart was analysed and although pressure falls were increasing in the south-west there was as yet no concrete evidence of what was to come; but things were beginning to happen. The warm front had moved north through London Weather Centre, therefore I thought it unlikely that the low would pass to the south of us as previously envisaged. The midday run of the fine-mesh forecast confirmed this by placing a low near Norfolk at 0600 GMT on the 16th (this was received too late to be used by the day duty). It gave a mean west-south-westerly wind of 35 kn (at 25 m above sea level) over Essex but not too much wind over the North Sea. It was now becoming obvious that amendments would probably have to be made and the sooner the better. Exactly what values to put on the wind speeds in the amendment and the timing of the onset of the storm were still in doubt.

There are normally two forecasters on duty dealing with the North Sea and most of the decisions that night were made after consultations between the two of us. It was decided that the new customer should be warned first as their forecasts were most in error (the previous forecasts issued by a competitor had been made available at London Weather Centre). An amendment was then written indicating that a major storm was expected to hit the English Channel and the North Sea later that night.

At this stage it was considered that there would be only a limited amount of time later in the night, so planning was done for the morning forecasts for the Mediterranean and also for parts of the North Sea which were thought unlikely to be seriously affected by the storm (the Moray Firth area). Between 2300 GMT and midnight a message was sent to all the locations which were under the authority of the new customer.

The 0000 GMT observations were analysed — south-south-westerly winds gusting to over 70 kn in Devon and northerly winds gusting to over 70 kn in Cornwall. Also there were marked pressure falls being reported over south-west England. The situation was deteriorating rapidly, therefore I rang CFO again to tell them that we were going to forecast hurricane force winds for the North Sea. Between 0030 and 0130 GMT messages were sent forecasting means of 60 kn and gusts to 90 kn to most of our customers — including the new one. Planning for the morning issue was renewed and by now the hourly observations were being scrutinized more closely with each hour as the situation deteriorated.

PRELIMINARY WARNING

THE DEPRESSION NOW MOVING ACROSS SOUTHERN ENGLAND ON ITS WAY TO THE NORTH SEA IS PROVING EXTREMELY VIGOROUS AND IT SEEMS LIKELY THAT MEAN SPEEDS AT 10 M OF 60 KTS ARE LIKELY IN THE NORTH SEA THIS MORNING AND AFTERNOON WITH GUSTS PERHAPS 80 OR EVEN 90 KTS. THE EXACT TRACK OF THIS LOW IS STILL UNCERTAIN AND CONSEQUENTLY EXACTLY WHERE THE STRONGEST WINDS WILL BE BUT YOUR AREA IS AT RISK. HOPEFULLY A MORE DETAILED ANALYSIS OF THE SITUATION WILL BE AVAILABLE BY THE TIME OF THE MORNING FORECAST SO THAT MORE PRECISE DETAILS CAN BE GIVEN.

The wind at London Weather Centre became a useful distraction — the power had failed, destroying a certain amount of planning, and the computer had failed at Bracknell. This proved to be a serious set-back. Not only would there be no computer guidance in the morning but also automated products

for numerous places in the North Sea would not be available and therefore forecasts for these areas would have to be done by hand from scratch.

The 0000 GMT charts were analysed but our sandwiches remained uneaten. As 0315 GMT approached, with only 3 hours 45 minutes to go before relief arrived, it was decided to begin the morning forecasts. The Mediterranean forecasts were then sent. The 0300 GMT observations were studied and it became evident that the low was heading for the oil rigs. But where, precisely, would it go? The senior forecaster at CFO was consulted and the problem was discussed. For some time it had become evident that there were two main areas of strong winds, one to the east of the centre and the other to the south. The movement of these areas was discussed, decisions were made, and a track taking the low across the north Midlands and turning to go northwards up the North Sea near the Greenwich meridian was decided upon. This proved to be very accurate. The Aberdeen forecaster was briefed while the forecaster at Sullom Voe was told that the storm would miss them.

The 0300 GMT chart was drawn and the forecasts prepared and sent (a task which incidentally took about 3 hours of continuous tapping on the word processor). The London Weather Centre forecaster on the Buchan platform rang and the situation was discussed. Other telephone calls were dealt with and eventually all the forecasts were prepared and despatched.

```
FORECAST 0800 TO 2000 GMT FRIDAY 16/10/87
WIND 10 METRES    NE 30 PROBABLY VERY SOON BECOMING VARIABLE 25 AS
                  THE LOW PASSES OVER YOU THEN VERY SOON BECOMING
                  SSW 45 WITH OCCASIONAL INCREASES 55 TO 60
GUSTS             ABOUT 80
WIND 50 METRES    NE 35 PROBABLY VERY SOON BECOMING VARIABLE 30 AS
                  THE LOW PASSES OVER YOU THEN VERY SOON BECOMING
                  SSW 50 WITH OCCASIONAL INCREASES TO 65
GUSTS             ABOUT 85
SIG WAVE HEIGHT   3.0 BECOMING 8.0
WAVE PERIOD       5 OR 6 BECOMING 9
MAX WAVE HEIGHT   12.0 OR 13.0 LATER WITH EXTREME WAVE NEAR 15.0
```

0700 GMT arrived and the sandwiches were still uneaten. It was time to go home, but nobody had arrived to relieve us. Nobody could get to work, there was no relief and the reality of the situation dawned — we would have to do it all over again. The 0600 GMT charts were drawn — there was still no fine-mesh forecast guidance from CFO but the planning for the afternoon forecasts began. At 1200 GMT my relief arrived and I was able to set off to start my holiday in Yorkshire. However, there were no trains from King's Cross — why weren't we warned?

Notes and news

The Professor Dr Vilho Vaisala Award

This has been awarded jointly to Dr J. Nash (Observational Requirements and Practices Branch of the Meteorological Office) and Mr F.J. Schmidlin (NASA Goddard Space Flight Center, Wallops Flight Facility, USA).

The award was given in recognition of the final report for the WMO International Radiosonde Comparison. The authors of the report, Dr Nash and Mr Schmidlin, were the project leaders of the comparison which took place in two phases, the first in the United Kingdom in 1984 and the second in the USA in 1985.

The comparison provided the most extensive examination of the quality of operational radiosonde measurements (i.e. pressure, temperature, relative humidity, geopotential height, and wind speed and direction) which has been conducted to date. As a result, reliable quantitative measurements of systematic bias between the temperature and geopotential height observations provided by different radiosonde types were made available for the first time. These are being used as the basis of adjustment schemes to improve the compatibility of radiosonde measurements for numerical weather forecasting.

Significant errors were identified in almost all the radiosonde systems which took part in the comparison. In most cases actions have subsequently been taken by the manufacturers or operators to eliminate or compensate for these errors and hence to improve the quality of operational radiosonde measurements. Infra-red cooling errors introduced by the use of white-painted rod thermistor sensors for temperature measurements were quantified. This demonstrated that, for this widely used sensor, the common practice of adjusting daytime temperature measurements to be compatible with those made at night, from the same station, will not produce the best estimate of the 'true' temperature.

Reviews

The little ice age, by J.M. Grove. 192 mm × 254 mm, pp. xxii + 498, illus. London, New York, Methuen, 1988. Price £85.00.

This substantial volume is, so far as this reviewer is aware, the first comprehensive collation and assessment of the world-wide evidence for an interval of cooler climate between, approximately, the sixteenth and early nineteenth centuries. As such it will be welcomed by climatologists, because this evidence will, by consolidating our knowledge of the past, help to pave the way for an increased understanding of climate, and of the impact of man-made changes, such as increasing carbon dioxide and other 'greenhouse' gases in the atmosphere.

The author aims not only to describe the 'little ice age' and its consequences, but also to give an account of our current understanding of its causes. In order that the conclusions be seen to be soundly based on facts, high standards for both scientific consistency and historical accuracy are set from the start. The introductory chapter stresses the author's choice of contemporary rather than secondary historical sources, and includes discussions of the uses and pitfalls of techniques such as carbon-14 dating of material in moraines, lichenometry, and dendrochronology. Throughout the book the evidence presented is carefully assessed in terms of the methods involved, and corroboration by independent information is sought if possible. Recorded events are interpreted with due caution; for example, some glaciers are unstable and their frequent surges need not be initiated by a colder or snowier climate.

The concern for accuracy and careful interpretation has not detracted from the anecdotal interest of the descriptive accounts of glacial activity between medieval times and the present, which take up well

over half of the book. The fearsome 'jökulhlaups', which are floods caused by, *inter alia*, subglacial volcanic eruptions in Iceland, are impressed on the reader's memory. So are the exorcisms of Mont Blanc's glaciers by the Bishop of Geneva; each exorcism was followed by a retreat of the glacier. The plentiful illustrations also enhance the descriptive accounts and include useful summaries in diagrammatical form for the various regions discussed.

As the author admits, the descriptive chapters are most complete for Europe, including Iceland, though central Austria (the Gross Glockner) is omitted, and least complete for Siberia and the Far East. If further data were to come to light for these areas, they would be exceedingly valuable. The author deliberately omits Antarctica because of the lack of information and the expected long time-scale of variations in the Antarctic ice sheet.

The discussion of the causes of the 'little ice age' is a well balanced summary and assessment of current understanding. It is put into context by the preceding chapter on the glacial history of the Holocene. Here again the information presented is as global as possible and is carefully, though more briefly, assessed and summarized.

The final chapter, on the physical, biological and human consequences of the 'little ice age' will be of greatest interest to historians and to those concerned with the potential societal and economic impacts of future climatic changes.

There are a few, mainly numerical, printing errors in the book. For example, the height of Pik Karla Marksa is unlikely to be 8726 m (page 203 — K2 is not as high as that); and the height of the Holocene tree-line in Scandinavia has probably only fluctuated by 200 m rather than 2000 m (page 315). On line 3 of page 194, read '1630s' for '1730s'. The autumns of the 1730s, 1740s, 1750s and early nineteenth century were dry in Figure 6.9 not wet as on page 194.

In all the accounts and discussions the author attempts to bring the reader up to date. This is generally done successfully, though one exception is the statement on page 259 that at present it is not known whether the cooling trend since the mid-twentieth century has come to an end or not. Numerous papers published during the 1980s have shown that this trend has ceased and, indeed, reversed.

This book is a valuable and scholarly compilation with an excellent set of illustrations and a substantial bibliography. It is to be regretted that at £85 many interested readers will not be able to afford to buy it.

D.E. Parker

Meteorology for seafarers, by R.M. Frampton and P.A. Uttridge. 214 mm × 305 mm, pp. xvii + 137, illus. Glasgow, Brown, Son and Ferguson, 1988. Price £27.50.

Although somewhat larger than most books (A4 format) it would be worth finding space on your bookshelf for this volume. In spite of some disagreements I may have — mainly with some of the contents in the chapters devoted to winds and circulation — this book is physically easy to read, with a particularly clear type-face, simple figures and a selection of colour photographs illustrating cloud types, and some showing the relationship between Beaufort force and the state of the sea.

Meteorology for seafarers is one of many nautical books by these publishers, and is a revision of Commander Burgess' classic *Meteorology for seamen* which is now nearing its 40th birthday. Between them, the authors have experience both at a theoretical level and on the sea itself, but they have avoided the pitfall of using jargon, and all acronyms have been spelt out in full at the first time of using.

There are 11 chapters in this book with the two largest devoted to the circulation, both on global and synoptic scales. As well as temperate areas, subtropical and tropical areas are considered, which these

days is becoming increasingly important as yachtsmen charter further and further from their home waters.

The authors begin by discussing the nature of the atmosphere, and then consider how to measure its quantities, taking in turn pressure, temperature and humidity. The radiation budget is balanced, and atmospheric stability then leads into clouds and precipitation. Winds and circulation are covered in sufficient detail to inform, without confusing, less experienced readers.

It is in the chapters on circulation and wind (my two particular 'hobby-horses') that I have mild reservations. Values of cyclostrophic force may be *largely* dependent on the pressure gradient, but the radius of curvature of the isobar also plays its part — adding to the strength of the wind with anticyclonically curved isobars, and diminishing the strength in the presence of cyclonic curvature. For this very reason picking the axis of a ridge to measure the gradient (to demonstrate the use of a geostrophic scale) is not really a very good idea. I appreciate that with a reading of 12 knots on the scale, the gradient wind correction is negligible, but it is a bad practice, and with closer isobars could easily turn an expected Force 8 into an observed Force 10 in temperate latitudes.

There also seems to be a tendency to discuss just one aspect of a topic under a bold heading, and then to present that one aspect as the definition — a dangerous point of view, especially in a reference book which is very likely to be used by readers of mixed ability.

The last two chapters relate to the organization of meteorological services, and how the national meteorological centres fit into the network of satellites and observing sites. Forecasting techniques are briefly looked at with a few examples of prognostic charts together with 'least-time' ship routeing. The final chapter has some thoughts on single observation forecasting, together with sources of additional bulletins — such as the Atlantic, as well as the more normal shipping forecast broadcast on BBC Radio.

I said initially that it would be worth having this on your bookshelf (and I will certainly carry it in my mobile library when instructing) but whether to buy this or for the same money buy two less expensive publications might be a difficult choice.

A.R. Ebling

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

An introduction to boundary layer meteorology, by R.B. Stull (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.220.00, US\$99.00, £64.00) presents fundamental concepts and mathematics of the subject prior to use, with physical interpretations, sample data, examples and exercises included. It is intended as a combination of textbook, reference and literature review for students with an undergraduate background in meteorology (or similar).

