Scientific and Technical Review

1992/93

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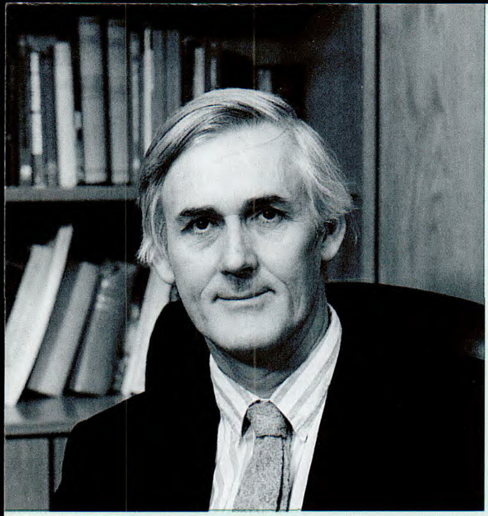


Chief Executive's foreword

Looking back on my first full year as Chief Executive, I am very pleased to report that the Met. Office has carried out its business with considerable success, and to thank, once again, our staff for their dedication and professionalism. We have an established position as one of the world's leading Meteorological Services, with our operational commitment to observing and forecasting the weather for the UK, Europe and the world. This was maintained without a break around the clock and throughout the year, providing a truly professional global service. Our scientific reputation is high and is essential to increasing the quality of our meteorological services to the public, our customers in defence, aviation, commerce and the public services.

This *Scientific and Technical Review* provides a detailed review of the activities which underpin the current services provided by the Met. Office. It also presents the research activities undertaken to improve the services and meet future requirements It accompanies the separately published *Annual Review and Accounts.* The annual review also provides details of various highlights of our activities. For example, as the UK's national meteorological service we provided warnings of severe weather; procedures for these have recently been strengthened to ensure more-accurate and timely advice for the public and emergency services. Our early warnings of heavy rain in South Wales and tidal surges in East Anglia alerted the public and emergency services, enabling them to take safety and preventive measures; forecasts of high winds alerted traffic controllers on the Dartford bridge over the Thames.

Conversely, predictions of settled weather enabled critical engineering projects, such as construction of the second River Severn bridge, construction of a crane in China and launch of a Trident submarine, to be carried out safely and efficiently. Fair-weather forecasts for film makers in Italy helped save time and costs. And longer-range forecasts of rain and temperature for 15 to 30 days ahead enabled UK forces with the UN in Bosnia to plan their operational logistics saving time, money and lives.

Examples like these, at home and abroad, demonstrate a growing appreciation of the benefits of accurate, specific and timely weather predictions.

Our largest single customer is the Ministry of Defence, for whom we provide forecasts for training and military operations anywhere in the world. In the past year this included support for air and ground forces in northern Iraq and in Bosnia. We have continued to improve our tactical advice concerned with the impact of meteorology on weapons, sensors and military operations generally.

As one of two World Area Forecast Centres for Civil Aviation, many leading civil airlines use our global forecasting capability to plan their routes to save fuel costs and avoid areas of severe weather and turbulence. We also provided warnings to aircraft on the distribution of potentially damaging dust following the eruption of Mount Pinatubo in the Philippines in 1991.

Environmental issues continue to play an important role. We have been designated as a regional centre for predicting atmospheric dispersion of chemicals or pollutants. Under contract to the Department of the Environment our Hadley Centre for Climate Prediction and Research continued to play a very full role in advising the UK Government and international community on the climatic impact of increasing greenhouse gases. We continued to be key players in the Intergovernmental Panel on Climate Change (IPCC) whose scientific assessments underpinned the Climate Convention signed by the UK at the UN Conference of Environment and Development (UNCED) at Rio de Janeiro in June 1992.

Despite the recession we achieved an impressive growth in our commercial activities with a 22% increase in invoiced value income and a corresponding growth in contribution to the core costs of the Office. Growth in international sales has been substantial and progress has been made towards a European agreement (ECOMET) for open commercial provision of meteorological services throughout Europe. New commercial services for aviation, operated jointly with the CAA, have developed rapidly during the year.

Good observations are the foundation of good forecasts. In 1992 we strengthened our observing network over the ocean to the west of the British Isles; on land we increased the number of automatic and semi-automatic observing stations. We continue to benefit greatly from the observations made by our partners in the World Meteorological Organization.

Good progress has been made towards completing and testing our Microwave Humidity Measuring Instruments (AMSU-B) being built under contract by British Aerospace, and a new weather radar, co-funded by the National Rivers Authority, was installed in Devon. A new European Community collaborative (COST) programme has begun to ensure that the weather radars in all European countries are compatible and contribute to improving short-range forecasting throughout Europe.

Our research programme led to further developments in our range of weather prediction models; we successfully introduced an operational model for producing local and regional forecasts for the British Isles. It is a measure of our international standing that by the end of 1992 many other national meteorological services were using our global forecasting model.

The Office has continued to play an active role in the WMO, and under the aegis of the WMO has been closely involved in new dialogue on the commercialization of meteorology.

Collaboration with private sector companies has been an essential element in the Met. Office method for developing new products — an early demonstration of the effectiveness of appropriate market testing of Met. Office policy.This has led to important developments such as MetFAX, which distributes up-to-date forecasts and weather information to pilots, yachtsmen and schools. In association with British Aerospace our PC-based Meteorological Information System (MIST) has been introduced, giving military and commercial customers ready access to meteorological data and forecasts.

We have now introduced a Quality Improvement (QI) programme. One of its first remits was to look carefully at the aims of our organization and establish a Met. Office Charter for staff (reproduced in our 1992/93 *Annual Report and Accounts*). Quality Improvement is a systematic approach to continuously improving our products, services and working practices.

We continued to recruit scientific and technical specialists of all ages. These were amongst the 200 staff trained at our College along with meteorologists from several other meteorological services.

Through all this activity, we have demonstrated that by encouraging and developing our staff and by national and international collaboration, the Met. Office will continue to provide the world-class meteorological service that the public and our customers have come to expect.

J.C.R. Hunt Chief Executive

Observing

Surface-based observing networks

Forecasters depend greatly on the quality of the output from Numerical Weather Forecasts. The accuracy of these forecasts, varying from local products of a few hours duration to global forecasts for several days, depends upon the input of observational data. In order to provide such data for purely national purposes, as well as for international exchange for the World Weather Watch, the Met. Office maintains a network of observing stations over the UK and adjacent seas. Contributions are also made to the WWW through the provision of observing systems on remote islands, mainly in the southern hemisphere, ships, aircraft and buoys.

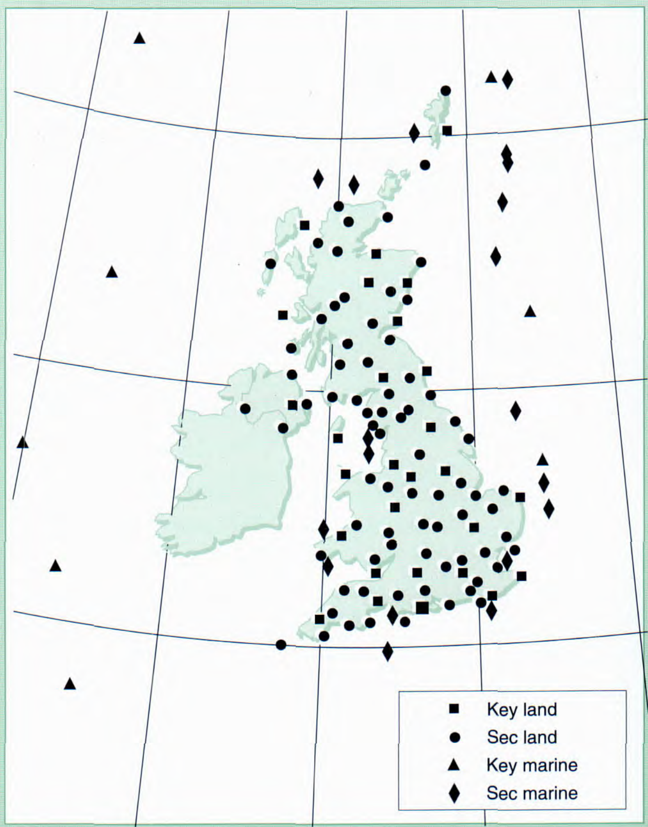


Figure 1. Location of main British observing sites.

The UK land-based observing network consists of around 240 surface observing stations. There are 30 Key surface observing stations evenly distributed and fully manned by professional staff and over 80 Secondary stations, some manned, some automated and some a combination. These all report throughout the 24 hours and key station data are distributed globally. The remaining 130 or so stations report as needed to meet specific local requirements. In all, 72 of the stations are manned by Met. Office staff at civil airports, Weather Centres, Defence Service stations and some dedicated observing sites. Increasingly, observers are being aided by the Semi-Automatic Meteorological Observing System (SAMOS). This leaves the human to input only the visual elements of the observation, such as present weather and cloud type. Valuable staff time is thus freed.

About 100 Auxiliary observing sites provide data which greatly enhance the information available to forecasters. These include coastguards, oil-rig personnel and private individuals whose efforts are much appreciated. The majority are equipped with PC systems which automatically encode and transmit the observations. At some stations SAMOS is being installed to augment the number of the observations. More than 60 fully automatic weather stations, including 19 marine automatic stations, provide data in the less hospitable regions such as off-shore and on mountain tops. Automated systems, to measure visibility and cloud base are now being introduced. A programme of equipment trials seeks to ensure that such systems meet user requirements for reliability and accuracy.

A network of 8 upper-air stations in the UK release balloon-borne instruments every 6 hours. These provide temperature, humidity and wind data from the surface up to several tens of kilometres. A recent innovation is the addition of ozone sensors to flights made from Lerwick.

For climatological purposes, the surface observations are supplemented by daily readings of temperatures, rainfall and sunshine. These are made by climatological observers who include private individuals, staff of agricultural colleges, Local Authorities and other organizations. Their data are of great assistance in establishing, from a larger network, the national climatology and its variability. Over 4000 rainfall observers throughout the UK help to maintain the rainfall database originally started by the British Rainfall Organization in the last century. Together with the Climate observers and synoptic stations these provide a total rainfall network of nearly 5000 stations.

All observing sites are regularly inspected and all data checked as part of the total quality philosophy applied to observations whether for operational purposes, other services or input into the national archive.

Marine observing

Voluntary observers on merchant ships provide much useful weather data from the oceans and provide additional reports of meteorological, oceanographical and wildlife phenomena. The Office gratefully acknowledges the cooperation of shipmasters and their companies for the supply of data.

The WMO Voluntary Observing Fleet numbers about 7000 including some 500 ships recruited by the United Kingdom. Thirty-two of these carry systems installed by the Office to enable weather messages to be transmitted via meteorological satellites at substantially reduced costs. Port Meteorological Officers visit ships of all nationalities, liaising with the crews to maintain good observing standards. These visits may also resolve causes of observational error, detected through data monitoring carried out during operational analysis in the numerical weather prediction programme suite or during subsequent archiving into historical data banks.

The UK-run Ocean Weather Ship *Cumulus* and about twelve North Atlantic container ships, one funded by the United Kingdom, make upper-air soundings by radiosonde balloon. *Cumulus* is a purpose-operated weather ship, gathering data to the west of Scotland. Very creditably, the full observational programme was maintained during her close encounter on 10 January 1993, with one of the most intense North Atlantic storms on record. Phenomenal seas and hurricane-force winds were experienced for 19 hours, and gusts reached 105 knots. The vessel also contributes to MOD (Navy) operations by collecting sea-water temperatures and salinities at various depths using expendable bathythermographs. Soundings are taken every six hours when on passage, and twice daily when on station. In common with all data collected on *Cumulus*, information is transmitted by satellite for immediate analysis ashore. The weather ship is also employed as a floating classroom for those seeking training in meteorological and oceanographical studies.

The five-station off-shore array of fixed buoys, supplying observations mostly from sea areas to the west of the UK, was maintained throughout the year with almost 100% data return despite a period of extremely severe winter storms in the north-east Atlantic. The inshore network was enhanced by the addition of an automatic weather station to the St. Gowan Light Vessel. Further operational deployments of North Atlantic drifting buoys were made throughout the year. A trial was mounted of a new combined surface current and meteorological buoy, developed by the Scripps Institution of Oceanography with funding from the World Ocean Circulation Experiment (WOCE). If successful this will offer a low-cost alternative to the current designs and meet requirements for both oceanography and meteorology.

Technical support to observing

The third phase procurement of SAMOS was completed with 80 systems now delivered towards the target of over 100 by 1994/95. By the end of the year 32 SAMOS installations were completed.