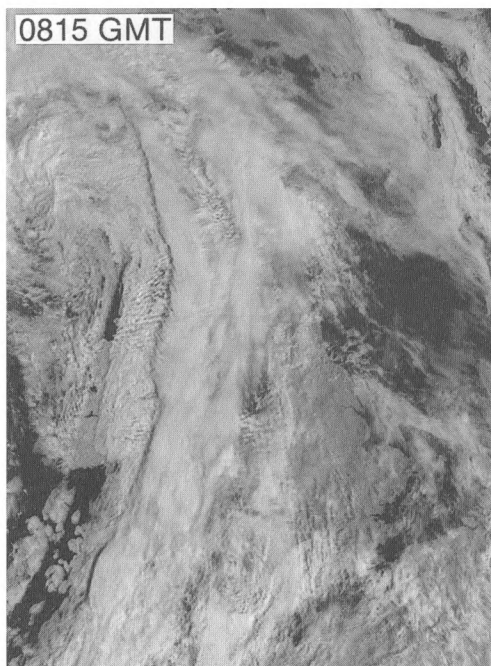
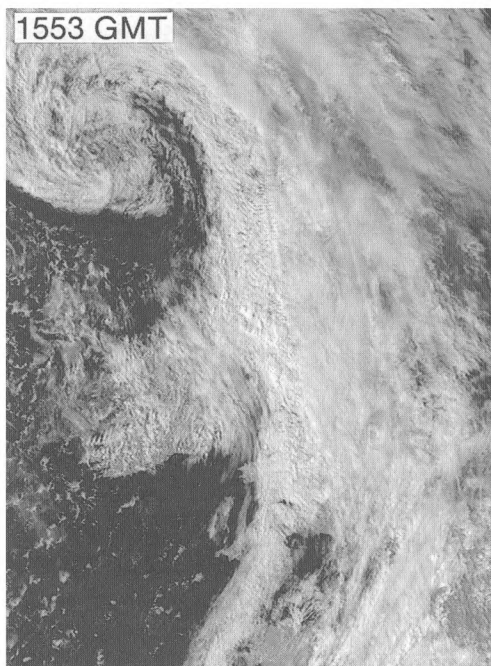
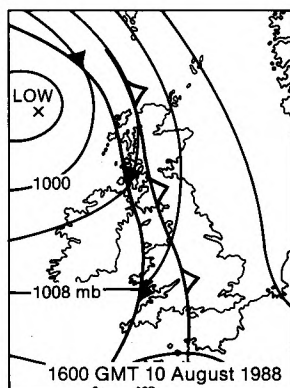
Sea surface sound, edited by B.R. Kerman (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.290, US\$149.00, £79.00) contains the proceedings of the NATO Workshop held at Lerici, Italy in June 1987. The central theme of the many and varied papers is 'What are the mechanisms causing ambient noise at the upper surface of the oceans?'

Satellite photographs — 10 August 1988 at 0815 and 1553 GMT

These NOAA-10 visible images show cloud associated with a split cold front as it moved into the British Isles. At 0815 GMT the rear edge of the upper front is readily identified by its shadow cast upon the lower cloud of the shallow moist zone (SMZ). The surface front lay some 100 km further west. By late afternoon (1553 GMT) the same lateral separation was evident over Scotland and northern England; both fronts had moved east at 15 kn. Further south, however, the upper front had progressed at about 35 kn and the surface front at only 22 kn, with the result that an intervening cloud-free slot was revealed between Brittany and Dorset. Subsequently this zone extended north-east bringing evening sunshine to much of south-east England.

The FRONTIERS display in the Central Forecasting Office at Bracknell showed the cloud top within the SMZ to be near 8000 ft (temperature 2 °C); cloud layers to the east reached to 30 000 ft (−45 °C).

Over southern Britain the heaviest rain fell within the strong, moist south-westerly flow of the SMZ, hourly accumulations reaching about 4 mm where there was orographic enhancement. FRONTIERS radar identified a narrow belt of maximum rainfall rate just to rear of the upper front. Once the fronts 'de-coupled', rainfall largely died out. Precipitation from upper cloud mostly evaporated before reaching the surface and rain in the SMZ became slight and intermittent as this zone moved clear of higher ground. Absence of seeding from above may also have contributed to its rapid demise.



Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

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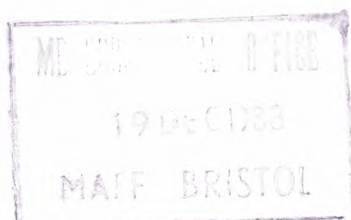
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THE METEOROLOGICAL MAGAZINE

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Introduction to fronts, Part I
Onset of Indian monsoon
The first 'obs' book
Summer School on The Storm

APR

December 1988

Met.O.982 No. 1397 Vol. 117

THE METEOROLOGICAL MAGAZINE

No. 1397, December 1988, Vol. 117

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An introductory review of fronts. Part I: Theory and observations

D.A. Bennetts, J.R. Grant and E. McCallum

Meteorological Office, Bracknell

Summary

This paper, on frontal meteorology, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. Part I describes important dynamical aspects of both the formation and structure of frontal zones, and Part II illustrates the main features through a case-study of a cold front which crossed the United Kingdom on 13 January 1983.

Here, in Part I, simple conceptual models are described which should help forecasters to understand frontal zones and thereby lead to a better appreciation of the data available from the increasing number of mesoscale observing systems that are coming into operational use. The paper is not intended to be a comprehensive review.

1. Introduction

Over the past decade there has been a considerable number of theoretical and observational studies into the formation and structure of frontal zones. Much of this work has followed directly from the new mesoscale observational techniques that were developed in the late 1960s and 1970s, and from modern computers that permit numerical modelling to take place at a similar spatial resolution to that of the observational data.

These mesoscale observational systems are now becoming available at forecasting offices. It is therefore appropriate to try and pull together the results from the many research papers, and give an overview of the meteorological processes that give rise to the mesoscale features that are now observed routinely within frontal systems.

The paper is divided into two parts. Part I discusses how frontal zones form, what determines their overall structure and the nature of sub-frontal-scale perturbations. Part II (Bennetts *et al.* 1989) is a case-study of an active cold front that crossed the United Kingdom on 13 January 1983 and is used to illustrate many of the conceptual models developed in Part I.

In Part I, every effort has been made to bring out the meteorology of the various features and to produce simple conceptual models. The paper is written with the practising forecaster in mind, and is intended to provide an understanding of the mesoscale features that are readily observed, both on satellite pictures and through the UK weather radar network data. To this end, many of the mathematical details are omitted.

2. Frontal theory

A great deal can be learnt about fronts by considering adiabatic, frictionless flow in a dry atmosphere. Water vapour will be important in describing some of the sub-frontal-scale features discussed later but, at this early stage in the paper, it is an unnecessary complication.

Consider a simple case in which a straight front is moving with the geostrophic wind speed, u_g (suffix 'g' denotes geostrophic) — the coordinate system and orientation of the front are given in Fig. 1(a). To understand the behaviour of the front it is helpful to consider motion relative to the front. In this case the situation is that given in Fig. 1(b). Note that now the x component of the wind relative to the front, u , is simply the ageostrophic wind.

Observations of fronts have shown that typical length scales along the front, L , and across the front, l , are $L \approx 1000$ km and $l \approx 100$ km, and that typical velocity scales of the relative flow along the front, v , and across the front, u , are $v \approx 10$ m s⁻¹ and $u \ll v$. Consequently, to a good approximation, a front can be viewed as being two dimensional, with no change in structure along its length. Also, following Hoskins and Bretherton (1972), it can be shown that a consistent set of equations describing the flow relative to a front are as follows

$$v = v_g \text{ where } v_g = f^{-1} \delta\phi/\delta x \quad \dots \dots \dots (1)$$

$$dv/dt + fu = 0 \quad \dots \dots \dots (2)$$

$$\delta\phi/\delta z = g \theta/\theta_0 \quad \dots \dots \dots (3)$$

$$d\theta/dt = 0 \quad \dots \dots \dots (4)$$

$$\delta u/\delta x + \delta w/\delta z = 0 \quad \dots \dots \dots (5)$$

where θ_0 is a reference temperature, f is the Coriolis parameter, g is the gravitational acceleration, t is the time and ϕ is the geopotential height. In the context of this paper the vertical coordinate, z , can be thought of as the geometric height, although in reality it is only equal to the geometric height in an isentropic atmosphere. Similarly w can be taken to be the vertical velocity. A detailed discussion of this coordinate system is given in Hoskins and Bretherton.

The most important point to note is that equation (1) states that the wind component parallel to the front is always in geostrophic balance. A consequence of that statement is that the ageostrophic component of motion (u, w) is confined to the cross-frontal plane.

Furthermore, geostrophic balance implies thermal wind balance; elimination of ϕ from equations (1) and (3) leads to the thermal wind equation

$$f \delta v/\delta z = (g/\theta_0) (\delta\theta/\delta x). \quad \dots \dots \dots (6)$$

The form may be unfamiliar, but the link between the vertical gradient of velocity and the horizontal gradient of temperature can be recognized.

From equations (2) and (5) it will be seen that the ageostrophic motion is driven through changes in the air motion parallel to the front, i.e. through changes in dv/dt . The form of this ageostrophic motion has been described by Hoskins (1978), but the mathematics are complex and a detailed exposition is not appropriate here. The importance lies in the results of the work which show that in a typical frontal zone the streamlines of the cross-frontal (ageostrophic) flow form closed loops, as shown in Fig. 2. The direction of the circulation depends on the nature of the baroclinic zone and, in the configuration of

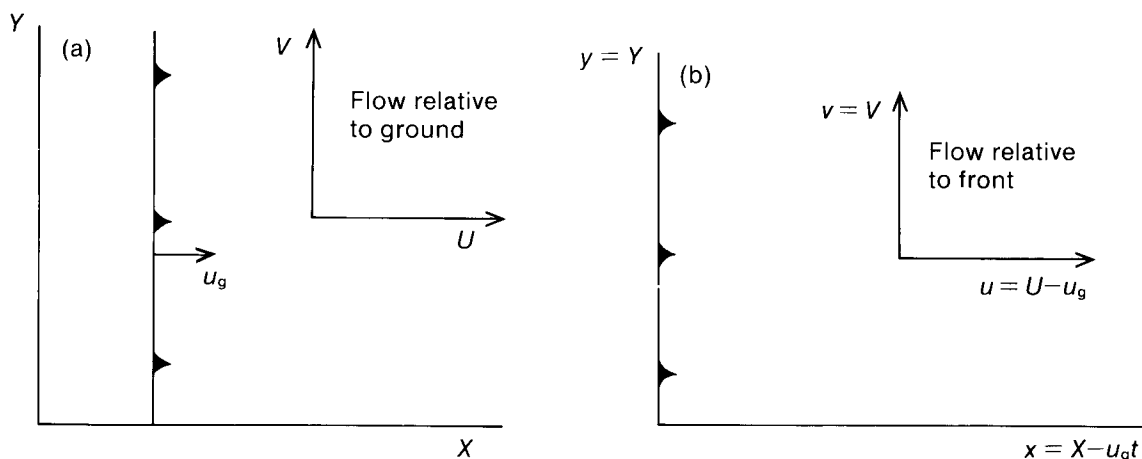


Figure 1. The coordinate systems and orientation of the front, (a) relative to the ground and (b) relative to the front. See text for explanation of symbols.

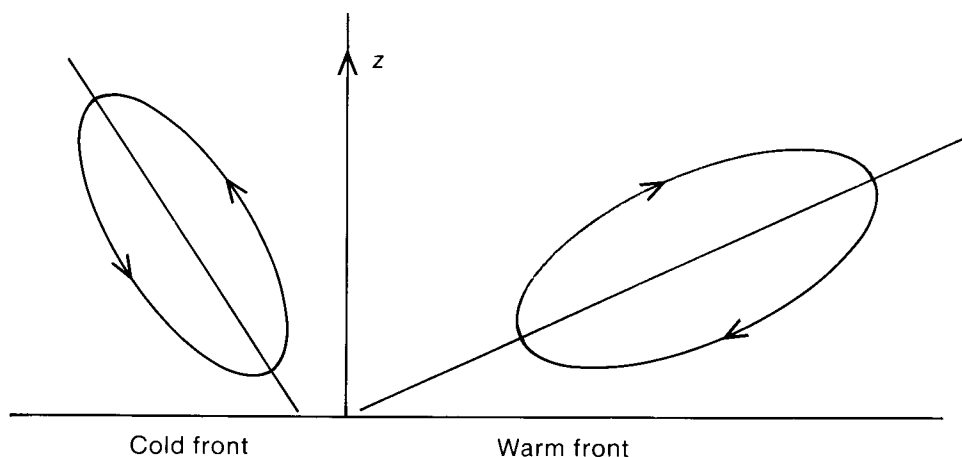


Figure 2. Schematic diagram of the cross-frontal ageostrophic motion. The direction of circulation depends on the nature of the baroclinic zone.

Fig. 2 (which is drawn with the observer looking towards the low pressure), it is found that on the warm front the circulation is generally clockwise while on the cold front it is generally anticlockwise.

Not surprisingly, there are similarities between the model in Fig. 2 and the familiar concept of air ascending and descending along the frontal surfaces. It may seem odd that all the streamlines in Fig. 2 cross the frontal zones, but that is due to the simplifications that have been made in developing the theory, in particular the omission of boundary-layer friction and ageostrophic effects near the jet stream. Both omissions will be discussed in more detail later in the paper.

In summary, the purpose of this section was to introduce the equations of frontal theory in their simplest form, and to show that the results of the theory are in agreement with the well established, observationally based concepts.

3. Frontogenesis

A front delineates the boundary between two different air masses and hence its position depends on the large-scale synoptic flow. However, the internal structure of the front depends on very local (mesoscale) processes. Unfortunately, such a separation of roles obscures the important linkage between synoptic and mesoscale motion — a linkage which is vital for the formation and maintenance of a frontal discontinuity. This linkage is discussed below.