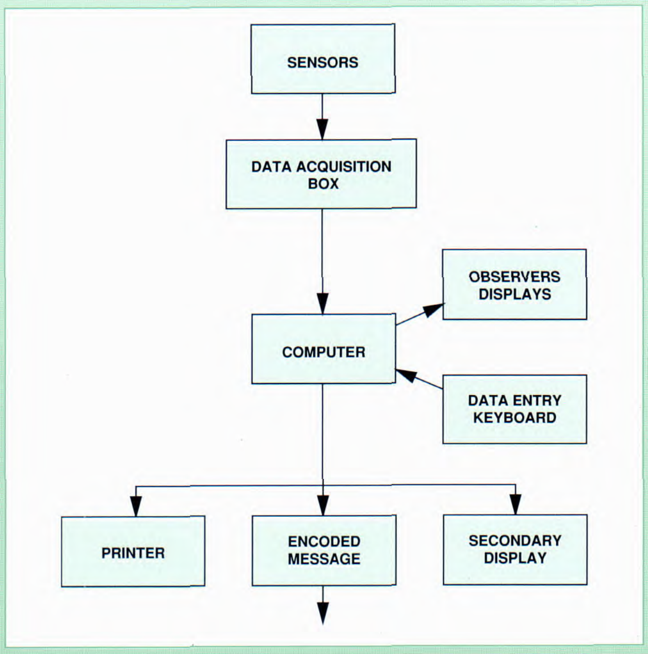


Figure 2. SAMOS schematic diagram.

Wind sensors were supplied for an international intercomparison sponsored by the Commission for Instruments and Methods of Observation (CIMO) of the WMO and hosted by the French Meteorological Service at Mt Aigoual.

A new weather radar system at Cobbacombe Cross in Devon was opened officially by the Minister of Agriculture, Fisheries and Food on 12 October, and a replacement radar at Clee Hill was installed during the year. Both these systems have Doppler processing and volume scanning facilities; new outputs such as precipitation phase are being studied by operational forecasters, data processors and numerical modellers.

The number of Aircraft to Satellite Data Relay Systems (ASDARs) in service increased by nine from the original 'first buy' of thirteen units. Negotiations are well advanced to install two UK-funded ASDARs on aircraft of Air Mauritius. These aircraft fly over some of the most data-sparse areas of the globe and ASDAR will facilitate the provision of high-quality upper-air data, especially valuable for local use and by numerical models. The WMO consortium has placed a contract for eight further ASDARs to be delivered during 1993.

An equipment and fault reporting database with on-line links to the Regional Maintenance Centres was brought into operational service during the year. This system records equipment serviceability and informs maintenance strategy. In conjunction with other elements of the observations quality control system, this will help to ensure that user needs for data are being met in a cost effective manner.

Observations from satellites

The Global Observing System is becoming increasingly reliant on data from satellites operated collectively by national meteorological services. These satellites will also increasingly make vital contributions to studies of climate and climate change by providing capabilities for long-term climate monitoring.

Geostationary satellites provide frequent images of the Earth and its clouds, measure cloud-top or surface temperature and detect regions of high or low water vapour concentration. They also provide telecommunications for the relay of conventionally observed data and the broadcast of processed products. Winds are derived by tracking the motion of clouds and used for input into numerical weather prediction models. The frequent images are particularly valuable as input to local short-range forecasts and 'nowcasting'.

Polar-orbiting satellites provide global coverage but less frequently. They provide soundings of temperature and humidity for input into numerical forecast models. Because the number of conventional soundings from manned stations on land and sea continues to decrease globally, the importance of, and necessity for, satellites as a cost-effective source of global data is increasing. These satellites also carry imagers which measure cloud-top or land/sea surface temperatures.

Operational space programmes, current and planned

Both morning and afternoon polar orbiting satellites are provided by NOAA while EUMETSAT provides the Meteosat geostationary satellite at 0° W and has loaned another satellite to NOAA to replace a failed GOES satellite at 75° W. The Met. Office contributes to the geostationary satellite programme through EUMETSAT, and to the current polar-orbiter programme by providing sounding instruments for the NOAA satellites.

Stratospheric Sounding Units, first flown in 1978, continue to fly on the NOAA series of spacecraft, the last flight model being due for launch in Summer 1993. An early development model, reworked within the Remote Sensing Instrumentation Branch of the Met. Office, is also being provided. This will probably be launched in 1994 to ensure continuity of data and provide an overlap and cross calibration with the next generation of operational instrumentation.

The next series of NOAA polar-orbiting satellites, due to come into operation in 1994, will carry improved microwave sounders collectively called the Advanced Microwave Sounding Unit (AMSU). There are two components; AMSU-A, provided by the USA, will primarily derive temperature whilst AMSU-B, provided by the Met. Office, will derive humidity profiles in the troposphere, and should also allow identification of rain cells with an indication of intensity. Under many cloudy

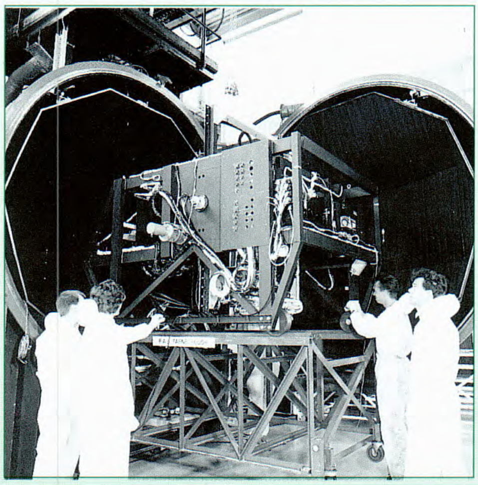


Figure 3 *AMSU–B in test rig about to enter thermal vacuum chamber.*

conditions the quality of soundings from these new instruments will be comparable to those available in clear conditions from the infrared sounding instrumentation. In addition, the improved horizontal resolution (45 km for temperature from AMSU-A, 15 km for precipitation and humidity) from AMSU-B, will provide useful image products. Two further instruments similar to AMSU-B will be required on NOAA polar-orbiters before the year 2000: these will be provided by EUMETSAT. Thus AMSU-B will be the first of a series of instruments providing the continuity essential for long-term climate monitoring in addition to meeting basic meteorological requirements.

The AMSU-B Engineering model and three Flight models are being built under contract by BAe and are being evaluated by the Met. Office. This is done by the Remote Sensing Instrumentation Branch in a special vacuum test facility within the DRA Space Simulation Centre at Farnborough. Acceptance tests were completed on the Engineering Model in May 1992; radiometric and operational characterization tests of the instrument followed. Detailed results obtained under simulated 'space' conditions showed that the instrument was operating satisfactorily within its specification. All three flight models are now in various stages of their test programme prior to acceptance and will be tested and characterized in the calibration facility during this year. It is expected that the first AMSU-B will be launched in 1996.

After 2000 the existing EUMETSAT geostationary Meteosat operational Programme (MOP) will be replaced by Meteosat Second Generation (MSG) with improved resolution and more frequent data. On the same time-scale EUMETSAT will also take over responsibility from NOAA for providing the 'morning' polar orbiter. An advanced infrared sounder is also under development and may be available in time for the first orbiter flight — if so it will provide a major step forwards in sounding with considerable improvements in vertical resolution.

The Office has played a major part in the decision-making meetings within EUMETSAT. The primary objective has been the achievement of cost-effective, operational systems capable of meeting meteorological requirements. Plans include utilizing existing expertise in National Meteorological Centres in the ground processing of both polar and geostationary satellite data to the maximum extent possible.

Space instrumental development

The Met. Office also needs to study and understand the requirements, techniques and available technology of future instruments to maximize benefits and maintain tight constraints on costs. Such studies are essential in order to influence the major programmes of the agencies. Office staff are members of national committees, delegates to international bodies and active members of the technical working groups that support them.

Studies include the evaluation of concepts for measurement of precipitation and clouds from space using active and passive techniques. These include a feasibility study of a space-borne cloud radar led by the Rutherford Appleton Laboratory. A study has been completed for ESA on the measurement of precipitation from space using passive microwave techniques.

More generally, studies of ways in which relatively small design changes can improve resolution and sensitivity, and significantly enhance the exploitation of imaging and sounding instruments have continued, partly in contract work for EUMETSAT.

Aircraft measurements and theoretical studies

The Microwave Airborne Radiometer Scanning System (MARSS) mounted on the MRF C-130 comprises two of the AMSU-B microwave channels (89 and 157 GHz) similar to those of AMSU-B. Results from earlier flights to investigate the properties of the sea surface and emission from water vapour have been accepted for publication. These observations are being used in developing a radiative transfer model which will be at the heart of the retrieval scheme for the new generation of microwave sounding instruments. The effects of clouds and precipitation are also being measured this year.

Plans are being made to extend aircraft studies to include high-spectral-resolution infrared measurements. These will be needed to support instrument design and the effective use of data from the high-spectral-resolution sounders planned for the future. These are aimed at significantly increasing the vertical resolution of future infrared sounders. There will be great benefit from flying infrared and microwave instruments on the same aircraft.

Telecommunication and computing

Most of the business of the Met. Office depends on adding value to information so that the most appropriate weather forecast or meteorological advice can be delivered to customers in a timely, effective and efficient manner. Man and machine both have key roles to play in maintaining services. Automated systems are now critical to the provision of those services and indeed to most of the Office's work. Such systems are now key components of observing systems, telecommunications, large-scale scientific computation, data storage and management, product delivery and presentation.

With information processing being so much at the heart of the Met. Office's activities, the best of proven technology is used wherever it is cost-effective. Much of that technology is to be found deep in the infrastructure of the Office, largely invisible to most customers, and to more than a few staff. The extent to which the Met. Office is a 'high technology' organization is highlighted in succeeding paragraphs in which the roles of such systems as the two Cray supercomputers and the 'non-stop' telecommunications processors are described.

The pace of change of technology and the exploitation of automated information systems by more parts of the Office, including those involved in management, administration and accounting as well as those in mainstream activities, has demonstrated the need for a comprehensive Information Systems Strategy to ensure that Information Technology is harnessed in support of the business aims of the Office. A strategy document has been drafted and distributed during the year and is now being used to guide developments. The strategy will be refined and developed with the help of both consultants and staff.

Operations

There are two main components to the routine operations managed by (C) Division. These are the Meteorological Telecommunications Centre (Met. TC) and the central computing complex (COSMOS). These two facilities are situated in the Richardson Wing of the HQ building at Bracknell, together with the supporting infrastructure for power distribution (including emergency supply) and cooling. The Central Forecasting Office is also located in this Wing, and depends critically on the facilities provided by Met. TC and COSMOS.

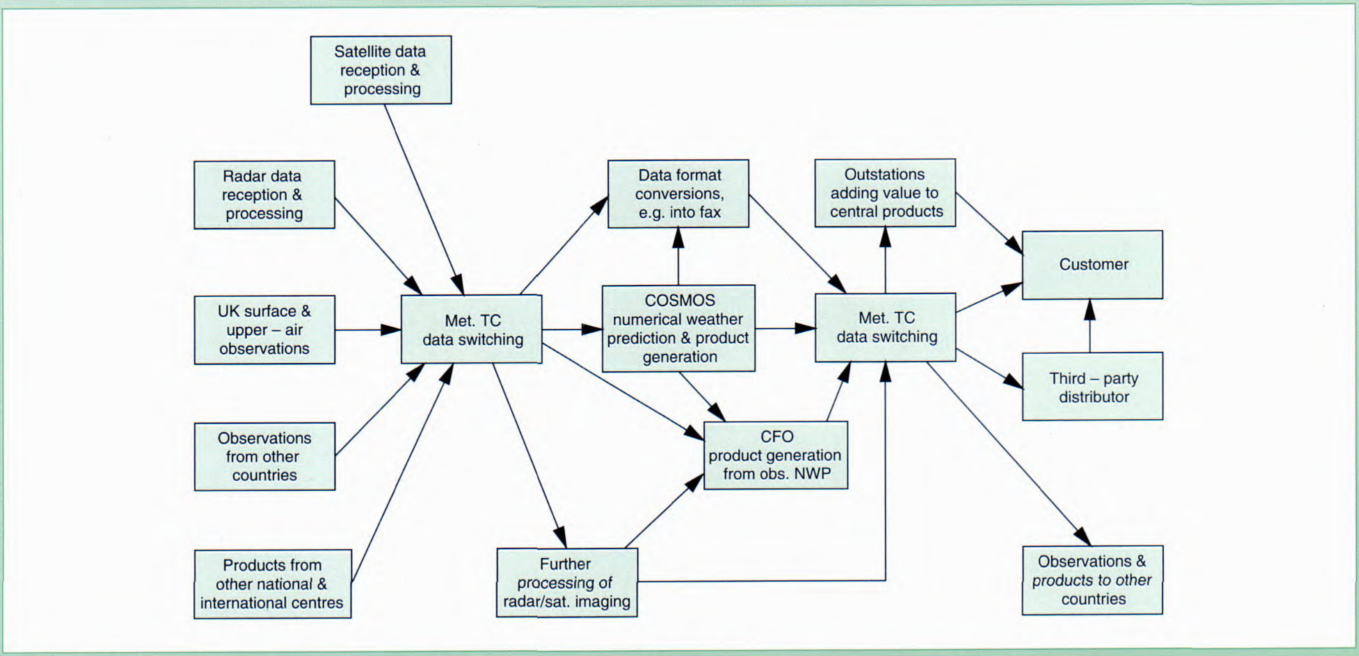


Figure 4. Simplified representation of data flow showing progressive adding of value.

The business of weather forecasting can be thought of as a process whereby value is added progressively to observational data to generate the products required by customers. Telecommunications and central computing play a vital role in this process.

The Met. TC operates round the clock, gathering and disseminating weather observations and products in a highly automated environment. This is accomplished by means of various networks connecting computers in Met. TC, other parts of HQ, at outstations, on customer premises, with value-added service providers, and equivalent facilities in other countries. The full picture is very complex, so two examples are given as illustrations.

(a) Observations are gathered from all over the world by means of the Global Telecommunication System of the WMO. A large computer-based message switch in the Met. TC is connected to neighbouring countries in Europe and to Washington, USA. Bulletins of observations and selected forecasts are exchanged using code forms specific to meteorology. To give an idea of the scale of operations, about 90 000 messages are received per day and 670 000 disseminated. More information about the message switch, known as TROPICS, is given below under 'recent developments'. Within the United Kingdom, observations originate from the Met. Office's manned and automatic sites, from staff of other organizations (such as HM Coastguard) and from ships, platforms and buoys at sea. Messages containing observations are fed to COSMOS and to outstations and exchanged with neighbouring countries. A recent development has been the facility to convert between messages in the WMO format and messages in X.400 format, the international standard for electronic mail.

(b) Products can be disseminated in many forms, WMO messages, computer-to-computer file transfer, telexes, analogue facsimile by landline or radio broadcast, and increasingly as 'faxes' to standard office fax machines. The last of these is achieved by an automated process which begins in COSMOS with pictorial output from the numerical forecast suite being encoded in T4 code, the internationally agreed digital coding for fax. The encoded product then passes over a local area network to a system (called ARTIFAX) which associates each product with a list of recipients and transmits, via PCs equipped with fax cards, through the Office's digital PABX, to customers on both public and private telephone networks. ARTIFAX also distributes faxes to third-party fax bureaux which support dial-in services for customers in aviation, marine, education and other markets.

The COSMOS computing complex is also operated around the clock, providing computing and database services in support of weather forecasting operations and research work. COSMOS is based on three main machines: two large-scale scientific processors (Cray Y-MP8) and a general purpose mainframe (an EX100 processor from Hitachi Data Systems).

The Cray machines are particularly well suited to the running of large scientific models and are able to achieve very high computational rates; for example in running the main global weather forecasting model, computation rates in excess of 1000 million calculations per second are achieved. Machines of this power are needed to run the current generation of numerical models so that the many output products can be available in the required elapsed time. One of the Cray machines is used in support of weather forecasting and general research work and the other one is reserved for support of the Climate Prediction Programme being undertaken for the Department of the Environment.

The EX100 mainframe is used to perform a wide range of functions including all data preparation for the Crays, processing of the data generated by the Crays, for example the generation of products for specific customers, and for the storage and archiving of large volumes of data. The EX100 supports a wide range of peripheral equipment including graphical output devices and has connections to networks and many other computing systems. Given the demands for new products and more complex forms of processing, the demands on the mainframe continue to increase at an annual rate of around 30%.

The bulk of services provided by the Meteorological Office depend on the central facilities of Met. TC and COSMOS. Given that it is very important for customers to receive their products in time, and because of the perishable nature of much meteorological advice, continuity of operations is of great importance. Over the years substantial investment has been made in hardware, software and in the development of procedures in order to provide a highly reliable service. Last year, new air-conditioning and electrical systems were installed to support the operations wing of the HQ building: this work was undertaken to improve the overall reliability of these essential support systems and hence the overall quality of service being provided. Further work over the next year in the provision of new standby generators will enable additional improvements in quality of service.

The operation of Met. TC and COSMOS used to be distinct in many ways, with different skills and techniques employed. Over the last few years, data communication has become largely based on computer networks, so there has been a rapid convergence in the skills needed to operate the two areas. Plans are now being prepared to merge Met. TC and COSMOS into a single operations centre, involving many small technical changes and the collocation of staff. The aim is to provide an even better service to customers at lower cost. For example, various help desks will be combined, providing a single point of contact for a member of staff or customer with a problem concerning the central computing or data distribution services.

TROPICS

Message switching is vital to weather forecasting and other operational services. Until about 20 years ago, messages were exchanged internationally using telegraphic techniques, with manual handling of miles of paper tape at switching centres. This activity was a high priority for automation and a series of developments led to a largely computer-based operation in the Met. TC by the mid-1980s. These developments, together with the impact of micro-electronics on telecommunications capacity, have made it possible to handle increasing amounts of data, such as observations from satellites and more-detailed forecast products, while reducing real costs. It became clear that the message switch installed in the mid-1980s would not cope with the growth beyond 1992 and so a replacement was procured. TROPICS (Transmission and Reception of Observational and Product Information by Computer-based Switching) is based on a fault-tolerant configuration of Tandem Cyclone/R equipment and was installed in November 1992. The large suite of application software and many circuit connections were transferred from the older switch progressively over the following 4 months, ensuring no loss of service to all the computers in the various networks attached to TROPICS. The new system now has sufficient capacity, and an upgrade path, to run this vital service for at least 5 years.

COSMOS enhancements

Over the last year, one of the main enhancements to COSMOS has been in the provision and development of new methods of data storage and handling. The general intent is to move towards a situation whereby all active data are kept on-line and magnetic tape is only used for data back-ups and for data archiving. In order to implement this concept, a substantial quantity of disk capacity, around 200 gigabytes, was installed in February 1993 to replace 80 gigabytes of capacity provided by equipment which was at the end of its life. The new equipment not only provides increased capacity, hence allowing users to keep more data on-line, but also better performance, with the new disk control units containing an increased amount of cache memory and providing other advanced functions.

Implementation of IBM's System Managed Storage (SMS) on the EX100 has begun. SMS provides an automatic mechanism by which free space on a group of disk volumes can be created by writing data, which has not been recently accessed, to tape in a compressed format. These data can be automatically retrieved when required. A similar mechanism, Data Migration Facility (DMF), on the Crays has also been implemented in the last year. This allows users to over-commit their file systems, with excess data been moved off-line automatically.

With SMS and DMF, it is necessary to ensure that tapes containing archived, or off-lined data, are remounted rapidly when required. To this end, the installation of an automatic tape cartridge system, began in March 1993. The new system, manufactured by Grau and supplied by Hitachi Data Systems, is designed to hold 28 000 cartridges and to mount cartridges when required. This system will service mount requests for tape drives connected to the three computers installed in COSMOS. The latest technology tape drives have been installed; these allow more data to be stored on each cartridge because more tracks can be written to across the tape and they are able to handle thinner tape (this allows the use of cartridges with double the length of tape).

During the last 12 months, the ESA version of IBM's MVS operating system has been installed on the EX100 machine. ESA has several additional facilities over its predecessor: in particular, it allows programs to use large address spaces and hence certain features of the secondary semiconductor memory ('expanded storage') available on the EX100 machine. These features allow the development of application software which will make use of the large real memory installed on the EX100 and should enable the full power of the machine to be realized.

Large-scale scientific computing

This service is based on the two Cray Y-MP8/864 machines, the use of which was described in the sub-section above about operations. An important break-point will occur in April 1994 when the lease on the machine used for climate change will expire. Planning for a follow-on system has begun and has had to take account of increasing prices in dollar terms and a fall in the value of the pound against the dollar. It has been concluded that the strategy of separate systems for work on climate change and numerical weather prediction is no longer affordable. Useful economies in both capital and running costs can be achieved by combining both lines of work on a single platform and removing some of the less intensive work to powerful workstations. The planning strategy is therefore now based on the principle of moving to a single more powerful system to replace the two Cray Y-MP8s in March 1994.

Weather Information System

The Weather Information System (WIS) is a broad strategy for improving the costs and effectiveness with which information is delivered and presented to both external customers and weather offices remote from the Met. Office's Headquarters. Cost reductions arise from rationalization of communications networks, less use of paper and lower costs of maintenance on up-to-date equipment. The rationalization of networks also enables a wider range of products and services to be offered in a timely fashion. From the technical viewpoint there are three main components to the implementation of WIS, namely the Outstation Display System, the Weather Information Network and the Outstations Production Unified System.

Outstation Display System

The Outstation Display System (ODS) is a system which allows forecasters in the outfield to receive both observational data and model products, and retrieve and display them in a wide variety of ways. Installation of the systems began in 1986, when the main front-line RAF fighter stations were equipped with systems. Since that time systems have been progressively introduced in all the Met. Office forecasting outstations both civil and military as well as Royal Naval and other offices. This major installation project has resulted in some 90 systems being deployed throughout the whole of the UK, and also in Germany, Cyprus and Gibraltar.

The ODS is based on hardware from Digital Equipment Corporation (DEC). At present MicroVax IIs, and VAX 3000 and 4000 series systems are used. The early versions of the system did not have a very sophisticated graphics display system. However, in 1990 a full graphics capability was added to existing systems and new systems were similarly equipped. At the front-line RAF stations dual systems are installed, one in the normal Met. Office and one in the hardened area of the airfield. Larger offices have multiple graphics screens attached to the ODS and places with a large number of forecasters, such as Aberdeen Weather Centre, have two systems in the same office. The data are presently sent to the ODS across the Civil Rented Data Network (CRDN) (this network is relatively slow and not designed with a high degree of redundancy). This is an interim measure and awaits replacement by the Weather Information Network (WIN) which will be fast and have resilience designed into it. The effect on the ODS is that, at present, a relatively limited range of data can be sent. When WIN is fully operational, a much larger amount of data, particularly model output data, will be sent to the outstations for display on the ODS.

The most recent phase of installation has seen ODS installed in the last of the Met. Office outstations. It has also seen the installation of backup systems in the form of workstations which are capable of running the system, albeit in a somewhat limited form. Each of the main systems has a backup system installed alongside it and data are fed to both systems so that the backup can rapidly be made operational in the event of a main system failure. The backup systems at the various Weather Centres have extra capacity. This will allow them to support sophisticated product generation software and allow them to communicate these products to customers in a variety of ways. The main ODS at each Weather Centre is also capable of supporting the product generation software so that full backup is available.

Software development on the ODS is controlled by the ODS User Group which meets twice a year. Users bring forward requests for facilities that they wish to be added to the system. These requests, if they are agreed to be suitable, are prioritized. Software releases containing the new facilities are issued to the users at six-monthly intervals. Telephone support to users is provided by the development team during normal working hours and by operations staff out of hours. While there remains a lot of software to be written to meet the users requirements in full, particularly when WIN becomes operational, the ODS is a relatively mature and stable system. The oldest processors are now some seven years old and some difficulty is being experienced in running the latest software on them. It is expected that these processors will be replaced in the 1993/94 financial year by the latest suitable DEC systems. ODS will continue to meet the needs of outstations for the foreseeable future.

Weather Information Network

The methods for distributing data and products from Bracknell to outstations and customers, and from outstations to their customers, are a complex mixture of ancient and modern, from analogue facsimile over private wires to the latest in computer-to-computer file transfer over Integrated Services Digital Network (ISDN). This diversity is expensive to run and difficult to manage. It has been apparent for many years that an integrated approach would bring many advantages, not least lower costs. The appropriate technology is a mix of message switching and other computer-based methods for gathering and disseminating data, using underlying data communication services such as packet-switching networks. The main component of this technical strategy is a message handling system conforming to the international X.400 (1988) standard.

This will form the Weather Information Network (WIN) spanning the major sources of meteorological data in the UK and the outstations where forecasters tailor the information to meet specific customers' needs. Nodes on WIN will also support connections to observing sites and onward links to customers. The implementation of WIN depends on the availability of message switches conforming to the standard; there are now several competing vigorously in this market-place. WIN also depends on the availability of the underlying communications infrastructure and, since many outstations are at military sites, this means a high dependency on military networks. WIN is planned for implementation over 1995 and 1996, with 1993 devoted to completion of the studies and 1994 to the competitive procurement.

Outstation Production Unified System

The Outstation Production Unified System (OPUS) is a project to improve customer service by linking together existing standalone and new systems at Weather Centres so that forecasters' productivity can be improved and delivery to customers simplified. A prototype system is now in place at Bracknell and is being used to test the design philosophy and implement the final system. The design is based on a local area network at each Weather Centre, using the backup ODS as a file server. The main ODS and backup ODS/file server are arranged so as to provide mutual backup so that both functions can be sustained in the event of a failure of either system.

HORACE

About eighteen months ago it was decided that the computer systems at the two Principal Forecast Offices in the UK at Bracknell and High Wycombe should be replaced. The project was named HQSTC OASYS Replacement and CFO Enhancement (HORACE). The previous systems had exceeded their design lifetime and replacements were required to automate further activities, to improve timeliness and availability of an improved range of forecasting products and to reduce the requirements for printed output.