Hoskins and Bretherton (1972) identify several synoptic-scale flow patterns that have the property of being able to tighten thermal gradients. Three of the most important in terms of the formation of fronts are shown in Fig. 3; Figs 3(a) and 3(b) represent motion in a horizontal plane, and 3(c) represents motion in a vertical plane. Regions such as depicted in Figs 3(a) and 3(b) are illustrated in Fig. 4. The label 'A' in

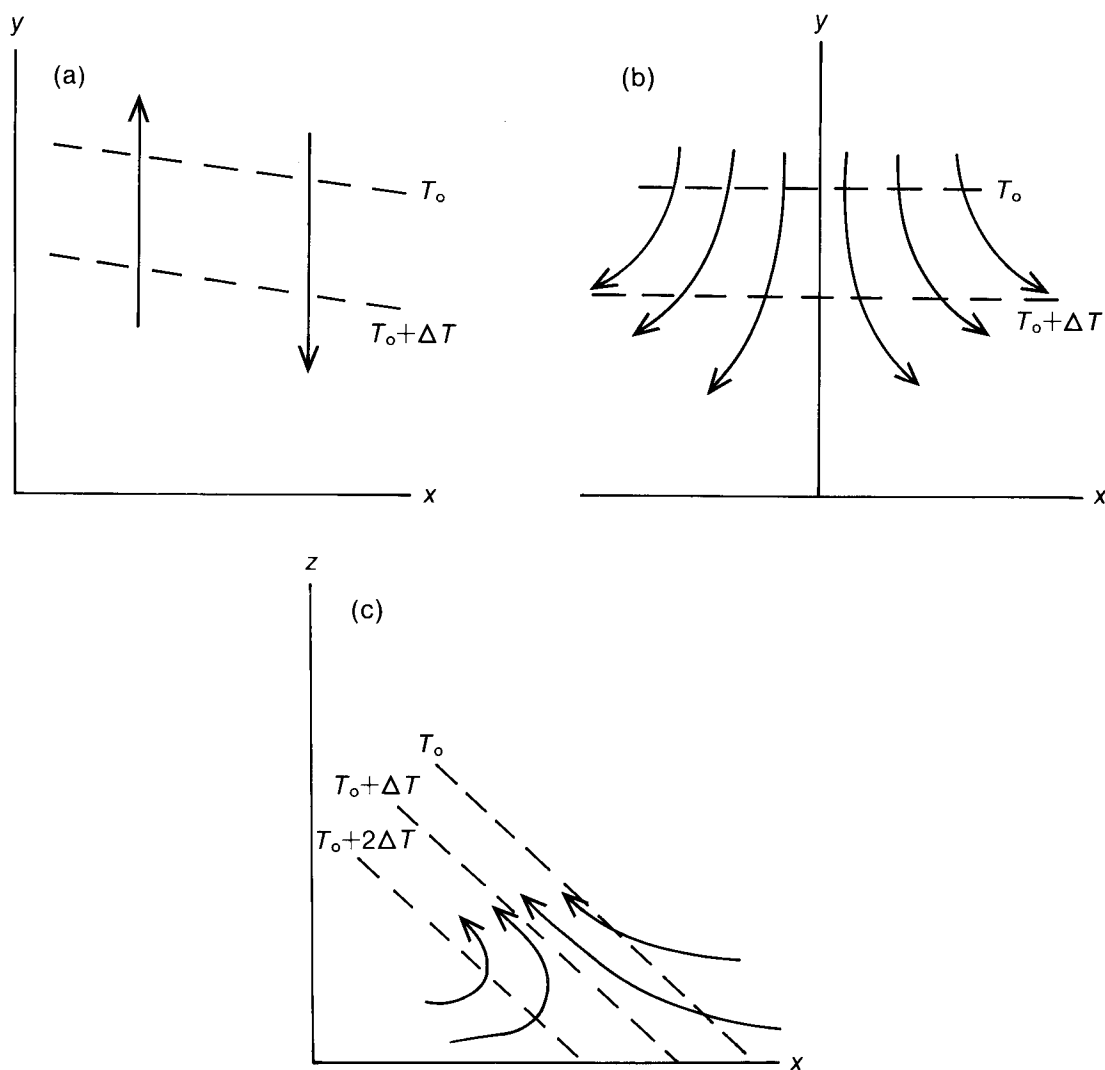


Figure 3. Three flow configurations which can intensify horizontal temperature gradients, (a) horizontal shear, (b) horizontal deformation, and (c) vertical deformation.

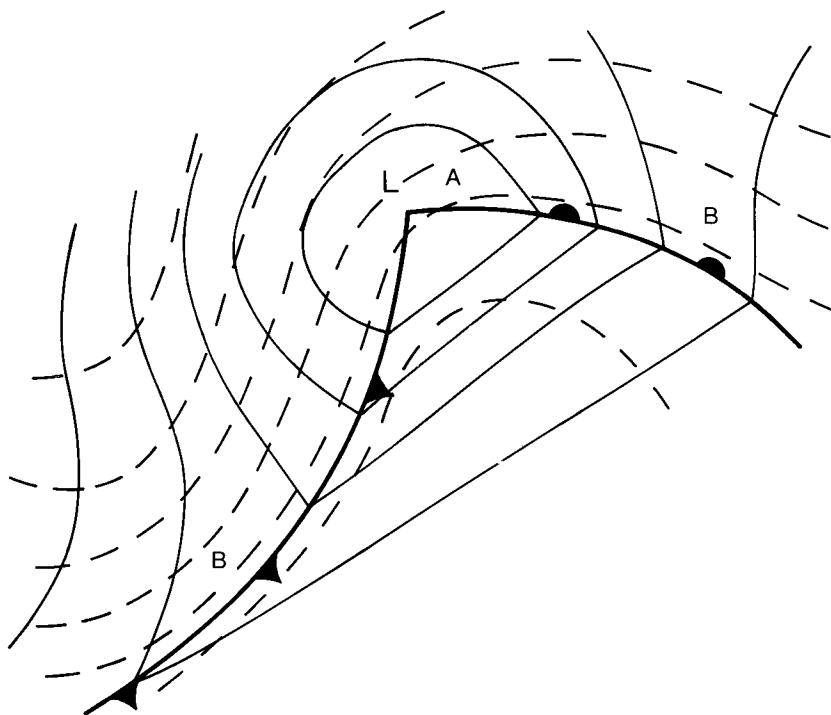


Figure 4. Depicted is a simplified schematic baroclinic wave. Dashed lines represent thermal thickness lines and solid lines the 1000 mb contours. A and B mark areas of horizontal shear and deformation, respectively.

Fig. 4 indicates a region in which the thermal gradient is being tightened due to a change in wind direction (as in horizontal shear, Fig. 3(a)) and 'B' regions of horizontal deformation (as in Fig. 3(b)). In both regions there is a tightening of the thermal gradient ($\delta\theta/\delta x$) and hence, because there is always thermal wind balance parallel to the front, a corresponding increase in $\delta v/\delta z$, i.e. the along-front wind component, v , increases with time, $dv/dt \neq 0$. Reference to the horizontal momentum equation (2) shows that if $dv/dt \neq 0$ then $u \neq 0$ and hence, from the continuity equation, $w \neq 0$. In consequence a tightening of the horizontal thermal gradient induces cross-frontal ageostrophic motion.

Consider now the frontal zone. The nature of the cross-frontal ageostrophic circulation has already been shown in Fig. 2. In Fig. 5, this circulation is superimposed on the potential temperature field (NB there is a simplification in this diagram that will be readily apparent when frictional effects are discussed in section 4); note particularly the region at the bottom of Fig. 5 at 'C', between the ascending and descending branches of the circulation, in which the temperature gradient is being compressed and hence strengthened (on the warm side of the baroclinic zone); compare this with Fig. 3(c). Therefore the cross-frontal ageostrophic motion tightens the thermal gradient.

Thus frontogenesis is a positive feedback mechanism between synoptic and mesoscale motion that works as follows:

- (a) synoptic-scale horizontal deformation fields locally tighten the thermal gradient,
- (b) since there must always be thermal wind balance along the front this implies an acceleration of v which induces an ageostrophic cross-frontal circulation, and
- (c) the induced cross-frontal circulation further tightens the horizontal temperature gradient, which increases v ... *ad infinitum*.

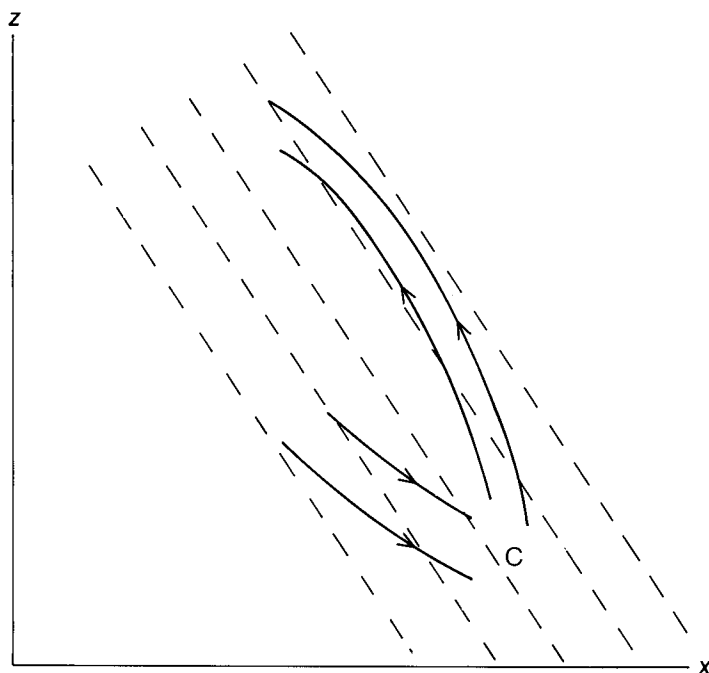


Figure 5. Cross-frontal ageostrophic circulation superimposed on the potential temperature field. Dashed lines represent lines of potential temperature and solid lines the streamlines of the cross-frontal circulation (from Fig. 2). The region, C, between the ascending and descending air is a region in which potential temperature lines are being compressed and hence $\delta\theta/\delta x$ is increasing.

The process is finally brought to a steady state by the effects of turbulent diffusion, when the frontal zone is typically about 1 km deep. This is, not surprisingly, a similar depth to the boundary layer, the physical processes which lead to the generation of turbulent diffusion being the same in both cases.

In summary, the theory provides a satisfactory explanation for the observation that fronts form on time-scales shorter than might be expected from consideration of the strength of the synoptic-scale deformation alone. It also accounts for the fact that fronts often maintain their identity for some time after synoptic deformation fields have weakened.

4. The conveyor belt

In section 2, fronts were discussed in the context of a frictionless environment. However, the effects of surface friction are important. Indeed, they are part of the reason why cold fronts have, in general, a steeper slope ($\approx 1:70$) than warm fronts ($\approx 1:150$).

Browning and Pardoe (1973) discussed a conceptual model that described the flow in the boundary layer associated with a surface cold front. They found a warm, low-level conveyor belt, typically 1 km deep and 100 km across, situated just ahead of the surface cold front. The warm moist air contained within the conveyor belt was subject either to 'rearward sloping ascent' whereby some of the warm air leaked up over the cold front or 'forward sloping ascent' where all the air remained within the conveyor belt, eventually ascending the warm frontal surface. These two models are depicted in Figs 6(a) and 6(b) (after Browning and Pardoe 1973). The model in Fig. 6(a) implies an active cold front while the model in Fig. 6(b) results in an active warm front. Observations confirm that depressions do not normally have both frontal zones active simultaneously.

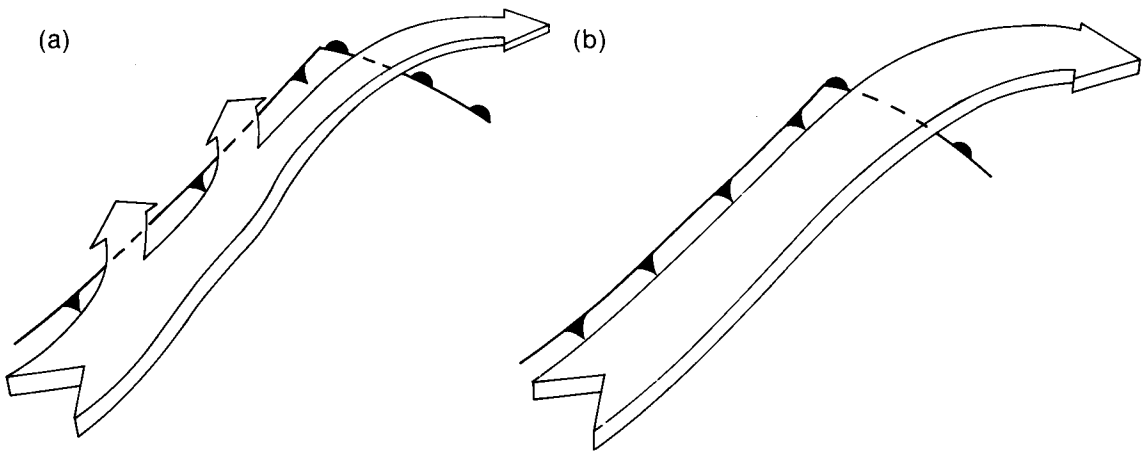


Figure 6. The motion within the warm conveyor belt relative to the surface fronts. Depicted are two models showing (a) rearward sloping ascent, and (b) forward sloping ascent.

Because the conveyor belt is a low-level feature, surface friction effects play a major role in its detailed structure. Consequently the air motion within it has a significant ageostrophic component and this modifies the cross-frontal (ageostrophic) circulation depicted in Fig. 2, the modification being strongest at the bottom of the circulation, where the simplified model depicted streamlines actually crossing the frontal surface. A full description of the interaction of the conveyor belt with the cross-frontal circulation has not been developed to date, but a conceptual model is shown in Fig. 7. In this model, air does not cross the frontal zone near the ground. Instead, the ascending branch of the cross-frontal circulation is fed by warm-sector air, as shown in the 'rearward sloping ascent' model illustrated in Fig. 6(a). In reality, most fronts will exhibit aspects of both models, some air leaking up the frontal surface from the low-level conveyor belt, and some crossing the frontal surface near the ground.

Turning now to the upper part of the front, the model shown in Fig. 2 also depicts the streamlines crossing the frontal surface. This is again a region in which there is significant ageostrophic motion, in this case associated with the jet stream. Because air can now enter and leave the cross-frontal circulation via the jet there is no longer a need for the circulation, as shown in Fig. 2, to cross the frontal surface. Fig. 7 illustrates this by leaving the streamlines open within the upper-level jet. There is thus the opportunity both for dry, stratospheric air to be drawn down the frontal surface, and for moist, tropospheric air to be injected into the stratosphere, as has occasionally been observed.

The above concepts are brought together in a model developed by Browning and Pardoe (1973) from observational evidence. This model is shown in Fig. 8 and the similarities with Fig. 7 are self evident. One point does, however, require clarification and that is the behaviour at the nose of the front where the streamlines are almost vertical. Observations show that there is often a narrow region (5–10 km wide) of heavy convective rain (a squall line) coincident with the surface cold front. Such a region cannot be predicted by the models discussed so far in this paper, because the simplifications have effectively removed from the equations the ability to simulate convection, the moist processes having been omitted. Consequently the effects of this near-vertical motion at the surface cold front need to be taken into account when comparing the theoretical model, Fig. 7, with the observational model in Fig. 8.

In summary, this section has shown how the basic model of the cross-frontal circulation may be modified through the inclusion of turbulent diffusion and convective processes to produce a model that simulates many of the features found in case-studies.

5. The low-level jet

It will have been noticed from Fig. 8 that the low-level conveyor belt is shown as a jet. It has also been observed that the gradients of velocity are very strong on the cold side but much weaker in the warm sector. Firstly, why should there be a jet and secondly, why should it have this asymmetric structure?

The conveyor belt brings warm moist air close to the surface cold front creating a locally strong, horizontal temperature gradient. From the scale analysis developed in section 1, features such as the jet, which have a two-dimensional structure (i.e. they vary in character much more slowly along their length than in either of the other directions) must be in thermal wind balance in the 'along-front' direction. Hence the thermal wind equation (6) applies to the jet. Suppose that, locally, the temperature gradient created by the conveyor belt was 1 K per 100 km greater than in the surrounding air. Then, with $f = 10^{-4} \text{ s}^{-1}$, $g = 10 \text{ m s}^{-2}$ and $\theta_0 = 280 \text{ K}$ equation (6) gives $\delta v \approx 3 \times 10^{-3} \delta z \text{ m s}^{-1}$. Since the jet maximum occurs at a height of about 1 km then typically the jet core is some 2–5 m s^{-1} faster than the surrounding air. This figure agrees well with the values found by Browning and Pardoe (1973).