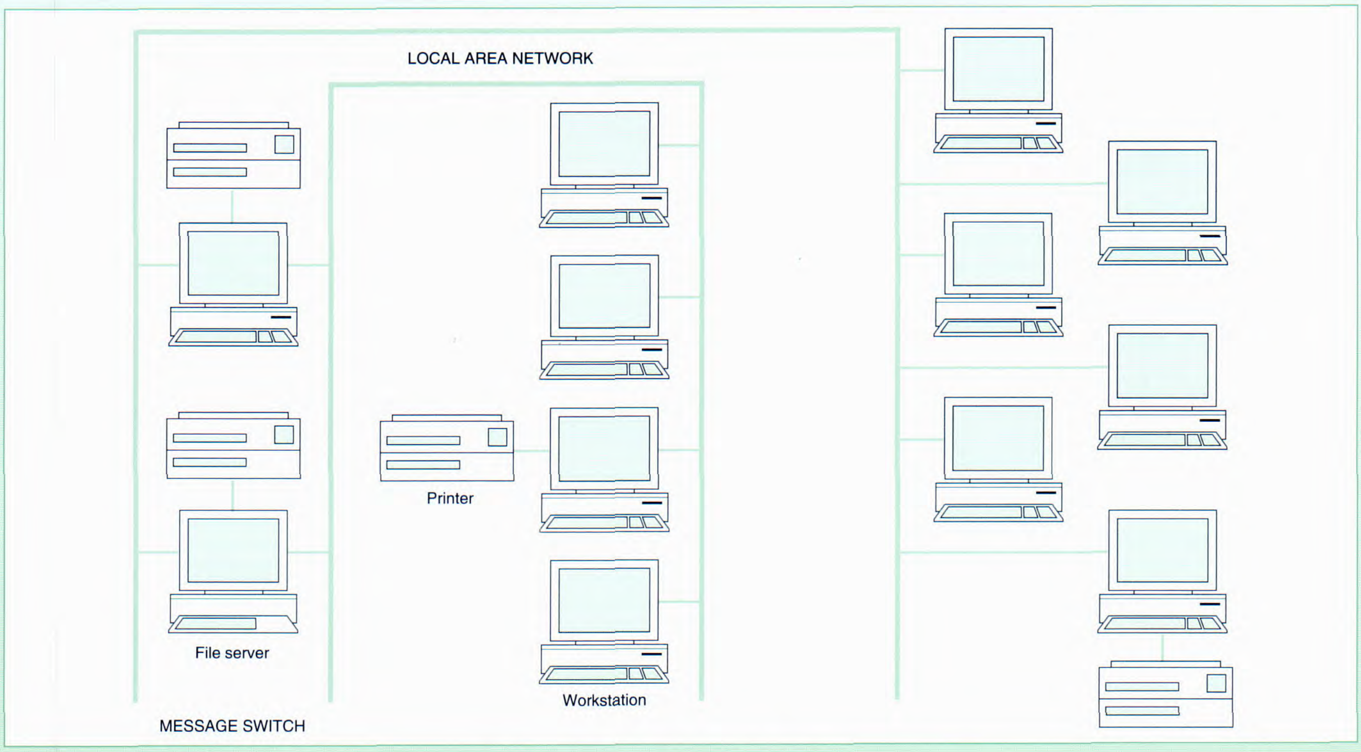


Figure 5. HORACE at High Wycombe

The HORACE project has been formally managed from the beginning. A management structure was set up to allow the users to define the requirement and to monitor and review the progress of the project. Formal design and analysis (CASE) tools have been purchased and all project and system documentation is produced in a standard format. The hardware for the High Wycombe system has been purchased by competitive tender and installed. A prototype system which provides hard-copy output and allows the users an early view of the Graphical User Interface is presently running. The hardware for the Bracknell system has been procured. The first full release of the High Wycombe application software is expected to be in place by late summer 1993.

The network at High Wycombe consists of a primary and secondary thin-wire Ethernet Local Area Network (LAN), see Figure 5. Two file servers are connected to this network, one of which acts as a standby. The LAN also supports ten workstations six of which have their own disk storage and four of which are diskless. A message switch at High Wycombe feeds data from Bracknell and the GTS to the system. In the event of a total failure at Bracknell, the system is capable of receiving all the data to allow full operation. The same message switch is used to disseminate output, produced on the system by the forecasters, to their various customers.

The network at Bracknell, see Figure 6, will be a very fast Fibre Distributed Data Interface (FDDI) network and will support 35 workstations. There will be connection to the mainframe and supercomputers so that model results can be made available. There will also be a connection to the main Met. Office internal network. This will allow the receipt of basic data and the dissemination of products in the same way as at High Wycombe. The operating system will be Unix and most of the software will be written in Fortran. C will only be used where it is strictly necessary. A Graphics User Interface (GUI) development package has been procured. This not only reduces the time spent in developing the GUI but means that all screens will be produced with the same 'look and feel.

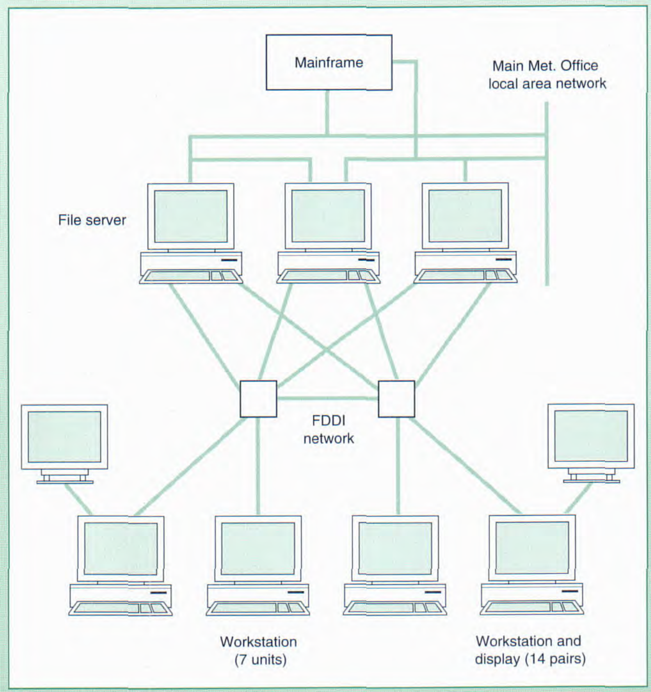


Figure 6. HORACE at Bracknell

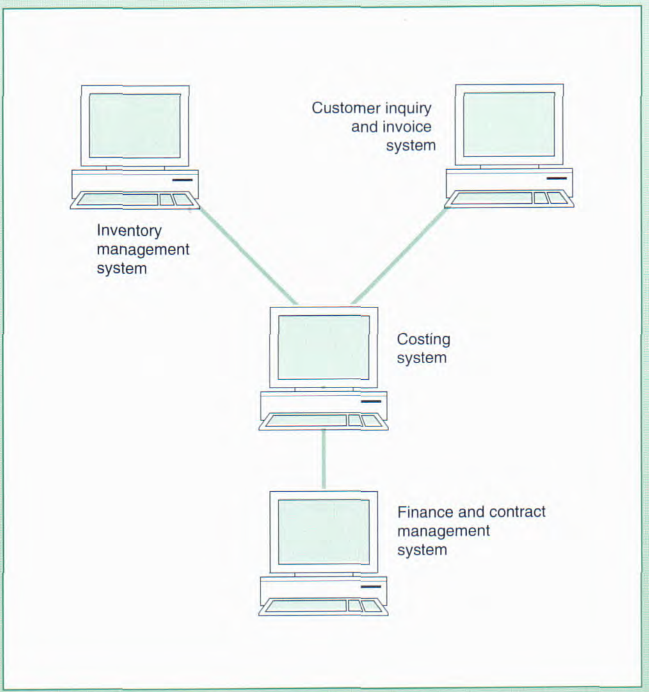


Figure 7. FAMIS.

The HORACE project is very challenging. The fastest workstations are required to give the necessary performance and deal with the very large quantities of data. The main challenge, however, lies in designing and implementing software which will persuade the forecasters that paper and pencil methods are inferior to screen-based ones. The HORACE project is due to run for another three years or so, but it has started well.

The Finance and Accounting Management Information System

The Finance and Accounting Management Information System (FAMIS) is designed to provide the Met. Office with financial and other information which enhances and complements present Vote Accounting information from the Met. Office. It also provides the information in a form more suitable for the commercial accounting requirements of the Met. Office in its role as an Agency. The system has been producing reports on a trial basis for about six months and, as the inevitable problems both with the software and hardware, data entry and integrity, are overcome, will be fully operational in the next few months. The various components of the system which are illustrated in Figure 7.

The Inventory Management System (IMS) automates the function of keeping track of the contents of the Met. Office stores. The system handles the ordering, delivery and replacement of stores. It also has the capability of producing management-level reports on such things as the value of all stores kept. The system produces monthly reports which are passed to the costing system for use in the monthly accounting runs. The IMS is a network of PC systems running software consisting of a standard stores accounting package with a few modifications for specific Met. Office requirements.

The Customer Information and Invoicing System (CIIS) runs on the IBM-compatible mainframe system using the Integrated Database Management System (IDMS) database package. The system has a large customer information database which is extensively used by the Commercial Services Branch of the Office. The system also tracks enquiries made to

Commercial Services and allows charges to be calculated if appropriate. The system also allows the on-line entry of invoices which are printed, checked and issued only from the Met. Office HQ, although invoices can be entered on-line from any of the fourteen Weather Centres scattered around the country. The CIIS also produces management reports of revenue and, particularly, a monthly report of debtors who can then be chased for payment. The system automatically produces three standard letters of increasing severity at fixed intervals, inviting payment. CIIS is also connected to the Costing System so that revenue income can be fed into the monthly accounting runs.

The Finance and Contract Management System (FCMS) is a sub-system of FAMIS which tracks the procurement of equipment and services through all the stages from initial financial approval being given, to final payment being made. It provides reports of the expenditure which has been made and committed from each equipment vote. Thus proper planning of equipment expenditure can be made so that budgets are spent but not exceeded. FCMS also provides reports for the Contract Branch on the status of all the contracts they are handling at any time. The system is based on a proprietary database with a considerable amount of bespoke development to make it meet the specific Met. Office requirements. It runs on a network of PCs.

The heart of FAMIS is the costing system. Its purpose is to collect all the expenditure and revenue for the previous month and attribute it to the relevant Met. Office department. This allows the cost of all the Met. Office's activities to be properly calculated and set against the revenue earned by the activities. The Costing System takes in data from the other three FAMIS sub systems and from the monthly disk of pay and expenditure produced by MOD. This data is analysed and a large and varied selection of reports is produced and distributed widely within the Met. Office. The Costing System runs on a PC network and is again based on proprietary packages with a significant amount of bespoke development. The target set for FAMIS is to produce the monthly accounts within five days of the arrival of the data disk from MOD. As the system becomes more stable and the data input more efficient, this target is being approached.

The Fixed Asset System, which is separate from those described above allows a record of Fixed Assets held by the Office to be maintained. The system calculates depreciation charges, additional depreciation charges (for current cost accounting purposes) and interest on capital for use by the costing system.

Central Forecasting

Data quality control and forecaster intervention

In order for a numerical weather prediction model to produce a forecast of the future state of the atmosphere it must be provided with an estimate of the initial conditions. This must be as accurate as possible, so sophisticated quality control processes need to be performed on all the observational data that are supplied to the data assimilation system. Much of this work can be carried out automatically using complex numerical algorithms, but it has been shown in the past that some form of human interaction, or 'intervention', with the system can sometimes be beneficial.

In the Central Forecasting Office (CFO) a team of experienced forecasters is responsible for this intervention task. Their job is to examine the data as they arrive in the main Synoptic Database and check their accuracy. This may be done by comparing an observation with some prior estimate of the value (a first-guess or background field) or against neighbouring observations. An important tool for the forecaster, which is not available to the automatic quality control, is the satellite picture. This may indicate a synoptic development which had not been forecast and thus does not appear in the background field.

The intervention forecaster can perform a variety of operations on the data. He may (a) correct, (b) reject or (c) support an observation — supporting an observation results in extra weight being given to that observation in the data analysis. However, probably the most important facility is the ability to create 'bogus' observations. This is usually done in data-sparse areas, such as over the southern hemisphere oceans, when satellite imagery suggests that the background field for the model is in error. During the last year this has been made easier. By specifying the old and new positions of the feature, and a few other pieces of information, the forecaster can invoke an automatic scheme which creates bogus data from the existing model fields but in the correct position. This facility was introduced on a trial basis and was initially available only for the tropics and southern hemisphere. After its utility was proven it was subsequently extended to include the north Pacific and finally the remaining areas of the globe.

Tropical cyclone verification

A global numerical weather prediction model with a horizontal resolution of around 100 km cannot be expected to resolve the detailed structure that exists at the heart of a tropical cyclone. However the essential features of the large-scale flow can be modelled to a sufficient degree of accuracy to enable useful forecasts of the storm track to be made.

Verification of these track forecasts (from the Met. Office global model) is performed routinely using a semi-automatic technique and over the last year this system has been improved and enhanced. For each tropical cyclone it is possible to produce a graphical representation of the actual and forecast tracks. As an example the figure shows the track of Hurricane Andrew, which caused widespread destruction over southern Florida in August 1992. In this case although the forecast tracks were good, the speed of movement was generally too slow.

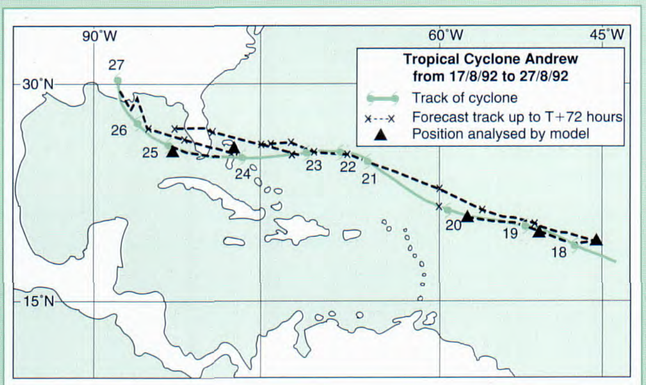


Figure 8. Track of hurricane Andrew and forecast movement.

Monitoring of marine surface data

In 1985, the Commission for Basic Systems (CBS) of WMO agreed that there was a need for global numerical weather prediction centres to monitor the quality of observations and to exchange statistics on a monthly basis. In 1988 three lead centres were nominated which would have a coordinating role of producing, at 6-monthly intervals, consolidated lists of suspect stations for given data types. The Met. Office was allocated the role as lead centre for marine surface data, which encompasses observations from ships, drifting and moored buoys and other fixed marine platforms.

Monitoring the quality of observations is based on the availability of a global reference field of good quality. It is recognized that the numerical data assimilation systems in use today can provide such a reference through the background field (or the short-period forecast from the previous analysis) and observation-minus-background (O−B) differences are at the centre of all monitoring work.

Perhaps the most important part of observation monitoring is ensuring that the information is fed back to the people that supply the observations, so that action may be taken to correct data sources that are suspected of producing erroneous data. It is encouraging to note that, since the Met. Office began compiling the 6-monthly consolidated report, the number of marine observing platforms listed as producing suspect observations of air pressure has decreased steadily. The latest report, issued in February 1993 for the period July to December 1992, listed just 64 observing platforms compared with 143 for the equivalent period in 1990.

The automatic generation of aviation significant weather charts

International civil aviation meteorological services are provided by two World Area Forecast Centres (WAFCs), which provide gridded global upper-wind and temperature NWP data, and by fifteen Regional Aviation Forecast Centres (RAFCs), which provide regional significant weather charts (SIG WX). The final stage of the world area forecast system for civil aviation envisages the two WAFCs generating global data to be disseminated via satellite. It is planned to start phasing out the RAFCs when the WAFCs demonstrate their capability of providing SIG WX on a global scale, in addition to the upper-wind and temperature data. The Met. Office at Bracknell is both a WAFC and a RAFC.

At present, Significant Weather charts for aviation provided by Bracknell are hand-drawn, using a variety of hard-copy charts as underlays, the resulting product is then passed to the Telecommunication Centre for dissemination. In order to support the commitment to provide global significant weather information, without a commensurate increase in manpower, a project has been set up in CFO to develop a system for automating the production and dissemination of significant weather charts. The aims of this project are:

(a) to automate, as far as possible, the production of significant weather charts, by providing suitable objectively derived first-guess fields and suitable editing tools.

(b) to completely automate their dissemination, whether internally (to other forecasters within the forecast office) or externally (via telecommunication links).

The automation of chart production is based on the use of computer graphics to generate the significant weather charts. This work began several years ago using graphics terminals attached to COSMOS, and making extensive use of kernel graphics routines provided by Central Computing. It quickly became apparent that the processing power of a graphics terminal was insufficient, and that the performance of a graphics workstation was required. The software package was initially ported to a SUN workstation, and is currently running on HP workstations in CFO. The facilities available to the forecaster have evolved with the provision of increasingly powerful hardware and enhanced software tools.

Initially the forecaster could display selected background fields, and use these data to build up the final product, which is 'drawn' on the screen. Facilities have been developed which allow the forecaster to define the position of a symbol and any associated text. These symbols are displayed on the screen, allowing the forecaster to see the product during all stages of its generation. This method mimics existing working practices, with the overlaying of different fields of NWP-derived data providing the soft-copy equivalent of viewing hard-copy charts on a light table.

The first change in working practices has been with the use of objectively derived first-guess fields. At present the forecaster uses tropopause heights produced from the numerical forecast. These data are displayed as symbols on the chart, each symbol can then be deleted or repositioned by the forecaster in order to improve the final product. Objectively generated first-guess fields of other variables, e.g. position of fronts, jet streams or areas of significant turbulence have been developed within the Forecasting Research Division. The extensive use of such fields awaits the introduction of a graphical editor, which will permit the user to move all or part of a symbol. At present, the forecaster can only draw or delete a complete graphical feature, graphical editing will be introduced over the coming months.

The final product is held as a computer graphics metafile (CGM), and stored for future reference within the system. The dissemination of this product is automated, the CGM being converted to 'T4-format' so that a facsimile product is available for automatic routing to all users.

Development and implementation of the system will be an incremental process, with facilities offered and area(s) of coverage increasing with time. An operational test of the package, for the generation of North Atlantic area charts, has been under way in CFO since July 1992. This user trial has tested the robustness of the package, enabling the development of extensive back-up and recovery facilities: it has also influenced the development of the package, resulting in considerable improvements to the available facilities. It is planned that the system will start to produce charts operationally for the North Atlantic area in April 1993. Work has already begun on the next extensions of the package which include covering the whole globe, and allowing for use by more than one forecaster. The symbols contributing to the chart are stored, together with their latitude and longitude, allowing reuse on other chart areas.

The aim of the significant weather project is total separation of the processes of generation and output. Once a forecaster has confirmed that a product is finalized, the underlying system will handle any further processing and reformatting which may be required in association with its dissemination.

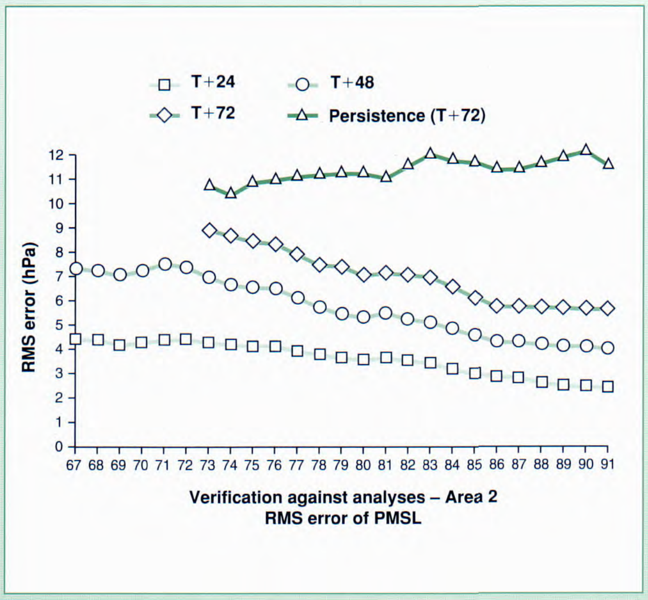


Figure 9. Verification against analysis over the North Atlantic — RMS error of MSL pressure

Evaluation of operational forecasts

Forecasts from the numerical models may be verified by a number of techniques which depend on comparing the model with some suitable reference value (for example, the observations at the time the forecast is valid) and determining the differences. Statistics of the differences are computed in each model run (twice a day). Summaries of the results are expressed as monthly or annual averages. Other verification schemes require a categorical analysis of the forecast events compared with what actually happened in reality. Results from these schemes are assessed by means of contingency tables.

During 1992 the performance of the numerical weather prediction models continued to improve, as demonstrated by the root-mean-square errors in forecasting the pressure at mean-sea-level over the North Atlantic. The reduction in the errors of the 2- and 3-day forecasts is the result of continued efforts to improve the model's treatment of dynamical and physical aspects of the atmosphere.

Post-processing of the forecast winds was used to correct a bias in model forecasts for aviation. Through the year, monthly mean wind-speed errors over the northern hemisphere were reduced to less than 1 knot. An improved scheme for verifying gale warnings was brought into use. This confirmed that 79% of gales are correctly forecast 6 to 12 hours ahead. Only 17% of the warnings could be considered to be mistaken, and some of these were due to timing errors.

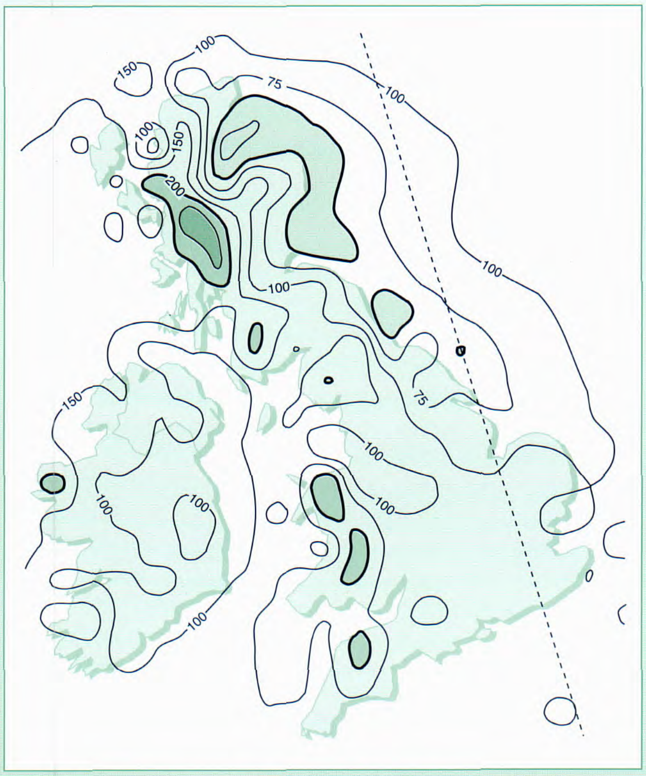


Figure 10. Total rainfall (mm) monthly accumulation. November 1992 data from Cray Limited Area Model.

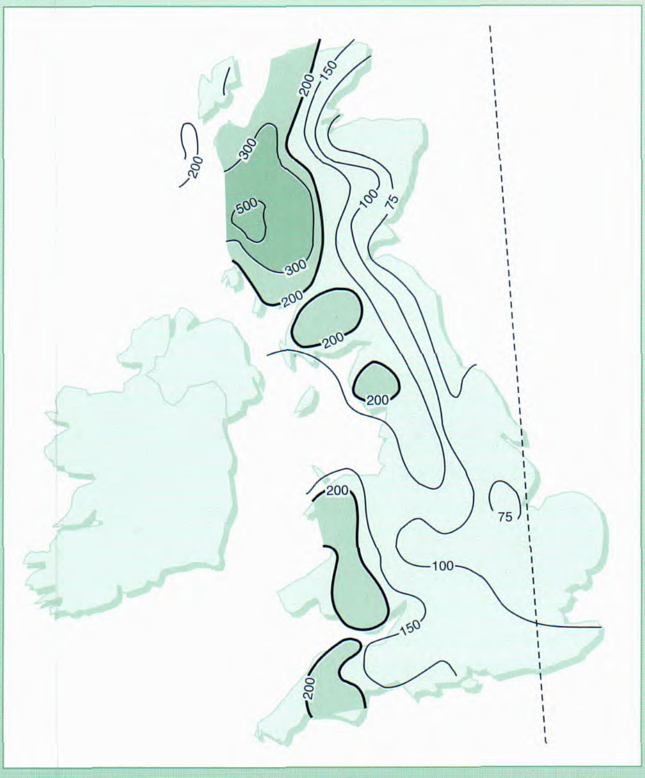


Figure 11. Total precipitation (mm) monthly accumulation. November 1992 MORECS data.

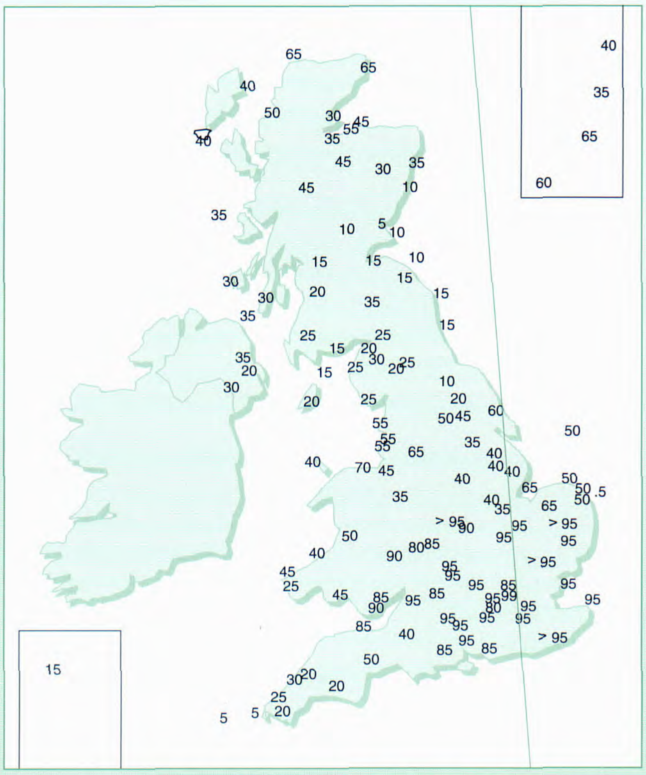


Figure 12. Showing the probability (%) that a station will have more than 0.1 mm of rain. A 36–hour forecast for the period 1800 to 2400 on 26 January 1993.