An interesting consequence of the above analysis is that, above the jet core, where $\delta v / \delta z$ becomes negative, there should be a region in which $\delta \theta / \delta x$ becomes negative. This point will be pursued in the case-study in Part II of this paper.

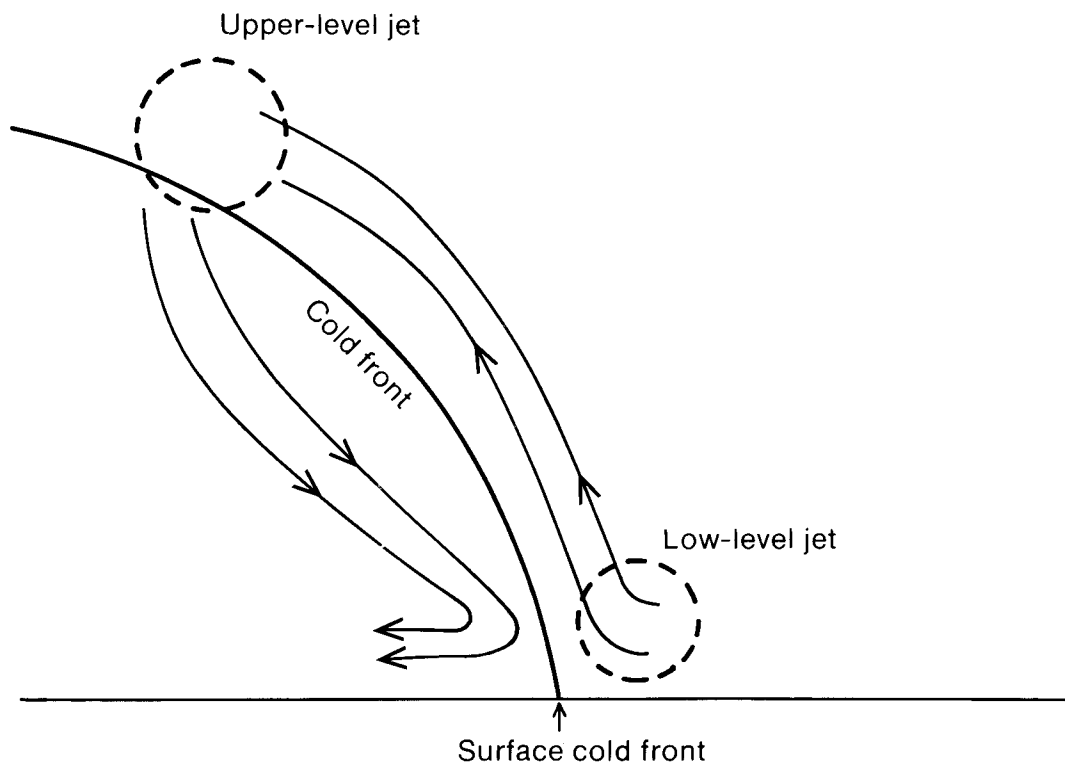


Figure 7. Cross-frontal ageostrophic motion when the effects of turbulent diffusion are included. Notice how the low-level jet acts as a source of air for the ascending branch and how the upper-level jet eliminates the need for the air to cross the frontal surface. Instead, air can enter and leave the jet stream, allowing dry stratospheric air to be brought down into the troposphere behind the cold front.

The second point is 'Why is the jet asymmetric?' Bennetts and Hocking (1973) showed that this was due to the difference in the vorticity on each side of the jet. The absolute vorticity, ζ , is defined as

$$\zeta = f + \delta V / \delta x + \delta U / \delta y$$

where U and V are the full components of velocity (not just those relative to the front — see Fig. 1(a)). However, because the variations along the jet are small compared with those across it, this equation reduces to

$$\zeta = f + \delta v / \delta x.$$

On the cold side of the jet nearest the front (see Fig. 8) $\delta v / \delta x$ is positive while on the warm side it is negative. Therefore on the warm side there is a limit imposed by the requirement that the absolute vorticity must not become negative, i.e. $\delta v / \delta x > -f$. Taking the jet maximum as $2-5 \text{ m s}^{-1}$ faster than the surrounding air, this implies that $\delta x > 20-50 \text{ km}$, i.e. on the warm side of the jet the horizontal gradient of velocity is weak and that the scale over which the jet decays is dictated by the difference between the maximum core speed and the ambient warm-sector air. If the difference is $j \text{ m s}^{-1}$ then the minimum distance is about $10 j \text{ km}$. This is well illustrated in Fig. 8, the jet decaying on a scale of tens of kilometres.

On the cold side there is no such restriction and therefore the gradient can become very sharp.

6. Instabilities on a front

The concept of a warm conveyor belt ascending above the warm frontal zone gives the impression of uniform ascent. In consequence, it may be supposed that the precipitation falling from frontal regions would also be uniform. However, this supposition is false and in fact the precipitation patterns exhibit

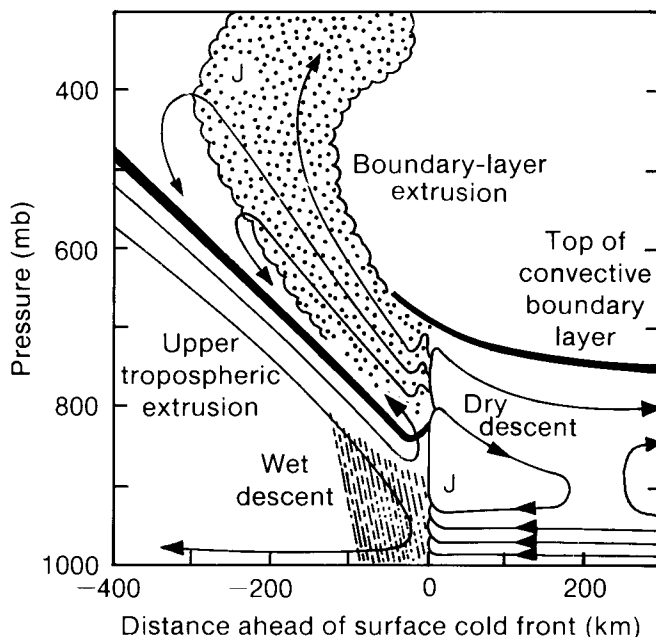


Figure 8. Schematic model of the airflow associated with a cold anafront. Thin lines are streamlines relative to the moving system. Thick lines represent the cold frontal zone and the top of the convective boundary layer. Regions of saturated ascent are stippled and jet cores, J, are marked (from Browning and Pardoe 1973).

features that are generally much smaller in scale than the frontal zone. Fig. 9 is a schematic diagram of various types of mesoscale rainbands that have been observed. Not all occur in every frontal system, indeed some systems exhibit none and have relatively uniform precipitation everywhere. However, each type of rainband has been seen, and can be expected to occur fairly frequently.

In this section the discussion will be confined to the wide rainbands, warm and cold frontal types 1a, 1b, 2 and 3b (see caption to Fig. 9). Type 3a is the cold frontal squall line that has already been discussed.

By way of an introduction to the subject, consider the absolute vorticity of a parcel of air in a frontal zone (this was introduced in section 5). Integrating the vorticity with respect to x , the cross-frontal coordinate, gives

$$\int \zeta dx = \int (f + \delta v / \delta x) dx = v + fx.$$

Now the momentum of a parcel of air is defined as mass \times velocity and therefore the momentum of a unit mass of air is ' v '. Recalling the relationship between vorticity and absolute vorticity (dv/dx to $dv/dx + f$) it is fairly natural to define the quantity

$$M = v + fx$$

as the absolute momentum.

In the horizontal momentum equation (2), u may be written as dx/dt giving

$$d/dt (v + fx) = dM/dt = 0.$$

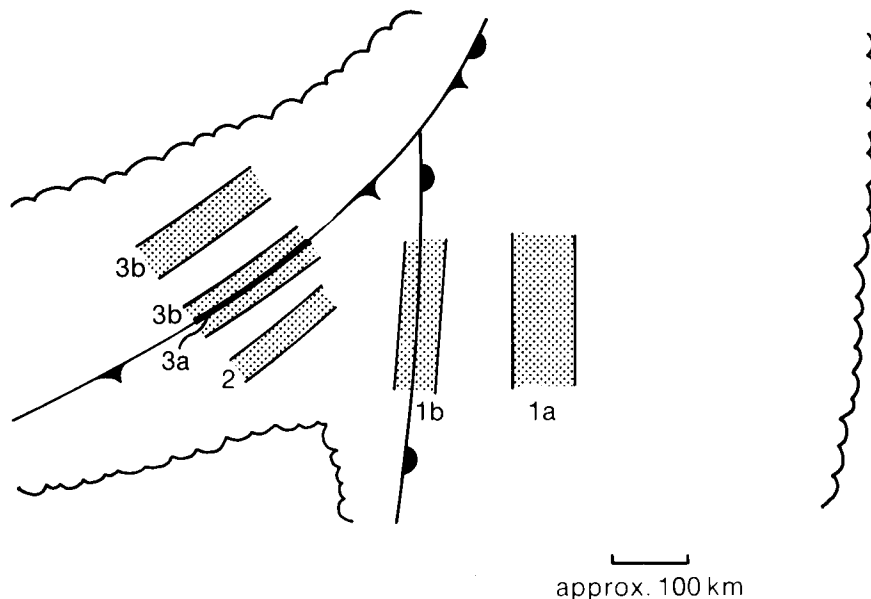


Figure 9. Schematic depiction of some types of mesoscale rainbands (stippled areas) observed in extratropical cyclones. The upper-level cloud shield of the cyclone is shown. Type 1: Warm frontal rainbands, of which type 1a occurs ahead of and parallel to the surface warm front, while type 1b coincides with the surface warm front. Type 2: Warm sector rainbands, which occur parallel to and ahead of the surface cold front. Type 3: Cold frontal rainbands, of which type 3a is very narrow and coincides with the surface cold frontal passage, while type 3b is wider and may straddle the narrow cold frontal rainband or lag behind it (after Matejka *et al.* 1980).

Therefore, within a frontal zone the absolute momentum of a parcel of air is conserved. Away from the frontal zone there is, of course, no such restriction on the air motion, and M need not be conserved. In the absence of diabatic effects, another conserved quantity is the wet-bulb potential temperature, θ_w .

Consequently, within a frontal zone, and only within a frontal zone, a parcel of air conserves both M and θ_w . If these two surfaces are parallel then conservation of both can be achieved (provided of course that the surfaces lie along streamlines). The case when they are not parallel is investigated below.

Consider Fig. 10 which shows two cases

- (a) M surfaces steeper than θ_w surfaces, and
- (b) θ_w surfaces steeper than M surfaces.

In both cases, if a parcel of air is displaced it will try to return to its original M and θ_w value, i.e. it will attempt to conserve both parameters. However, the restoring mechanisms are different. Restoration with respect to θ_w is achieved through buoyancy forces (as with convection) which act vertically, whereas restoration with respect to M is achieved through motion along geopotential surfaces, ϕ , which are nearly horizontal.

In Fig. 10(a) consider a parcel of air displaced along a line at an angle between the angles of the θ_w and M surfaces. Because both M and θ_w (generally) increase with height, the parcel enters a region of higher θ_w , it is colder than surrounding air, and therefore it sinks. Similarly it enters a region of lower M , the restoring force is to the right, in the direction of increasing M , and the resultant force opposes the motion (stability).

In Fig. 10(b) a similar displacement has a different effect. The parcel now enters a region of lower θ_w , is hotter than its surroundings and therefore rises; it also enters a region of higher M hence the restoring force is to the left, i.e. in the direction of decreasing M . Note now that the restoring force is in the same direction as the motion (instability). Given the slightest disturbances, the forces act to accelerate the parcel in the same direction as the initial motion.

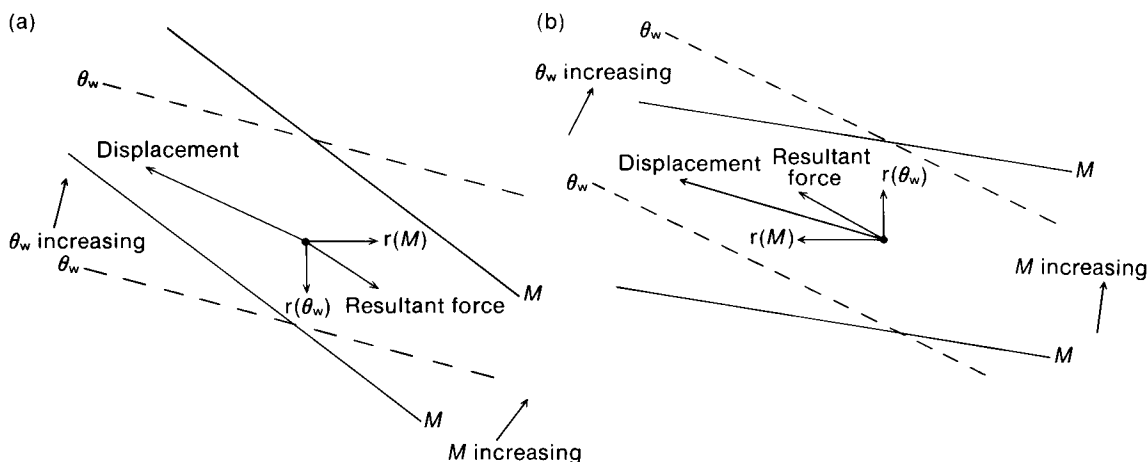


Figure 10. Restoring forces, $r(M)$ and $r(\theta_w)$, generated when a parcel of air is displaced from M and θ_w surfaces. In case (a) the M surfaces are steeper than θ_w surfaces and the resultant restoring force opposes the displacement (stability), and in case (b) θ_w surfaces are steeper than M surfaces and the resultant restoring force is in the same direction as the displacement (instability).

This may be summarized as follows. If M and θ_w surfaces are parallel, then the atmosphere is 'neutral' and parcels of air may move easily along M and θ_w surfaces. If M surfaces are steeper (Fig. 10(a)) than θ_w surfaces, the atmosphere is 'stable' and external energy is required to generate movement. If θ_w surfaces are steeper (Fig. 10(b)) than M surfaces then the atmosphere is 'unstable' and energy is spontaneously released, allowing instabilities to grow until such time as all the (available) energy has been released, and the M and θ_w surfaces are again parallel.

The above analysis follows that given by Emanuel (1982). The instability is sometimes referred to as 'slantwise convection', slantwise because the motion takes place along θ_w and M surfaces, which are generally at a shallow angle to the horizontal, and convection because of the similarity with the way in which the convective process take place. An alternative name is 'Conditional Symmetric Instability' (CSI) (Bennetts and Hoskins 1979), because instability is conditional on the θ_w surfaces being steeper than the M surfaces, and because of the symmetrical shape of the resultant streamlines.