The Limited-Area Model is the Office's main source of numerical guidance for forecasting precipitation. Despite the difficulties of treating the complex physical processes that are involved, the model had a success rate of 74% in predicting precipitation events over the UK from 24 hours beforehand. Charts of one month's distribution of rainfall show that the model captures many of the features seen in the real world, as shown, for example, by the results for November 1992.

Model Output Statistics (MOS)

The Model Output Statistics product range was expanded to include temperature forecasts for 120 stations around the world, and Probability of Precipitation forecasts (PoP) for 120 UK stations. The PoP product is derived from Global model data, and is available in 6-hour steps out to T+72 from the midday and midnight runs. Currently the product is on trial in the Central Forecasting Office and the Figure 12. shows a forecast chart for the period 18 UTC on 26 January to 00 UTC on the 27th, at a lead time of 30 to 36 hours.

The PoP values for each station are probabilities that the station will have more than 0.1 mm of precipitation in the 6-hour period. The forecast shows a frontal system which passed through south and east England, and the shower probabilities behind it, with the west coast of Scotland more likely to have rain than the east coast.

Defence Initiatives

Introduction

The primary task of the Defence Services (DS) Division of the Meteorological Office is the provision of meteorological services to the RAF, Army, MOD (PE) and, to a lesser extent, the Royal Navy. Our forecasters serve at just over 50 airfields and ranges in the United Kingdom, Germany, Mediterranean and South Atlantic and, increasingly, deploy (as uniformed Mobile Met. Units) in direct support of the Armed Forces in crisis areas. These days, our forecasters do not merely predict the weather, they quantify how this weather will effect the performance of vehicles, sensors and weapons in the field. Commanders rarely ask if it will rain or snow — they wish to know whether mountain roads are still passable by Warrior armoured vehicles; how much the performance of night-vision goggles or infrared sights will be degraded and, effectively, how their range of tactical options is constrained by the weather.

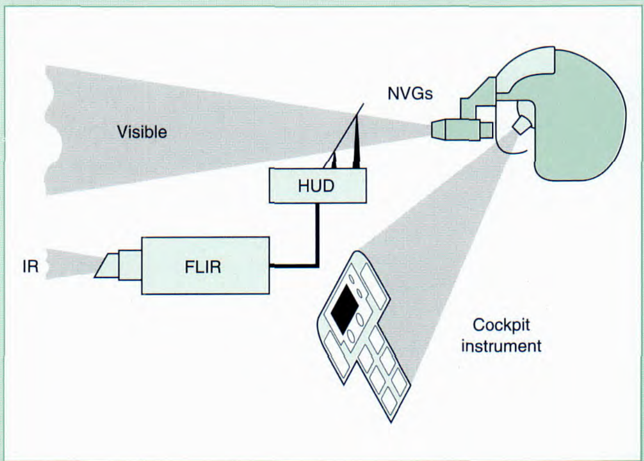


Figure 13. Illustration of the 'Nightbird' set-up.

This article concentrates on the efforts of the DS R&D team to make available Tactical Decision Aids (TDAs) which convert meteorological information into a form which facilitates operational decision making. For completeness, brief mention is also made of the work of other DS staff who ensure that the necessary raw data can be made available to forecasters in the field and that products can be displayed on military systems where they can be integrated with, and weighed against, other factors (such as intelligence data) in the decision making process. Work undertaken by the Division in support of civil emergency planning and response is also described. Other defence-related work concerns the subject of ocean forecasting which is being conducted by the Forecasting Research (FR) Division and this is also discussed

Electro-optics

Electro-optic devices are becoming widely used by the forces as they can give a significantly enhanced capability for night-time operations. There are two types of electro-optic device being used: Night Vision Goggles (NVGs) and Forward Looking InfraRed (FLIR). The use of these systems has been integrated into the 'Nightbird' system, as illustrated in Figure 13, which was developed to meet the operational requirement for night attack by fast jet aircraft. The FLIR imagery is projected onto the pilot's Head-Up Display (HUD) and, by using complementary cockpit lighting, can be viewed whilst wearing NVGs. The FLIR and NVGs operate in different parts of the spectrum and are largely complementary systems since each is affected by environmental conditions in different ways.

NVGs

NVGs are helmet mounted image intensifiers which operate in the red and near infrared region of the electromagnetic spectrum, i.e. 0.6–0.9 μm. Being image intensifiers they are illumination limited and suffer from both too little light (i.e. too little to amplify) and too much light (which can lead to saturation, i.e. to the photomultiplier tubes shutting down). Meteorological factors play an important role in that cloud layers can significantly reduce the amount of moonlight or starlight, e.g. thick frontal cloud can reduce the light level by more than a factor of ten, but can also lead to enhanced levels because of reflected 'cultural' lighting (i.e. that light originating from towns and cities). Predictions of the ambient light level and moon position are currently provided to support the use of NVGs. These can help identify those occasions when NVGs will become ineffective.

The operational night illumination model which is used by the Met. Office treats the effect of cloud rather simply. However, several illumination models developed in the United States incorporate a scheme which allows cloud layers to be modelled in more detail. A limited set of measurements, made by staff in the United Kingdom a few years ago, suggested that the US models tended to overestimate the light level in cloudy conditions by a factor of about 1.5. Equipment is currently being procured to enable further data to be collected to validate these models properly. The equipment will provide radiometric measurements, filtered to match the response of NVGs, in addition to the usual photometric measurements, and will assist in the development of a more-accurate operational model.

FLIR

FLIR systems operate in the 8–12 µm window and respond to the difference in radiance emanating from various objects. This consists of both emitted and reflected long-wave radiation. The thermal contrast between objects is the major component of the scene signature. However, the thermal contrast seen by FLIR is related to, but not the same as, the difference between the actual target and background temperatures. Consequently the performance of FLIR systems is not influenced by ambient light levels, but is affected by thermal contrasts and atmospheric transmission (or visibility) in this region of the spectrum.

Figure 14 shows an example of an image taken directly off the FLIR fitted to the Harrier Nightbird trials aircraft based at the Aeroplane and Armament Experimental Establishment (A&AEE), Boscombe Down. This example, which was taken in 'pitch black' conditions under which NVGs would have ceased to operate, shows how a runway can stand out from its surroundings due to its thermal contrast. Also visible is another aircraft ahead. However, both the thermal signature of the scene and the infrared 'visibility' are affected by various meteorological conditions. Poor thermal contrast can result from thermal crossover around dusk and dawn, thermal washout after rain, and also in strong winds. FLIR systems cannot see through cloud or thick fog, and poor infrared visibility can occur as a consequence of thin fog or mist, precipitation and high absolute humidity.

Although well established models exist for calculating infrared transmission, there are problems in determining the thermal signature. However, various thermal contrast models do exist and there is an active programme to assess these models, both theoretically and against measured data.

A sophisticated Tactical Decision Aid (TDA) has been developed by the USAF which predicts the performance (target acquisition ranges) of FLIR systems given the meteorological conditions, the nature of the target and its background, and the sensor characteristics. Trials of this, the USAF Mk. III IR TDA, have been conducted jointly with the RAF Central Tactics and Trials Organization/Strike Attack Operational

Figure 14. Example of a FLIR image showing an airfield runway and aircraft ahead.

Evaluation Unit at A&AEE, Boscombe Down. The results obtained so far suggest that the model is able to predict thermal crossovers and FLIR 'dead' times, but that the detailed range predictions are not yet sufficiently reliable to be useful operationally with the navigation FLIR system on the Harrier GR7.

Ongoing research and development is necessary in order to realize the full benefit from such TDA models, which have the potential for use with a variety of new infrared systems, e.g. the Thermal Imager And Laser Designator on the Tornado GRl. Future plans are for such TDA predictions to be made available on future military information systems such as the Advanced Mission Planning Aid (AMPA).

Anomalous radio propagation

Meteorological conditions can significantly affect the propagation of radio waves and microwaves, and can often lead to anomalous propagation (anaprop). The dominant mechanism for anaprop is atmospheric refraction, or bending of the radar beam. Abnormal gradients in the vertical profile of the radio refractive index lead to sub-refraction, super-refraction, and in extreme conditions, ducting. Ducting occurs when radio waves become trapped in a shallow quasi-horizontal layer. Such ducting layers can occur both immediately above the surface and as elevated layers.

Sub-refraction usually leads to a degradation in sensor performance whilst super-refraction gives rise to extended propagation ranges. In ducting conditions detection ranges can be significantly extended when both the target and the radar are in the duct, whilst reduced detection ranges can occur for the region above the duct due to the presence of a radar 'hole'.

The current operational TDA for predicting these effects is the US Navy Integrated Refractive Effects Prediction System (IREPS), which is based on ray tracing. Figure 15 illustrates the effect that a duct can have on a radar when it is above, in and below the duct. This shows that the height of the radar relative to the duct is critical in determining the pattern of radar coverage.

Recent research by the Rutherford Appleton Laboratory (RAL) for the Defence Research Agency (DRA), Malvern has shown that a Parabolic Equation Method (PEM) can give much more accurate predictions and provide quantitative information on the propagation. Figure 16 shows an example comparing a prediction from the RAL PEM to one from IREPS for a radar at 20 m height in conditions with a 260 m deep surface-based duct. It is anticipated that DS will replace the current IREPS model with the RAL PEM for providing propagation predictions. RAL have established links with the RN and the US Navy who have also adopted the PEM.

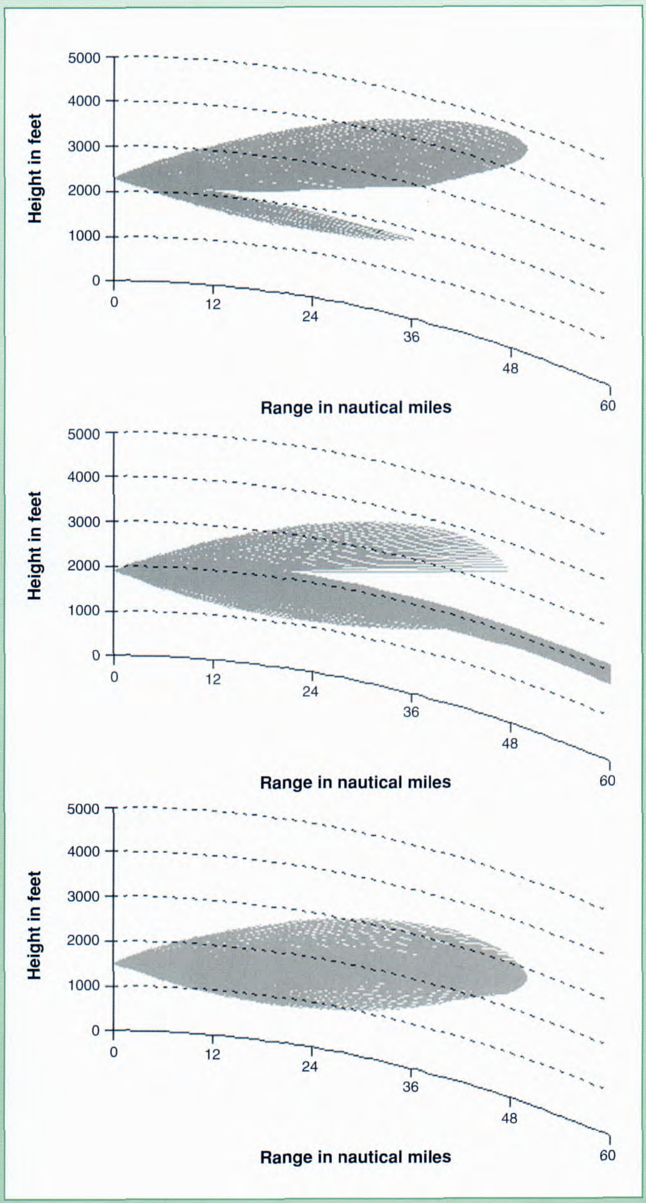


Figure 15. IREPS predicted radar coverage in conditions with a radar duct around 2000 ft for (top) radar above the duct, (middle) radar in the duct, and (bottom) radar beneath the duct.

These models can only give reliable predictions of radar coverage if there are representative profiles of temperature and humidity available. However, these are unlikely to be available at the spatial and temporal resolution required. For this reason attention has turned to the potential of the Met. Office Mesoscale Model for refractivity forecasting. During 1991 an assessment was carried out which showed that, although the Mesoscale Model was capable of predicting some low-level ducting situations, as shown in Figure 17 for example, overall the model profiles were not sufficiently reliable to be useful. The main reason for this was the way that the model was initialized, since upper-air data from radiosondes were not used directly and the vertical profiles were derived from the limited-area model. Consequently the initial profiles were far too smooth and did not contain sufficient detail on any low-level inversions/hydrolapses that were present. However, the new mesoscale unified model (introduced in December 1992) has an initialization scheme in which these data are assimilated directly. This should lead to more vertical detail and better predictions of the refractivity profile and the propagation conditions. An investigation of this is currently under way.