The instability forms as rolls within the frontal surface, similar to the closed circulation shown in Fig. 2, although on a smaller scale — typically there are two or three rolls within the frontal zone. In addition, because it can only develop in regions where the θ_w surfaces are fairly steep, a favoured region for this type of instability is within the ascending branch of the cross-frontal circulation.

Because the rolls develop within the frontal region they form as 'two-dimensional' features, i.e. variations along their length are small compared with those in the other two directions. In consequence, the rolls may be visualized as cylinders embedded within the frontal surface, with the major axis approximately parallel to the front — strictly they are parallel to the thermal field. There are obvious similarities between these rolls and the wide, warm and cold frontal rainbands which are typically some 50 km across, 100–200 km long, and form parallel to the frontal surfaces.

The streamlines of a single CSI roll produced from a numerical integration are shown in Fig. 11(a); depicted are the streamlines across the roll, i.e. in a plane perpendicular to the front. The size is larger than would be expected to develop in the atmosphere as the whole model domain (300 km in the horizontal by 10 km in the vertical) was pre-set to conditions suitable for the instability to grow. In the atmosphere, such regions are much smaller and therefore the rolls will be correspondingly reduced in size. It is envisaged that within a frontal zone there are likely to be two or three rolls as illustrated in Fig. 11(b).

An interesting property of any closed circulation is that, given sufficient time, it will 'overturn' any conserved quantity. In particular, a roll, embedded within a frontal zone, will overturn the θ_w surfaces, as illustrated in Fig. 12. Such a process leads to convective instability and therefore if CSI developed, for example, within a warm frontal zone, mid-level convective instability could result. Reports of convective development within warm fronts are fairly common and have hitherto been difficult to explain.

7. Frontal rainfall

It is now possible to visualize how non-uniformities develop within frontal precipitation. In Fig. 13(a) the air is shown ascending over a uniform frontal surface. The vertical velocity is (approximately) constant within the ascending air, and in consequence the rainfall will be (approximately) uniform as shown in Fig. 13(b).

If CSI develops within the ascending air then the motion due to the developing rolls (Fig. 13(c)) will be superimposed on the motion shown in Fig. 13(a) and the resultant vertical velocity profile will be as in Fig. 13(d). The consequent rainfall pattern is also shown in Fig. 13(d). In addition, as will be recalled from section 6, the rolls are capable of overturning θ_w surfaces and hence releasing convection. Lines of showers will therefore develop, embedded within the frontal surface. As the vertical velocity in the

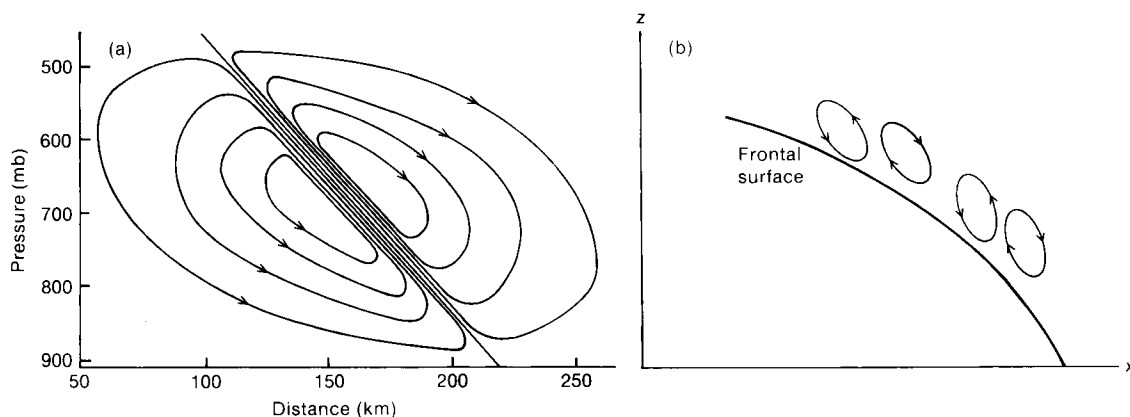


Figure 11. (a) A single Conditional Symmetric Instability (CSI) roll growing in a large, uniform domain which is everywhere unstable to CSI. The streamline intervals are in arbitrary units, but note the strong, narrow updraught in the centre of the disturbance compared with the weaker, descent regions, and (b) schematic diagram of CSI rolls growing in a more confined frontal region. Two rolls are depicted developing in the warm, moist ascending air.

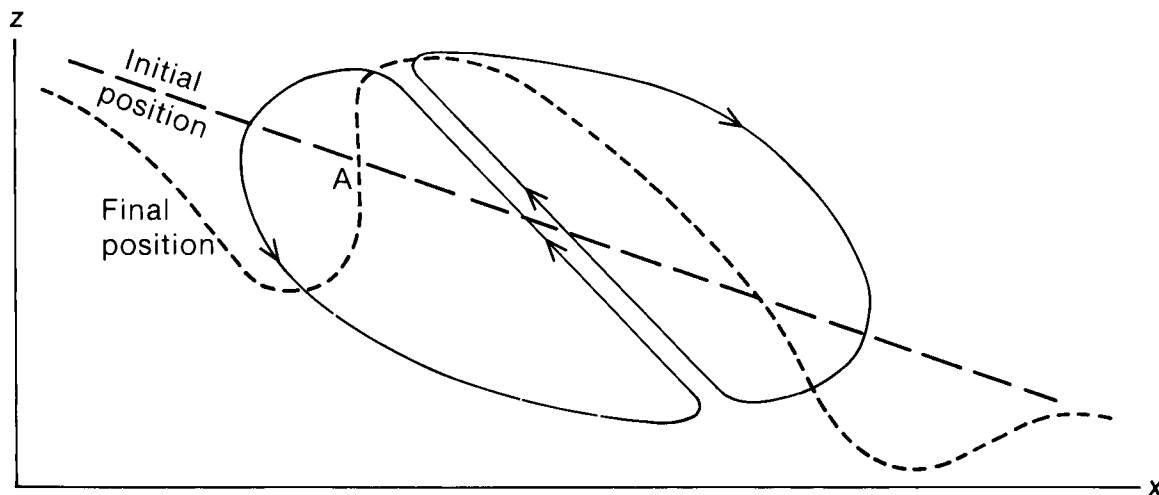


Figure 12. Schematic diagram showing how any closed circulation can 'overturn' a conserved quantity. Solid lines are streamlines and the heavily dashed line the initial position of the conserved quantity. The lightly dashed line shows the position after a period of time. Note how the line 'overturns' at the point marked A. If the conserved quantity were θ_w , convection would be likely to develop.

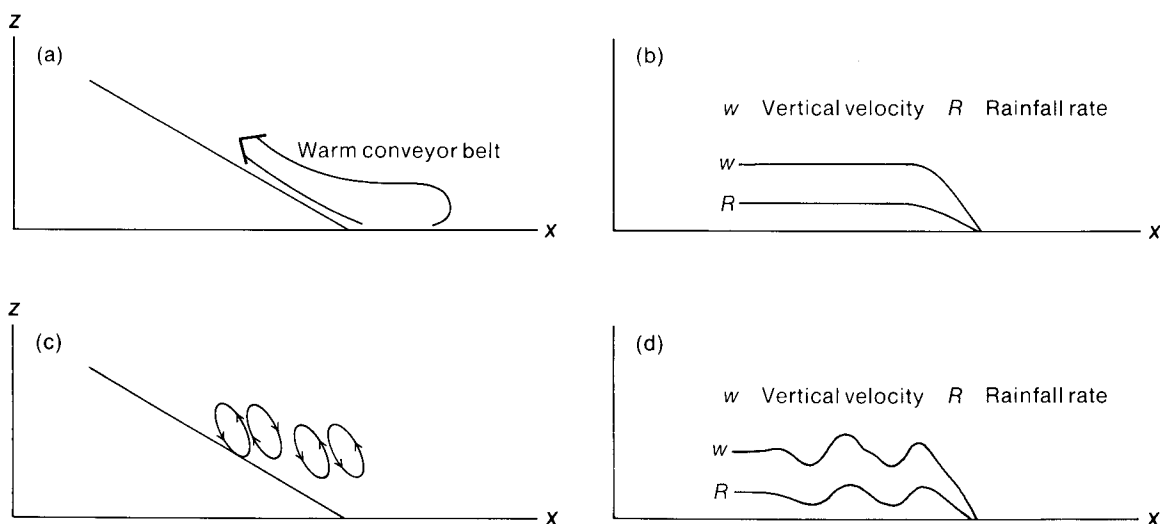


Figure 13. (a) Schematic diagram of air from the warm conveyor belt (rearward sloping model) ascending a cold frontal zone (without line convection being present). (b) The vertical velocity of a parcel of air ascending the front. Note that the ascent is (approximately) uniform away from the surface frontal position. Also shown is the resultant rainfall rate (R) associated with uniform ascent. (c) Embedded instabilities superimposed on the frontal surface. For clarity, the frontal-scale ascent has been omitted. (d) The vertical velocity and rainfall rate, after modification by Conditional Symmetric Instability.

convection is so much greater than that in the rolls, it has not been shown on the diagram but the result is to enhance the banded nature of the rainfall.

The presence of instabilities embedded within the frontal surface leads to non-uniformities in the frontal precipitation, the scale of these being typically 50 km in the cross-frontal direction and some 100–200 km in the along-frontal direction.

The rolls are embedded within the ascending air of the conveyor belt as it rises up the frontal surface. Hence the resulting lines of heavier rain will gradually move away from the surface front. Given the right conditions, these will be replaced by further rolls developing in the source region.

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A note on the normal dates of onset of summer monsoon over south peninsular India

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Summary

There are some large differences between the dates of onset of the summer monsoon published by the India Meteorological Department (1943) and those obtained by Subbaramayya *et al.* (1984). Consequently the normal dates of onset of the summer monsoon over south peninsular India have been re-examined by the method of change in slope of cumulative rainfall. The dates obtained by the slope method at the west coast stations in this investigation have been found to agree with those obtained by Subbaramayya *et al.* It is not possible to determine the onset dates at stations east of the Western Ghats in the south exclusively by the slope method because of the heavy pre-monsoon thunderstorm rains. In view of the similarity of the basic causes of the pre-monsoon rains and the monsoon rains, it is suggested that the pre-monsoon thunderstorm rains over south peninsular India are referred to as 'local monsoon' or 'little monsoon'.

1. Introduction

The normal dates of onset of the summer monsoon over India and the surrounding region (Fig. 1(a)) were published by the India Meteorological Department (1943). Those dates were obtained from the characteristic rise in the cumulative 5-day mean rainfall curves at a number of stations. An alternative approach was taken by Subbaramayya *et al.* (1984) who prepared a chart (Fig. 1(b)) of mean dates of onset based on the principle that the onset of monsoon at any place should be associated with the first westward-moving rain-storm of the summer season in that area. In the southern parts of the country, however, an additional condition, namely that the rains should be accompanied by strong westerlies, was also considered. Though, in general, Figs 1(a) and 1(b) agree, there are some major differences over the south peninsula. For example, the mean date of onset over the extreme south peninsula according to Fig. 1(b) is 20 May while Fig. 1(a) shows it as 1 June. This is quite a large difference and, therefore, the normal dates of onset by the method of cumulative mean pentad rainfall curves have been re-examined. It was particularly important to do this because Ananthakrishnan *et al.* (1967) have referred to another chart published by the India Meteorological Department in 1943. The commonly known chart in Fig. 1(a) is a modified version of this earlier chart and bears significant differences from it. The modifications were made specially in the areas where the pre-monsoon thunderstorm rains merge into monsoon rains; this was done by experienced meteorologists considering other factors such as clouds, isobaric gradient and winds. The rules they followed in modifying the chart are, however, not known.

2. Data and analysis

The India Meteorological Department (1965) has published the normals of daily accumulated rainfall at all the synoptic stations for the period 1901 to 1950. Cumulative mean rainfall curves for a number of stations have been prepared starting from the beginning of March. To determine the date of onset at any station, two tangents to the cumulative rainfall curve were drawn, where the rates of increase of cumulative rainfall are constant, before and after an increase of slope, see Figs 2 and 3. The meeting point of the two tangents is taken as the date of onset at that station. At some places the increase in the trend of the cumulative rainfall curves occurred in two stages. In such cases two dates have been

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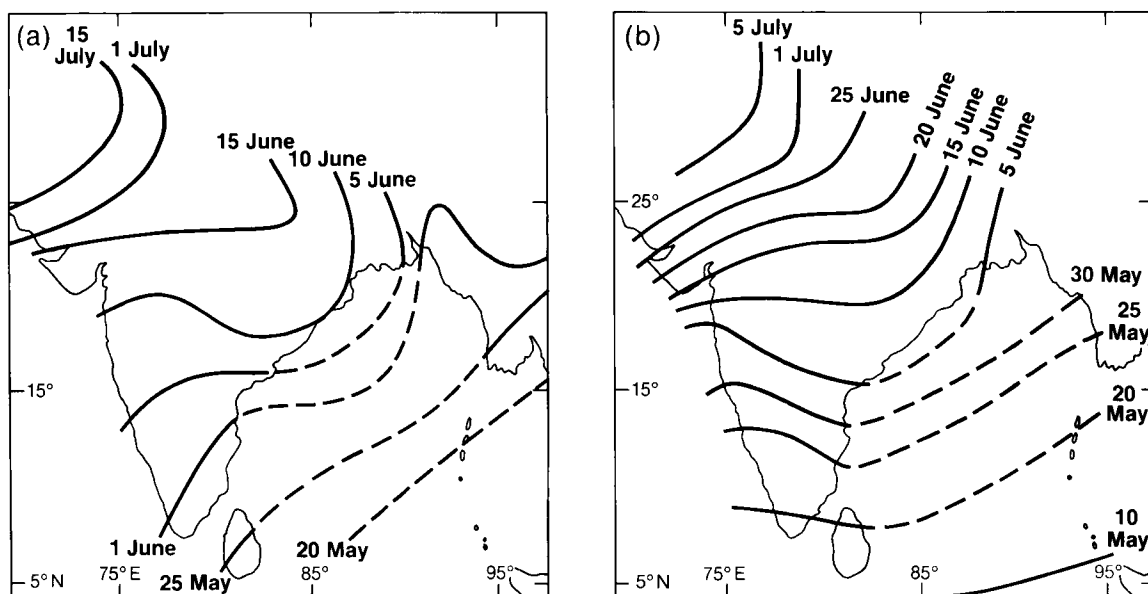


Figure 1. Normal dates of onset of the summer monsoon, (a) after India Meteorological Department (1943), and (b) after Subbaramayya *et al.* (1984).

obtained corresponding to the two stages of increase in the slope of the curves. The dates thus obtained are plotted on a chart and their variations are examined in the light of synoptic developments in the area.