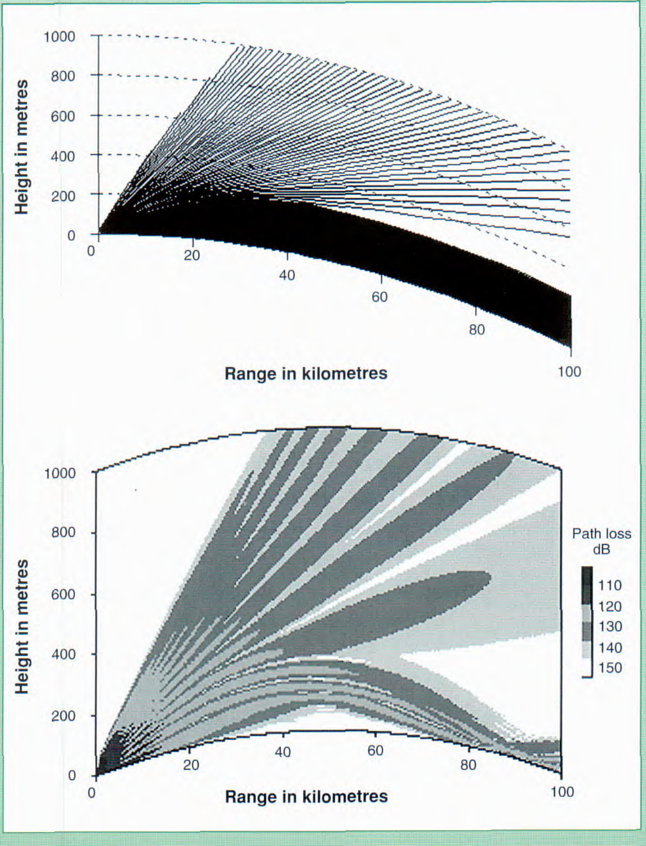


Figure 16. Examples of predictions for an S-Band radar at 20 m height in conditions with a surface-based duct 260 m deep from (top) IREPS, and (bottom) the RAL PEM.

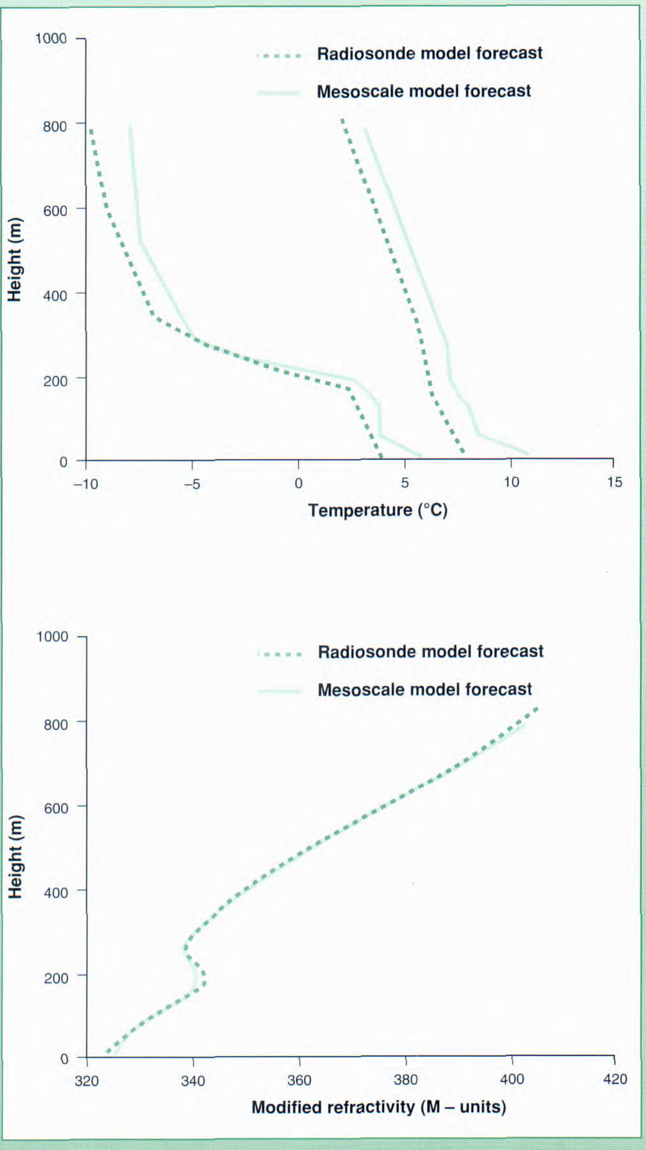


Figure 17. Radiosonde and mesoscale model forecast profiles of (top) temperature and dew-point, and (bottom) modified refractivity for Hemsby at 12 UTC on 8 May 1991.

Noise forecasting

Predicting levels of noise is of growing importance at many ranges in the United Kingdom. Complaints of noise disturbance are becoming more widespread and the ranges are becoming increasingly aware of the need to minimize noise pollution. Over the past ten years or so, noise forecasting has become an important task at various range met. offices and the predictions have been used by the ranges to reduce the level of complaints. However, complaints do still occur, partly because of limitations in the accuracy of the noise forecasts and partly due to the necessity for trials to be completed on schedule.

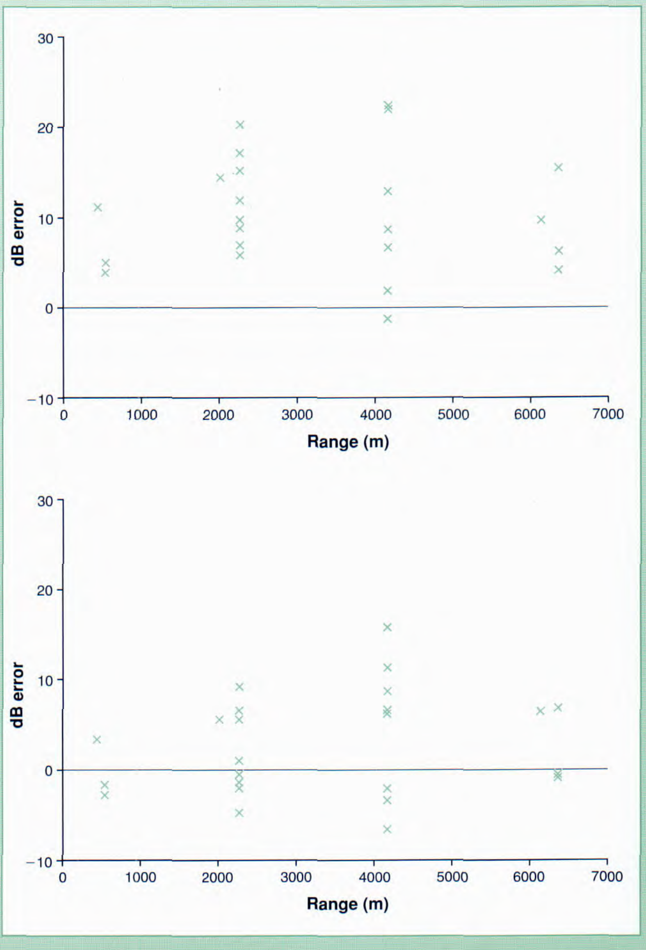


Figure 18. Noise-level prediction errors (dB) for (top) the Larkhill Mk. II, and (bottom) the new acoustic model for the downwind enhancement region from the Shoeburyness trial data.

Since 1987 the Chief Safety Officer, MOD Directorate of Defence Health and Safety, has been sponsoring research into developing better methods for predicting impulsive noise. Much of this work has been undertaken by the Department of Applied Acoustics, University of Salford, in collaboration with the DS Division of the Met. Office. An important aspect of this research programme has been the development of more-sophisticated acoustic models.

During the spring of 1992, a new acoustic model was installed at the range met. office at the Proof and Experimental Establishment (P&EE), Shoeburyness for a validation trial. For the trial, remote monitoring units (RMUs), developed by the University of Salford, were deployed on the range along a 10 km line. These devices were activated by range officers to record noise waveforms from selected firings/explosions. The trial was conducted through to the end of 1992, enabling an extensive database of noise measurements, together with the relevant meteorological data, to be collected. Also over the period, low-level (i.e. up to 1 km) wind data from a Doppler sodar and from the Met. Office Mesoscale Model were collected and their applicability to noise forecasting assessed.

This evaluation showed that the accuracy of winds derived from the on-site Vaisala PC-Cora radiosonde system were more accurate above 150 m than those from the sodar (e.g. at 300 m the 1 SD error of the PC-Cora winds was 1.4 m s^{-1} and 16°, whilst for the sodar it was 1.9 m s^{-1} and 23°). The forecast winds at 300 m from the Mesoscale Model, although less accurate (2.0 m s^{-1} and 31°) than those measured, looked sufficiently reliable to allow useful acoustic forecasts to be made.

Figure 18 shows an example of the noise measurements and model predictions obtained in the sound enhancement zone during the trial. The enhancement zone is that region, which occurs downwind, where high noise levels tend to occur. The results, where each point refers to the mean of an ensemble of similar firings, show that the new model had a mean prediction error of 2.6±5.5 dB, whilst that from the old Larkhill Mk. II model was 10.4±6.2 dB, suggesting that the new model is capable of giving a marked improvement in prediction accuracy. Improved parametrizations are also being developed, which should result in more-accurate predictions in the upwind sound shadow region.

The new model forms part of a complete prediction package including meteorological input and editing facilities, acoustic calculations and graphical displays and output. The package is designed to run on a 386-based PC (or better) and is modular in structure so that improvements to both the meteorological data processing and acoustic calculations can be incorporated relatively easily. Future upgrades are likely to incorporate a 'Parabolic Equation' model for the acoustic calculations, which has the potential to handle spatially varying meteorology, turbulence, changing surface characteristics and undulating topography.

Ocean forecasting

The ability to exploit the underwater environment tactically is important for the Royal Navy (RN) in submarine and antisubmarine operations. The present lack of detailed knowledge of the underwater environment is a factor limiting the effective use of sonar equipment since sound paths in the ocean are strongly modified by the temperature and salinity structure. Better knowledge of the ocean state offers the opportunity to choose tactics which can use the ocean to advantage, either to enable detection or to avoid counter detection.

The ocean, like the atmosphere, changes on a number of time-scales. Some of the changes are driven directly by atmospheric systems which pass over the ocean, others are generated internally. The Forecasting Ocean Atmosphere Model (FOAM) is being developed by the Forecasting Research (FR) Division for the RN to provide 3-dimensional predictions of the ocean structure. At the heart of FOAM will be a numerical model of the ocean. This will be based on an established ocean model which has been used for studying climate change. Although the basic form of the model has been in use for many years, the model is under constant development as the representations of the physics of the ocean are improved while retaining the proven reliability of the underlying computer code.

A successful forecast system relies on much more than the forecast model itself. Observations are essential to provide the best estimate (analysis) of the ocean from which the forecasts can start. Existing systems at the Met. Office are being extended to allow full processing of oceanographic observations which are received in real time to allow them to be quality controlled and passed to the forecast system. A major part of the development of FOAM is to produce a method of combining observations with model fields to produce the best analyses. Techniques which have proven successful for forecasting the weather are being adapted for use in ocean models.

Forecasts are of little use to the end user unless they are able to receive them in a timely fashion. The Met. Office already has effective methods of delivering large quantities of numerical data to users, and these will be extended to deliver products from the FOAM system. The Defence Research Agency (DRA) is working closely with the Met. Office to develop tools which will allow ocean forecasters to interpret the model output in tactically significant terms and to perform the vital task of transmitting the data to the end user — either at a forecast centre on shore or in a ship at sea.

Other models are already being used to help the ocean forecaster. The Met. Office uses models of surface waves to provide forecasts of wind-sea and swell and a mixed layer model of the north-east Atlantic, developed jointly by the Met. Office and the DRA, is undergoing trials by the RN.

Early designs for FOAM required it to produce forecasts for the Atlantic and Arctic Oceans, but the needs of the Navy are changing, and the area proposed for FOAM is changing with them. Emerging from discussions is a flexible configuration for the system in which a coarse-resolution, but eddy-resolving, model of a large area (possibly global) is run routinely, with much-higher-resolution models of limited areas of special interest being run as necessary. This would achieve a compromise between the need for efficiency in the use of computing resources and the requirement to provide detailed information for any operational area. If feasible, this concept would allow the sub-models to be prepared with a lead time of a few weeks in response to changing needs. Some areas of permanent interest may have high-resolution models running continuously. A prototype for FOAM is expected to become operational in 1997, but this time-scale depends on the upgrade programme for the replacement supercomputer at the Met. Office.

Operational Decision Aids

Predicting many local weather details is currently well beyond the capability of even mesoscale NWP models. For this reason DS are introducing a suite of Operational Decision Aids (ODAs). These are models, designed to be run locally by the outstation forecaster, for predicting critical weather parameters. Over the past year or so, a number of ODAs have been issued for outstation use. These include models to predict runway icing conditions, low-level wind flow (specifically for the Porton range), soil moisture content/deficit (to aid trafficability forecasts for the Army) and dew deposition on laser targets.

Forecasting low cloud and fog is critical at many military airfields, since such conditions can severely curtail flying activities. A PC-based Air Mass Transformation (AMT) model is currently on trial at a number of key DS outstations. This model has been developed for DS by Atmospheric Processes Research (APR) Division and should provide a valuable tool in assisting forecasters to predict such conditions. The AMT model is discussed in more detail in the APR section. A possible future application of an AMT model may be to predict range-dependent profiles for input to the RAL PEM for radio propagation prediction.