3. Results and discussion

3.1 Onset dates

The cumulative mean rainfall curves at some of the stations are presented in Figs 2 and 3 (Fig. 4 shows the location of the stations and the abbreviations used to identify them). The west coast stations (e.g. Trivandrum (TRV), Cochin (CHN) Mangalore (MNG), and Bombay (BMB)), the Arabian sea island stations (e.g. Amini (AMN) and Minicoy (MNC)) and north peninsular India stations (e.g. Malegaon (MLG), Hyderabad (HYD) and Kalingapatnam (KLM)) show a sudden increase in the trend of the curve and the date of onset could be determined without difficulty as set by the criterion (see Fig. 2).

At stations in the extreme south (e.g. Palayankottai (PLK) and Pamban (PBN)), the slope of the curve is steeper in April itself and less steep in the monsoon months of June and July (see Fig. 3). At stations further north and east on the east coast (e.g. Cuddalore (CDL) and Nellore (NLR)) of south peninsula, the rainfall curves have a double bend with an inflexion in between. At Nellore, however, there is a second steady steep rise in the curve after the second bend. Consequently two dates have been obtained. Similarly at some interior stations (e.g. Bangalore (BNG) and Chitradurga (CHT)) the curves also have a double bend. But in these cases, the initial change in the slope itself is quite pronounced and persistent for a long time. At stations further north (e.g. Cuddapah (CDP), Bijapur (BJP) and Gulbarga (GLB)), the increase in slope occurred in two stages. Therefore, the dates at these stations were determined on the basis of the second stage increase in the slope of the curves.

The dates of onset of the monsoon as determined from the above type of diagrams are presented in Fig. 4. The dates over north peninsula are quite comparable to those in Fig. 1(a) as well as Fig. 1(b).

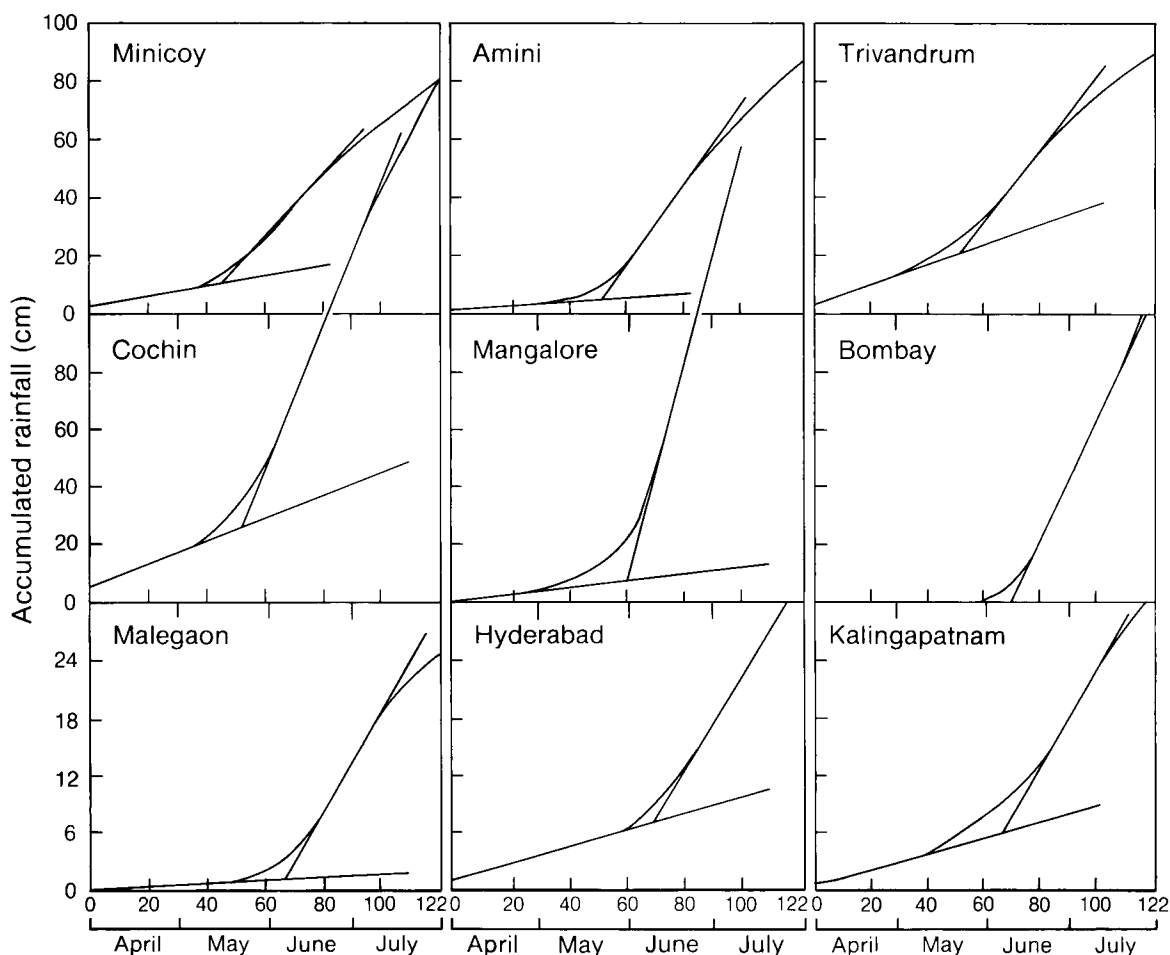


Figure 2. Cumulative mean rainfall curves at a selection of stations with days from the beginning of April shown. See section 2 for an explanation of the line construction.

However, in the extreme south on the west coast, the date of onset according to the present analysis is as early as 20 May — this agrees with Fig. 1(b) but not Fig. 1(a). To the east of the Western Ghats the dates are very different from those in Figs 1(a) and 1(b). There is in fact a discontinuity in the dates on either side of the Ghats. The dates on the eastern side are early; in the south the difference can be as much as 6 weeks. There is a narrow area in the Ghats where the dates are later by 7–10 days compared to those on the western side at corresponding latitudes.

The early rains over south peninsula can be referred to as pre-monsoon thunderstorm rains. These rains were overlooked in the studies by the India Meteorological Department which resulted in Fig. 1(a); continuous onset-date lines across the Ghats were drawn by considering other meteorological factors as mentioned in section 1. In that process, the onset dates on the west coast also might have been altered. Elsewhere the onset dates in the south, according to the slope-change method, also agree with those in Fig. 1(b) obtained by Subbaramayya *et al.* (1984).

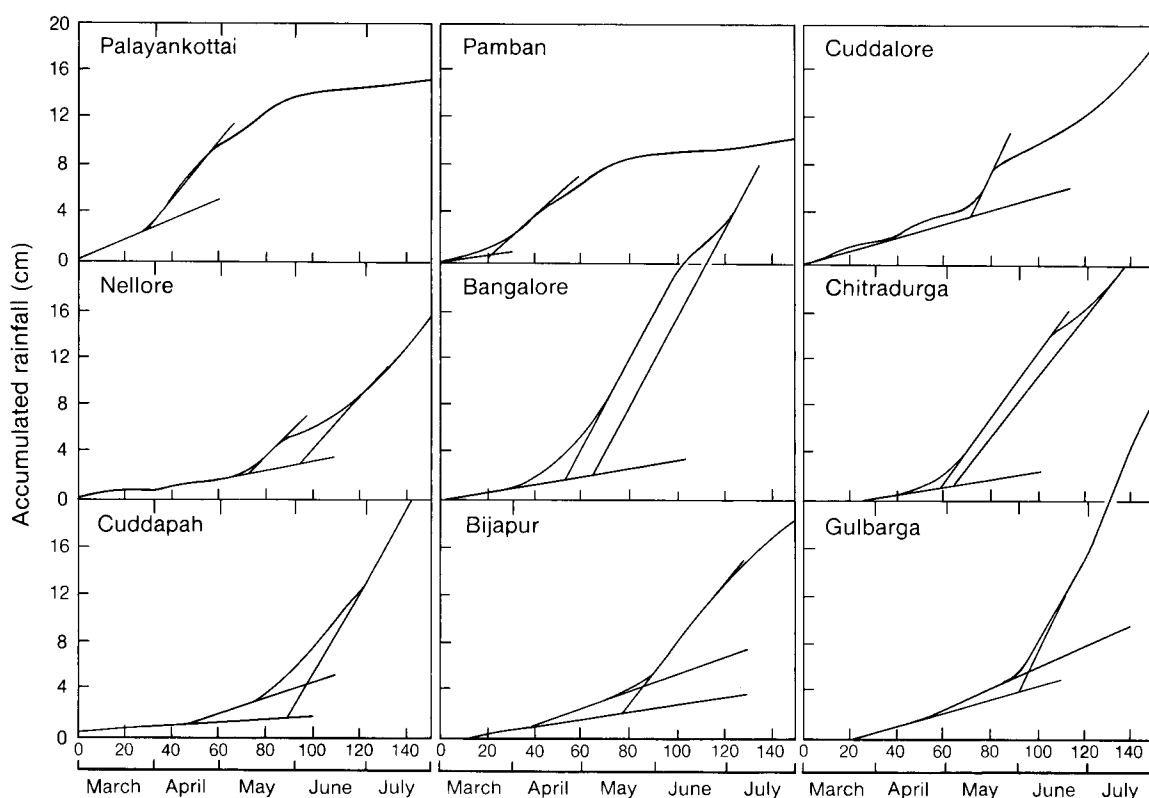


Figure 3. As Fig. 2, but for another selection of stations with days from the beginning of March shown.

3.2 Pre-monsoon thunderstorm rains

As summer progresses, a north-south elongated low develops over the western parts of peninsular India in March due to excess heating of the land (Fig. 5(a)) and high pressures with anticyclonic circulations appear over the Bay of Bengal and Arabian Sea. During April the heat low deepens and its centre is displaced north-eastwards (Fig. 5(b)). However, a trough extends from this low to the extreme south of peninsular India. A wind discontinuity exists in the heat low between northerlies over the west coast and south-easterlies/southerlies over the south-east peninsula. The latter veer to become south-westerlies over northern parts of the east coast (Figs 6(a) and 6(b)). The southerlies, as they come from south Bay of Bengal, have maritime tropical air-mass characteristics and when that air passes over the heated land convective precipitation occurs.

During this period, troughs in the easterlies in the south progress westward and when they come to the longitude of the heat low, the easterly trough is intensified and the south-easterlies over the east peninsula penetrate farther into the interior. Similarly when a westerly trough in the north is in phase with the heat low, the south-easterlies are again strengthened. On such occasions the convective activity is enhanced.

As the summer season further progresses through May and June, the heat low is not only deepened but is also displaced initially northwards and later to the north-west (Figs 5(c) and 5(d)); this ultimately culminates in the establishment of a continental-scale heat low with its centre over north-west India and Arabia. During this period the anticyclones over the Bay of Bengal and Arabian Sea weaken and a

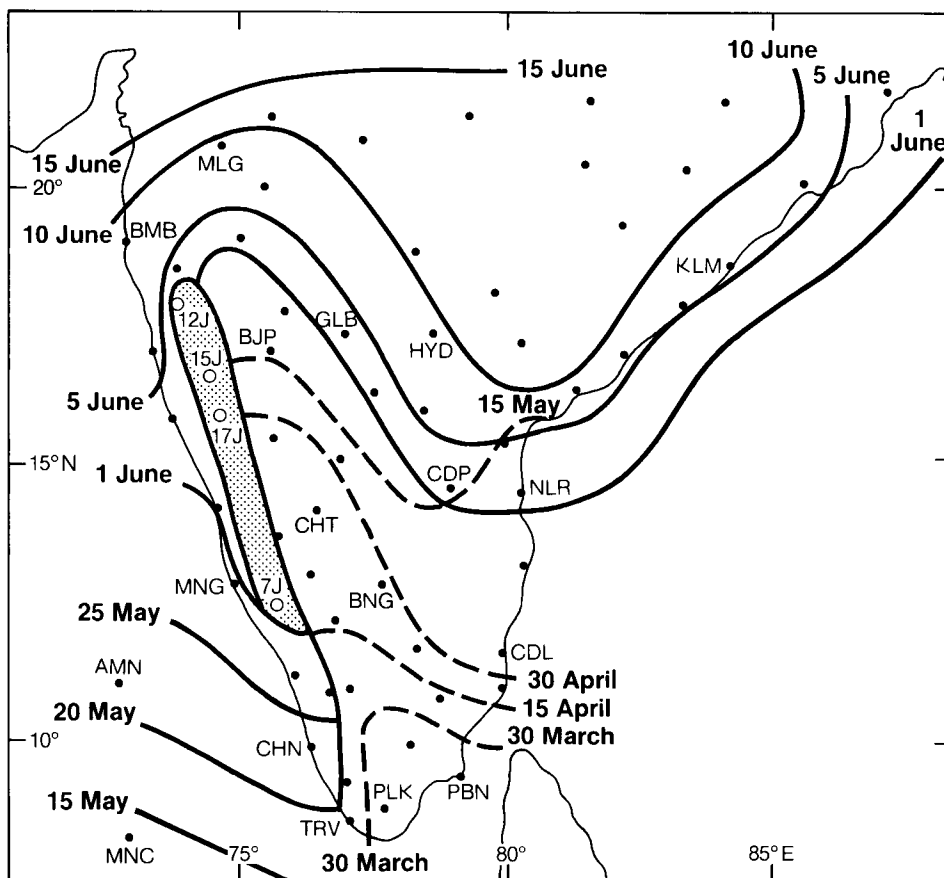


Figure 4. Normal dates of onset of the monsoon by the method described in section 2. The dots indicate the location of stations and those mentioned in the text are accompanied by an abbreviated name. The dashed lines indicate the dates of change of slope of cumulative rainfall curves which do not agree with the normal dates of onset. 12J etc. in the dotted area (Western Ghats) represent 12 June etc.

pressure gradient across the equator is established. As a result of this, the equatorial maritime air from the southern hemisphere is driven into the heat low over central and west Asia, which is responsible for the monsoon rainfall over India.

It is clear from the above sequence of events that the physical basis of the pre-monsoon rains is basically the same as that of the monsoon rains. However, while the monsoon rains are associated with the equatorial maritime air mass, the pre-monsoon rains are due to the tropical maritime air mass. The general circulation associated with monsoon rains is of continental scale while that associated with the pre-monsoon rains is of subcontinental scale. It is, therefore, appropriate to refer to the southerlies/south-westerlies over the Indian peninsula during April and early May, and the associated rains, as 'local monsoon' or 'little monsoon'.

The cumulative rainfall curves in south-east and east central peninsula first showed increases in their slope because of the little monsoon. But with the advance of the equatorial maritime air from the Arabian Sea, the rains over the lee side of the Ghats have decreased due to rain-shadow effect. However, at stations in south central and east peninsula the rainfall has again increased due to monsoon depressions, depending on the extent of their influence to the south.

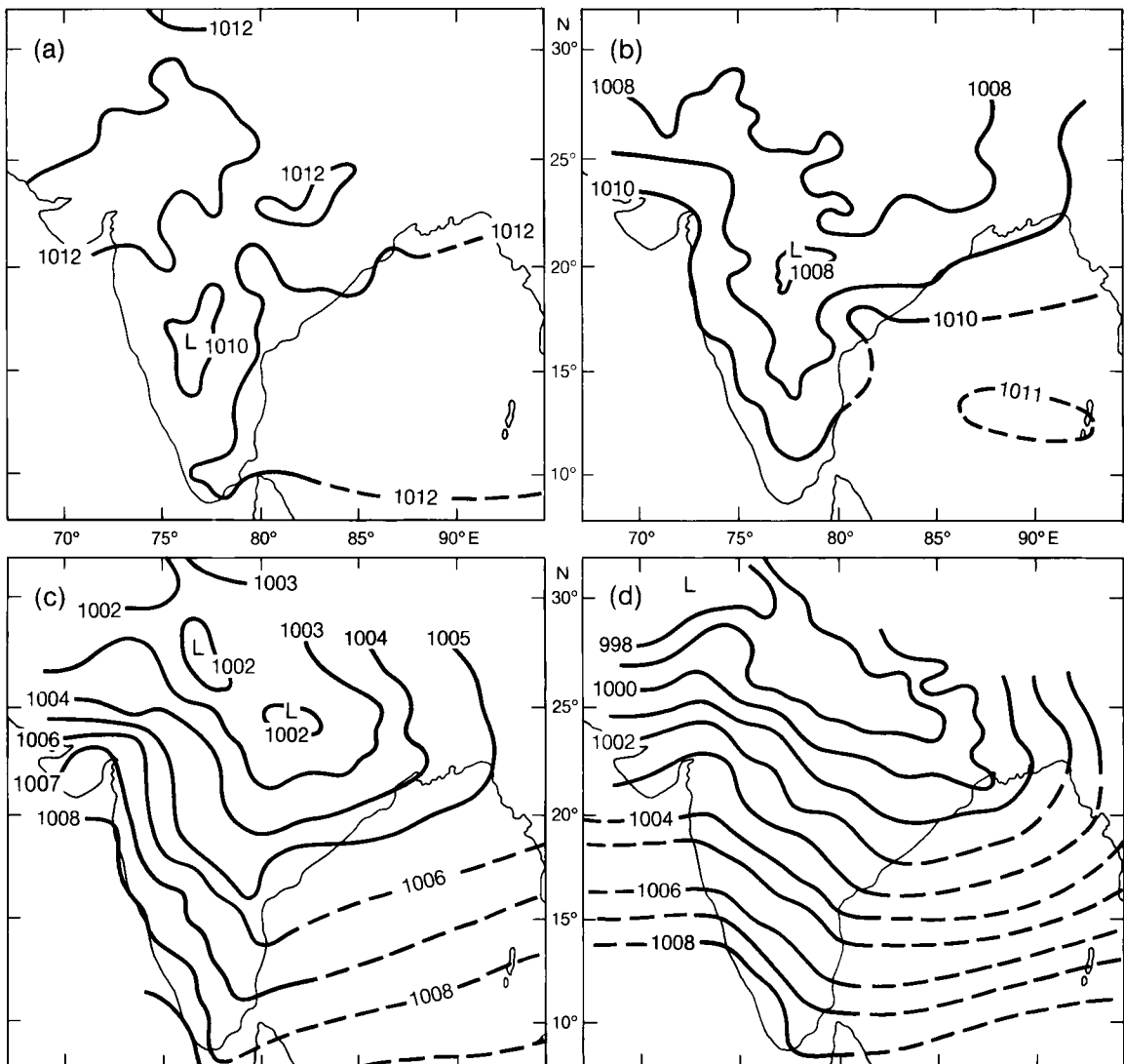


Figure 5. Mean-sea-level pressure distributions (mb) in the fourth pentad of (a) March, (b) April, (c) May, and (d) June.

It is not clear why the cumulative rainfall curves at some stations on the Ghats showed change of slope at dates much later (7–10 days) than at the west coast stations. This needs a more detailed study of the synoptic climatology of the rains at those stations.

4. Conclusions

The normal dates of onset of the monsoon at the stations on the west coast of south peninsular India, as determined by the method of change in slope of cumulative rainfall curves, are much earlier than those published by the India Meteorological Department (1943). The dates agree with those obtained by Subbaramayya *et al.* (1984) based on the principle that the onset of monsoon should be associated with the first westward-moving rain-storm of the summer season.

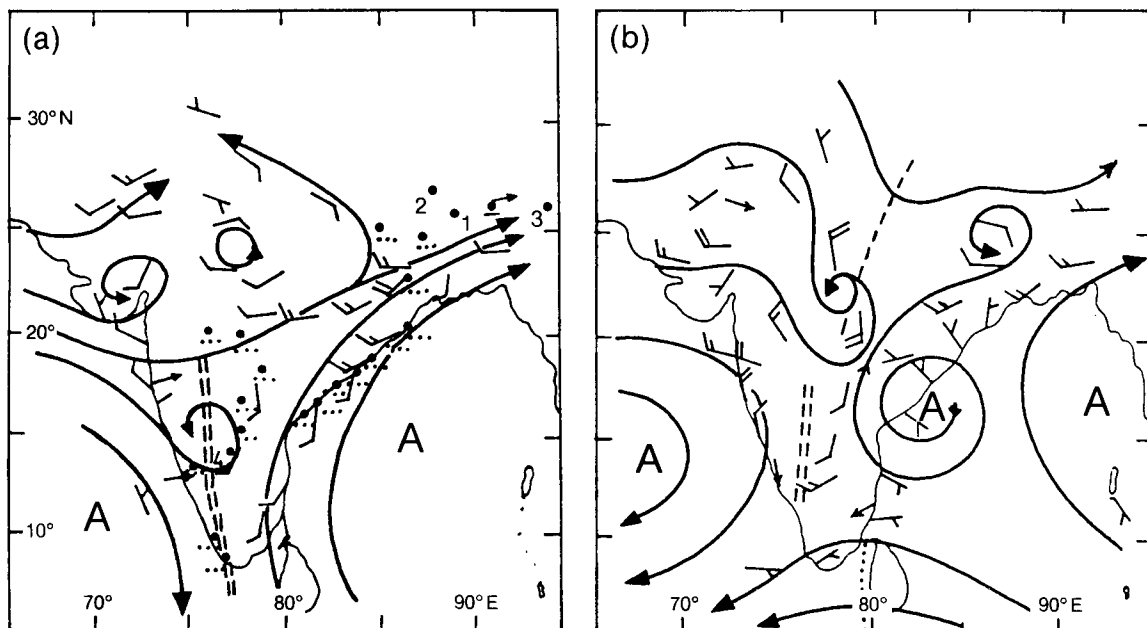


Figure 6. Streamlines at (a) 0.6 km and (b) 850 mb at 00 GMT on 20 April 1988. In (a) rainfall is shown: three dots in a line indicate rainfall less than or equal to 0.25 cm and the short full lines indicate rainfall between 0.25 and 0.5 cm, and larger rainfall amounts are given to the nearest centimetre. The double dashed line indicates wind discontinuity, and in (b) the single dashed line indicates a westerly trough and the dotted line a trough in the easterlies.

The monsoon rains in the extreme south, east of the Western Ghats, are less intense than the so-called pre-monsoon rains. The pre-monsoon rains, as they are also associated with differential heating and reversed local circulations, may be referred to as the 'local monsoon' or 'little monsoon'.

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The first 'obs' book?

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Summary

The scheme proposed by Robert Hooke in 1663 for observing and recording the weather is discussed.

It is tempting to imagine that methodical ways of observing the weather were introduced in the mid-nineteenth century when meteorology became organized on an international basis. However, the following extracts suggest that the natural philosophers who formed the Royal Society of London anticipated the requirement by nearly 200 years.

Papers by Robert Hooke, who was the first curator of experiments at the Royal Society, include contributions to the development of meteorology that represent a watershed in the history of the subject. One such is his 'Method for making a history of the weather'. However, it is not clear whether the work published by Hooke was all his own creation or whether he was inspired by contemporary luminaries such as Robert Boyle, Christopher Wren and Isaac Newton.

According to Birch (1757) 'Mr Hooke's paper concerning the observables for making a history of the weather was read...' at the meeting of 7 October 1663. A printed version was published by Sprat in 1667 with a French translation published in Geneva in 1669. The following extracts are transcribed from the second edition of Sprat's *The history of the Royal Society of London* (Sprat 1702), a copy of which is held in the National Meteorological Library, Bracknell.

Hooke starts:

For the better making a history of the weather, I conceive it requisite to observe,

1. The Strength and Quarter of the Winds, and to register the Changes as often as they happen: both which may be very conveniently shewn, by a small addition to an ordinary Weather-clock.

2. The Degrees of Heat and Cold in the Air; which will be best observed by a sealed *Thermometer*, graduated according to the Degrees of *Expansion*, which bear a known proportion to the whole bulk of Liquor, the beginning of which gradation, should be that dimension which the Liquor hath, when encompassed with Water, just beginning to freeze, and the degrees of *Expansion*, either greater or less, should be set or marked above it or below it.

3. The Degrees of Dryness and Moisture in the Air; which may be most conveniently observed by *Hygroscope*, made with the single beard of a wild Oat perfectly ripe, set upright and headed with an *Index*, after the way described by *Emanuel Magnan*; the conversions and degrees of which, may be measured by divisions made on the rim of a Circle, in the *Center* of which, the *Index* is turned round: The beginning or Standard of which Degree of *Rotation*, should be that, to which the *Index* points, when the beard, being thoroughly wet, or covered, with Water, is quite unwreathed, and becomes straight. But because of the smallness of this part of the Oat, the cod of the wild *Vetch* may be used instead of it, which will be a much larger *Index*, and will be altogether as sensible of the changes of the Air.

At this time there was much interest in the development of thermometers and hygrosopes. In 1663/64 Hooke devised a device to standardize the calibration of thermometers; this shows that he appreciated the need for standardization and was able to implement his ideas. Also, at about the same time, Dr Goddard of the Society was investigating a hygroscope which used a lute string (gut?) with pulleys and a cylinder.

Hooke continues:

4. The degrees of Pressure in the Air: which may be several wayes observed, but best of all with an Instrument with Quicksilver, contrived so, as either by means of water or an *Index*, it may sensibly exhibit the minute variations of the Action.

5. The constitution and face of the Sky or Heavens; and this is best done by eye; here should be observed, whether the Sky be clear or clouded; and if clouded, after what manner; whether with high Exhalations or great white Clouds, or dark thick ones. Whether those Clouds afford Fogs or Mists, or Sleet, or Rain, or Snow, etc. Whether the under side of those Clouds be flat or waved and irregular, as I have often seen before thunder. Which way they drive, whether all in one way, or some one way, some another; and whether any of these be the same with the Wind that blows below; the Colour and face of the Sky at the rising and setting of the Sun and Moon; what Haloes or Rings may happen to encompass those Luminaries, their bigness form and number.

6. What Effects are produc'd upon other bodies: As what Aches and Distempers in the bodies of men: what Diseases are most rife, as Colds, Fevours, Agues, etc. What putrefactions or other changes are produc'd in other Bodies; As the sweating of Marble, the burning blew of a Candle, the blasting of Trees and Corn; the unusual sprouting, growth, or decay of any Plants or Vegetables: the putrefaction of bodies not usual; the plenty or scarcity of Insects; of several Fruits, Grains, Flowers, Roots, Cattel, Fishes, Birds, any thing notable of that kind. What conveniences or inconveniences may happen in the year, in any kind, as by floods, droughts, violent showers, etc. What nights produce dews and hoar-frosts, and what not?

7. What Thunders and Lightnings happen, and what Effects they produce; as souring of Beer or Ale, turning Milk, killing Silk-worms, etc.

8. Any thing extraordinary in the Tides; as double Tides later or earlier, greater or less Tides than ordinary, Rising or drying of Springs; Comets or unusual Apparitions, new Stars, *Ignes fatui** or shining Exhalations, or the like.

They should all or most of them be diligently observed and registered by some one, that is alwayes conversant in or neer the same place.

Having listed what should be observed, Mr Hooke then considers how these observations should be recorded 'so as to be most convenient for the making of comparisons, requisite for the raising *Axioms*, whereby the Cause or Laws of Weather may be found out.'

Hooke then prescribes the forerunner to the daily registers of meteorological observation which are now used. The related illustration from Sprat's book is reproduced. The recording of wind, temperature, moisture and pressure seems to have been relatively straightforward, but how to record the 'faces of the Sky' he clearly found more perplexing:

But for the faces of the Sky, they are so many, that many of them want proper names; and therefore it will be convenient to agree upon some determinate ones, by which the most usual may be in brief exprest. As let *Cleer* signifie a very cleer Sky without any Clouds or Exhalations: *Checker'd* a cleer Sky, with many great white round Clouds, such as are very usual in Summer. *Hazy*, a Sky that looks whitish, by reason of the thickness of the higher parts of the Air, by some Exhalation not formed into Clouds. *Thick*, a Sky more whitened by a greater company of Vapours: these do usually make the *Luminaires* look bearded or hairy, and are oftentimes the cause of the appearance of Rings and Haloes about the *Sun* as well as the *Moon*. *Overcast*, when the Vapours so whiten and thicken the Air, that the *Sun* cannot break through; and of this there are very many degrees, which may be exprest by a *little*, *much*, *more*, *very much overcast*, etc. Let *Hairy* signifie a Sky that hath many small, thin and high Exhalations, which resemble locks of hair, or flakes of Hemp or Flax: whole varieties may be exprest by *straight* or *curv'd* etc. according to the resemblance they bear. Let *Water'd* signifie a Sky that has many high thin and small Clouds, looking almost like water'd Tabby, called in some places a Mackeril Sky. Let a Sky be called *Waved*, when those clouds appear much bigger and lower, but much after the same manner. *Cloudy*, when the Sky has many thick dark Clouds, *Lowring*, when the Sky is not very much overcast, but hath also underneath many thick dark Clouds which threaten rain. The signification of *gloomy*, *foggy*, *misty*, *sleeting*, *driving*, *rainy*, *snowy*, reaches or racks *variable*, etc. are well known, they being very commonly used.

Experienced observers may judge for themselves how near Hooke was to the ten main types of cloud—and 130 years before Luke Howard.

Mr Hooke concludes by advocating a global, or at least national, network of observers working to a common standard. Then 'the Method of using and digesting those so collected Observations...will be more advantageously considered' because 'A workman being then best able to fit and prepare his Tools, for his work, when he sees what materials he has to work upon.'

Having read these instructions it seems a shame that they were never implemented as they appear adequate for setting up a basic observing network. Why then were Hooke's proposals not implemented?

* Will-o'-the wisp

ROYAL SOCIETY.

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A S C H E M E

At one View representing to the Eye the
Observations of the Weather for a Month.

Days of the Month and place of the Sun. Remarkable houls.	Age and sign of the Moon at Noon.	The Quarters of the Wind and its strength.	The Degrees of Heat and Cold.	The Degrees of Drinels and Moisture.	The Degrees of Pre- lure.	The Faces or visible ap- pearances of the Sky.	The Nota- ble Effects.	General De- ductions to be made af- ter the tide is fitted with Observations: As,
4 8 14 II 12.46 4 12	27 Q 9. 46.	W.	2. 9 3. 12 3. 16	4. 1 5. 2 6. 3	29. 10 29. 8 29. 8	Clear blew but yellowish in the N. E. Clouded to- ward the S. Checker'd blew.	A great dew. Thunder, far to the South. A very great Tide.	From the last Q. of the Moon to the Change the Weather was very tem- perate, but cold for the season; the Wind pretty constant be- tween N. & W. A little before the last great Wind and till the Wind rose at its highest, the Quick- silver continu'd descending till it came very low; water wch it began to re- ascend, &c.
15 II 15.40 6 10	28 O 2. 4. 51.	W. S. W. 1	7 4 2 1	8 9 10 11	29. 8 29. 8 29. 8 29. 8	A clear Sky all day, but a little Chec- ker'd at 4. P. M. at Sun- set red and hazy.	Not by much so big a Tide as yesterday. Thunder in the North.	
16 II 14.37 10	N. Moon. S. 12 7. 25 A. M. II 10. 3. &c.	S.	1 10 &c.	1 10 &c.	29. 10 29. 8 &c.	Overcast and very low- ring.	No dew upon the ground, but very much upon Marble- stones, &c.	

Z 2

D L

One reason was that the economic and political climate was not ready, and another may be that the seventeenth century natural philosophers were too busy discovering and inventing, and had little time for routine, applied science. The range of interests was remarkable; for example, Waller reported that Hooke was involved with such divers matters as astronomy, optics, geometry, horology, the trade of felt making, music and sound, the structure of animals' muscles, flying, hydrology, earthquakes, navigation, etc. Also after the great fire of London in 1666, the Royal Society, the Lord Mayor and the King were so impressed with Hooke's model for rebuilding the City that he was appointed City Surveyor.

In his book *Micrographia*, published at the beginning of 1665, Hooke described, among other things, 'the Baroscope, Hygroscope, an Instrument to graduate Thermometers'. So it is remarkable that this 'Method of making a history of the weather' lacks any reference to a rain-gauge. It seems likely, however, that Hooke did not wish to poach ideas from Wren who was not only a friend but had proposed a

‘Weather-clock’ some time before 1664. By 1669, according to Waller (1705), ‘Some Contrivances were shewn by him to be added to the Weather-clock, as a Hygroscope, a contrivance to measure the quantity of Rain, Snow or Hail fallen in a certain time; which Engine was soon perfected in all its parts, and set up in the Repository.’ In fact Hooke built and refined Wren’s Weather-clock which was perhaps the first automatic weather station, complete with tipping-bucket rain-gauge — but that is another story!

Acknowledgement

I am grateful to the Librarian of the Royal Society for providing some additional references.

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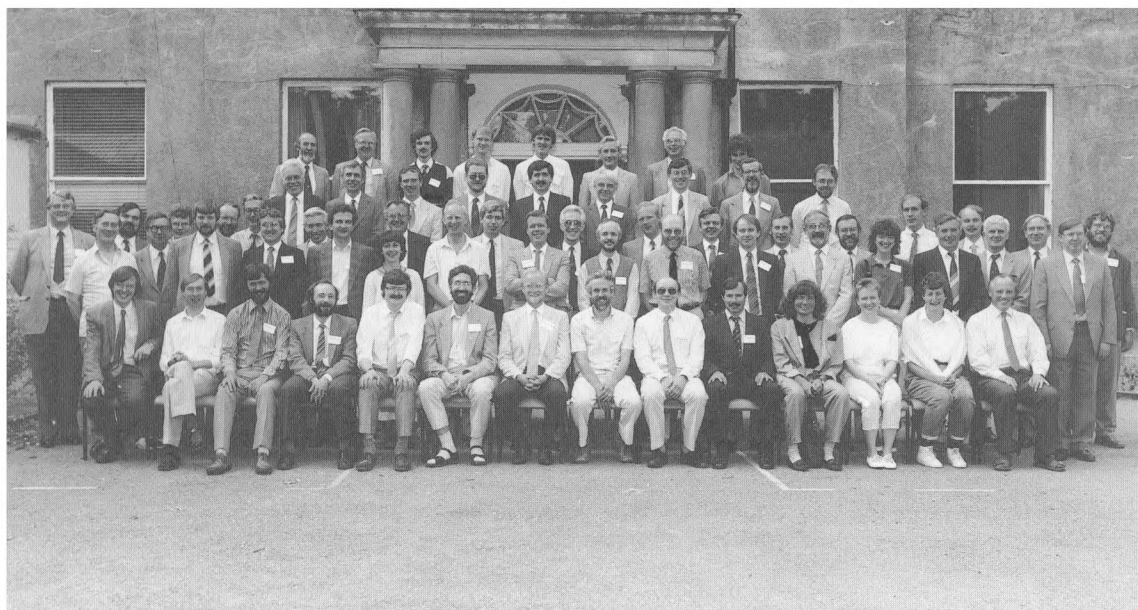
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Conference report

Summer School on the October Storm, Meteorological Office College, Shinfield Park, 20–22 July 1988

This was the third summer school organized by the Meteorological Office College, following very successful ones on the diagnosis of numerical weather prediction (NWP) products in 1987 and mesoscale meteorology in 1985. The original idea was to hold them every two years but the events of 15/16 October 1987 and the intense interest raised by the storm and its prediction led to a summer school being held a year early. It was a highly popular event with 69 people taking part and further applicants being turned away. Unlike previous summer schools the majority of participants had a background of forecasting. There was a large Meteorological Office contingent from outstations, Headquarters research branches and the Central Forecasting Office; three universities were represented and there were participants from Jersey, Ireland, France, Germany and The Netherlands.

The great strength of this type of meeting is the wide range of backgrounds of those attending and the opportunities it offers to widen one’s own experience, both during the case-study sessions and in conversation afterwards in the bar. It was shorter than the previous summer schools, lasting three days, which allowed only just enough time to become familiar with the subject. The participants were divided into nine groups of about six people, with an adviser assigned to each group to guide them through the large volume of case-study material. This included satellite pictures, print-outs from the FRONTIERS radar network, charts of plotted observations and a wide range of model products. The order of events was: case-study work, followed by group presentations and finally lectures from the experts. On the whole the idea that the groups sorted out their own ideas before listening to the lectures worked well, and indeed there was lively discussion throughout all the case-study sessions.



The first of the two case-studies concerned the analysis of the meteorological situation. All the observational evidence during the 24 hours leading up to the storm was presented as well as analyses and forecasts from the model run which, with adjustments and fine tuning after the event, was found to give the best forecast. This case-study provided an excellent example of the problems of analysis in the data-sparse regions over the oceans. Accurate analysis in these regions is highly dependent on the observations received from ships which unfortunately often prove to be unreliable. In a study of all the re-analysed surface charts in the period leading up to the storm it was found that of the 60 ship reports which lay within the area of interest, 17 were suspect in either their pressure or wind report. Central to the analysis of the system, which deepened to become the destructive low centre, was the associated cloud structure identifiable on satellite imagery as a 'cloud head' or wedge-shaped cloud mass lying in the cold air and separated from the main frontal cloud by an incursion of dry stratospheric air. We heard a great deal about this type of cloud structure in the lectures which followed. Geoff Monk (Meteorological Office), in a fascinating presentation of cloud imagery from other notable storms in the North Atlantic, gave evidence that most if not all cases of this characteristic cloud formation are followed by explosive cyclogenesis. In this case the cloud head developed some 36 hours before the storm reached its full strength. His explanation of the physical processes at work was followed up in more detail in a lecture by Glenn Shutts (Meteorological Office) which required an ability to think clearly in three dimensions.

In the interlude between the two case-studies we heard from Brian Hoskins (University of Reading) on some theoretical aspects of cyclogenesis and, in an additional lecture fitted in on Wednesday evening, Jean-François Geleyn of the French Meteorological Service gave us the French perspective on the storm. Like their UK counterparts they were faced with the problem of how to interpret conflicting numerical guidance, in this case from their own models and ECMWF. In the event they issued warnings of winds gusting to 150 km per hour over northern France 48 hours before the storm, though the forecast was downgraded later principally as a result of being influenced by a very misleading T+36-hour forecast from ECMWF.

The second case-study concerned the forecast material available from various runs of the fine-mesh and mesoscale models. Central to the case-study was the operational fine-mesh forecast from 00 GMT on 15 October which gave such poor guidance at the time. Its failure to develop an intense low led to a great deal of discussion on the accuracy of the initial analysis, and participants at the summer school could make use of a wide range of model output not normally available to the forecaster. The merits of various methods of interpreting NWP products were given a good airing. Martin Morris (Meteorological Office), in a lecture towards the end of the meeting, advocated the use of forecast vertical velocity and thermal advection to identify development areas. Charts of potential vorticity and Q-vectors featured much during the three days and there was strong recommendation from the theoreticians for their usefulness as a diagnostic tool. Whatever the merits of a diagnostic product as a means of understanding the meteorological developments after the event, its usefulness to forecasters depends on what it can tell them about the likely accuracy of the current numerical prediction they are faced with. Although there are grounds for believing that potential vorticity may be useful in this respect, this was not demonstrated at the summer school. There is indeed much yet to learn about the interpretation of numerical forecasts.

The remaining material available for the second case-study included the forecasts from the operational fine-mesh and mesoscale models with data time 12 GMT on the 15th. There were also forecasts from an experimental version of the fine-mesh model with a new data-assimilation scheme. In all cases the forecasts were a distinct improvement on those from the 00 GMT run and gave some indication of strong winds over south-east England. The mesoscale model was particularly impressive in this respect, though it was not the version in use at the time. Less impressive was the layout of the mesoscale model output which had incomprehensible headings and so many contours and symbols on some charts that they became illegible.

Reading through the questionnaires filled in by the participants it is clear that the summer school was considered a great success. Its smooth running was due to much hard work by Roy Kershaw and Will Hand at the College and by members of the Forecasting Research Branch of the Meteorological Office who provided the case-study material. Certainly a meeting with this format successfully brings together the different disciplines within meteorology and is well worth continuing in the future.

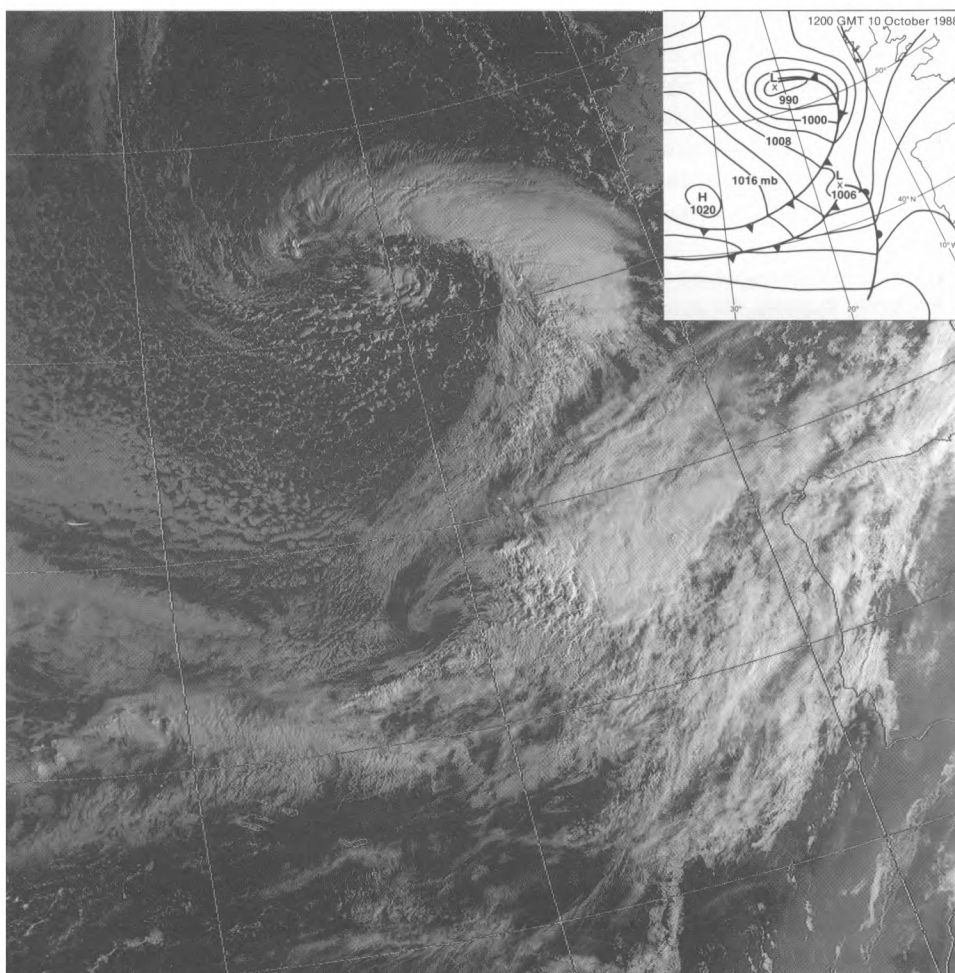
C.D. Hall

Satellite photograph — 10 October 1988 at 0926 GMT

This visible image shows two separate cloud systems as they approach western Europe. The northern system, seen as a 'comma' shaped cloud band, originated some 24 hours earlier as a band of enhanced convection within an unstable polar air mass. The band marks a cold frontal zone. There is little evidence from either the imagery or surface observations of a corresponding warm front.

The southern cloud area, centred off north-west Iberia was associated with the major upper-tropospheric jet stream. Cirrus ahead of the system is seen over Biscay, whilst further west the cloud progressively thickens and is partly convective. Within the low cloud at the rear of the system, a small vortex can be seen marking the surface low-pressure area.

During the following 24–36 hours, the cloud systems gradually merged to form an instant occlusion. As the cloud from the northern system reached the British Isles considerable rainfall occurred, with parts of south-west Ireland receiving more than 50 mm. Serious flooding occurred in Cornwall where over 40 mm was recorded.



Photograph by courtesy of University of Dundee

Meteorological Magazine

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