Nuclear Emergency Response

The nuclear accident at Chernobyl in the spring of 1986 led to a Government enquiry into the best way of dealing with such incidents. This resulted, in January 1988, in the publishing of the National Response Plan (NRP) to deal with the consequences for the United Kingdom of overseas nuclear incidents. The main component of the NRP is the nuclear emergency response system and national gamma radiation monitoring network known as RIMNET (Radioactive Incident Monitoring NETwork). A number of Government Departments and Agencies are involved in the NRP. These include the Ministry of Agriculture, Fisheries and Food, the National Radiological Protection Board, the Department of Trade and Industry (DTI) and the Met. Office. The Department of the Environment (DOE) is the lead authority for overseas incidents, whilst the DTI would assume responsibility for a domestic incident.

The Met. Office has three roles to play in its RIMNET involvement:

1. At a network of evenly distributed offices, it is host to gamma radiation sensors (there are 92 sites in all, 85 at Met. Office sites and 7 at other MOD establishments). These are automatically polled once an hour (or more frequently should the need arise), the readings being stored on a Central Database Facility at the DOE.

2. If a radioactive cloud moves into an area of rainfall, radioactivity at ground level is likely to be increased due to 'washout'. Consequently, there are 41 met. offices where rainwater collectors can be activated when required to enable a measurement of wet deposition to be made. The wet-deposition readings, as analysed by designated laboratories, would then be used to ascertain whether there are any areas where livestock and foodstuffs, etc. are in danger of contamination.

3. In the event of an overseas nuclear accident threatening the United Kingdom, an emergency cell, the Technical Co-ordination Centre (TCC) would be opened at the DOE and manned by representatives from various Government Departments, including the Met. Office. All relevant information (including data from the 92 gamma radiation monitors, and any other supplementary data supplied by approved bodies) would be collated at the TCC and used to brief Government ministers, the Emergency Services, the Press, etc. at a dedicated Information Centre.

One of the main roles of the Met. Office representative at the TCC would be to brief upon the output from the Met. Office Nuclear Accident ModEl (NAME). This program is run on the Met. Office central computer and provides detailed plume analysis, its expected movement, airborne pollution concentrations and wet and dry deposition up to six days ahead, and if necessary, hindcasts for up to ten days as well. (Further technical details of NAME were given in last year's Review on page 41.) NAME would be run on a regular basis, up to twice daily, and its output transmitted to the TCC along a dedicated line. The predictions from NAME, that would be available to the TCC meteorological representative, who would also have access to a weather radar rainfall display, would enable him to comment upon possible 'hot spots' due to washout.

Information technology

Defence Services aim to provide ever increasing value for money to the MOD customer, whether Navy, Army, Air Force or one of the support organizations. The final installations of the Outstation Display System (ODS) were achieved in 1992, bringing all DS forecasting stations to a common standard of technology and a leap forward in quality and timely service to the customer. The improvement does not stop here though; it is planned to connect ODS to the Outstation Communications Processor (OCP) and the Weather Information Network (WIN) over the next 1 to 5 years. These steps will allow an even greater variety of raw data and products to be made available to forecasters. These data will, in turn, be used by the forecasters at their workstations to provide standard forecasts and increasingly specialized mission-critical and mission-specific advice to the defence customer.

The customer is increasingly investing in information systems, for operations, administration and planning. It is on these systems that the customer wishes to interact with meteorological data, so it is to these systems that the forecaster must deliver his information. To meet this requirement, Defence Services has set itself the objective of delivering the best product on the appropriate system in time to allow military staffs to make the right decision. WIN, as a system operating on MOD X.400 networks, will allow this objective to be met, with small, medium and large messages, both textual and graphical, being passed to the appropriate user workstation.

For the RAF, the Automated Low Flying Enquiry and Notification System (ALFENS) is expected to deliver meteorological data and forecasts to the user. Phase I of ALFENS should become operational in late 1994, and give the facility of displaying centrally generated, but manually input, alphanumeric data on the system. This process will be automated shortly after Phase I is operational. Phase II will follow several years later, bringing full text and graphics functionality, and will allow the forecaster to input dedicated products created on ODS via the OCP.

The enhanced services provided by WIN and ODS will also be required by the Armed Forces on deployed operations anywhere in the world. Planning has started on the development of a mobile version of ODS which will be supported by secure military satellite communications. This project will, for the first time, bring modern Information Technology to the front-line meteorologist, together with the ability to connect into secure military mission planning systems in the field.

Commercial Services

Science and technology in Commercial Services

Commercial Services Division builds on the Office's technology and its core services to generate revenue and to contribute to the cost of running the Office. This process involves developing the Office's products and services to meet the needs of commercial customers. This short review concentrates on a limited number of areas and describes how, using its scientific and technical skills (and where appropriate those of other organizations), Commercial Services tries to respond to customer's needs.

Use of new technology

Changes in technology have to be harnessed to allow Commercial Services to do its job more efficiently. At the same time customers are becoming more sophisticated in their use of technology and are expecting the Met. Office, as an information provider, to interface to their systems. The following sections show how new technology is being used to satisfy these demands.

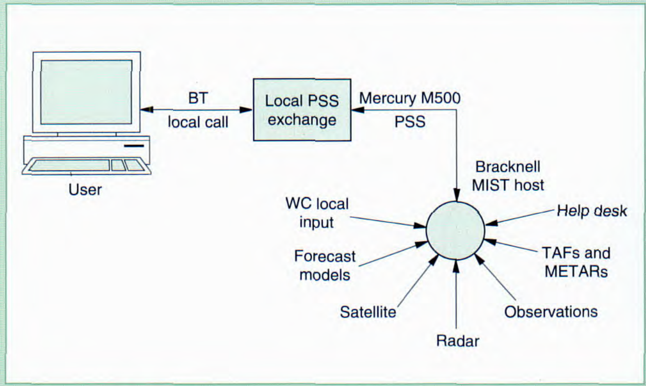


Figure 19. Databases accessible to a MIST user.

The Weather Centres are the regional sites for the production and distribution of information. At present, this is accomplished by a variety of unconnected special-purpose computer systems and data links. An enhanced system, OPUS, based on a network of PCs and Apple Macs, is planned for installation at all Weather Centres over the next two years. Work over the past year has concentrated on demonstrating the feasibility of the scheme and setting up a test system in Bracknell. The aims of OPUS are to integrate the present facilities; automate as many of them as possible; enable the free interchange of data within and between the Weather Centres and Bracknell; present a standard user interface to the operators; and provide a unified method of external data communications.

At the same time, the opportunity will be taken to retire the obsolescent message-preparation system. OPUS will also increase productivity and enable better connectivity to customers' systems.

Many users of meteorological information have access to PCs and quite logically expect the information to be available to them. Last year's Technical and Scientific Review documents described the MIST system, developed by the Systems Development Branch of the Office to serve the needs of Defence Services. Unfortunately this system was tied to the use of internal communications links and therefore inappropriate for use in a commercial environment. Recognizing the commercial potential in such a system the Office, in collaboration with the Earth Observation and Science Division of British Aerospace, undertook to develop a variant of MIST that used the ordinary public switched telephone network. Using this everyday technology meteorological data can be made available at modest cost to anyone with a PC and modem. British Aerospace is also contracted to meet the needs of Defence Services and the Civil Aviation Authority for offshore helicopter operations from within the same development activity, thereby ensuring common software and reduced maintenance costs. Figure 19 shows how a dial-up user accesses and interrogates the database of products and information. Essentially users just download, and therefore pay, for the information required. The dial-up system has proved quite resilient and flexible. We have already had one customer dialling into the system, via INMARSAT, from a moving barge in the North Sea. Other modes of access are also possible. The customer can subscribe to a leased line, a comparatively high-cost option for the user who demands large volumes of up-to-date data. A variant of the MIST system suitable for use in public areas has been demonstrated. In this public display variant the MIST HOST dials the display terminal and downloads updated information at regular intervals. It is hoped to set up a satellite broadcast variant during the coming year.

TV has particular requirements and GETMET has been designed to meet these. It is a PC-based weather graphics system with a high-speed dial-up link (ISDN 64 Kbits/sec) to Bracknell. Data and products generated on the Office's mainframe computers are downloaded onto GETMET where specialized software and hardware are used to generate TV compatible formats, or to transfer the information to even more specialized production equipment. The processing abilities on GETMET enable products to be customized. This includes processes such as the selection of geographical area of coverage and the generation of pseudo 3-D satellite pictures. The first systems have just been installed at International Weather Productions, a Met. Office Business Unit supplying these needs.

The range of dial-up fax services has expanded over the past year. These are premium-rate dial-up services accessible by almost anyone with a fax machine. The information resides on a specialist voice and fax processing computer provided by Vodata Ltd (part of the Vodaphone Group) and resident at one of their digital exchanges. Generator and battery power supplies are provided and, should the main system fail or be overloaded, calls are routed to information held on a duplicate computer. The products are updated by simple fax transmission from either ARTIFAX in Bracknell or direct from Weather Centres. New products include satellite images.

Telephone services are being enhanced to complement these new fax products. Coastal weather observations are collected and sent to Telephone Information Services by a PSS link. Callers to Marinecall can select an option of hearing these reports which are presented in a concatenated speech bulletin — words and phrases linked together based on the underlying coded observational data.

Specialist forecasting services

Pollution

It was against the background of an increasing awareness of environmental issues that the Office and Warren Spring Laboratory, under contract from the Department of Environment, collaborated in setting up a semi-operational scheme for forecasting pollutant concentrations at a number of sites throughout the UK. Warren Spring Laboratory provides the pollutant emission concentrations on a regular grid, and a simple ozone transport and photochemical model. The Met. Office developed a simple 'box-model' for estimating concentrations of NOx and sulphur dioxide. Both of these models require forecast meteorological parameters as input. The ozone model requires information on where a parcel of air, forecast to be at a given location at a given time, has been in the preceding 120 hours. This type of data is readily provided by the Met. Office's 3-D trajectory model. All these processes have been integrated and pollutant concentration forecasts for the following day are produced by 0600 UTC and the results forwarded automatically to computers at Warren Spring Laboratory for checking and onward distribution.

OpenRoad

OpenRoad is a major service both in terms of Met. Office resources involved and the revenue it generates. The objective is to provide cooperating Local Highway Authorities with guidance on whether to salt and grit the roads under their jurisdiction during periods of cold weather. This service is provided by Weather Centre staff who produce forecasts on a PC, using a one-dimensional model of the road, its thermal characteristics and the overlying atmosphere. The Weather Centre staff input forecasts of cloud type and amount, screen temperature, dew-point and wind speed for specific sites into a PC. Some Weather Centres have 30 to 40 such sites spread across large meteorologically inhomogeneous areas. Additional information such as the actual road surface temperatures are input semi-automatically and then the forecaster runs the road surface temperature forecast model. The results, consisting of a time sequence of site-specific road surface temperatures and road states, are then transmitted via a Bureau Service to the cooperating Local Authorities. It is a sophisticated process that is undergoing continual modification and improvement.

This year has seen an attempt to provide first-guess forecast meteorological input from the Unified version of the mesoscale model and to make this input available on a forecaster's PC. The forecaster then checks the inputs, and amends them if necessary, before running the model. It is hoped that this process will save forecaster time without degrading overall performance.

Offshore

The Offshore Forecasting Unit at Aberdeen Weather Centre provides forecast services to the oil and gas industries. The Unit is often called upon to provide a forecaster 'on-site' for the critical phases of an operation. A common requirement is to have a forecaster offshore during the installation programme of a new field. On-site support can begin at the fabrication yard prior to the float-out of a new jacket, and continue in the North Sea during the launch and subsequent deck fitting. It is now common for platform decks to be fully constructed onshore, towed out on a barge, and then lifted onto the recently deployed jacket. Lifts of over 10 000 tons are becoming more frequent. These are carried out by gigantic crane barges. This delicate and extremely expensive operation is very weather sensitive. Spiralling costs set against a stagnant crude oil price are forcing support companies to work out of season. Under such circumstances time and opportunity are at a premium. The need for 'state-of-the-art' weather forecasts is crucial to the success of these operations. A Met. Office forecaster offshore has access to a wide variety of data. The more traditional methods of receiving facsimile charts and observations by radio are still used but have become secondary to the acquisition of model output. Atmospheric and wave model output are supplied direct to a forecaster by tele-fax and teleprinter and are fine-tuned to provide detailed site-specific forecasts. More recently the MIST system has been successfully deployed offshore to download model data via INMARSAT. During the last year full spectral output from the Limited Area Wave Model has become available and a study to integrate this with barge response models is now under way. The new outputs include one-dimensional wave spectra which show how wave energy varies with frequency and how it develops in time. Figure 20 shows a two-dimensional wave spectrum. This gives the directional as well as the frequency dependence of the wave energy. The tracking of long-period swells is crucial to barge operations where resonance can induce inordinate movement of the vessel. The Offshore Forecast Unit is a good example of a specialist unit which draws on and integrates the skills of several Office Divisions. This cohesive approach has been the mainstay of the Office's success and dialogue continues with modellers, technicians and administrators to continue evolution of the service. HEEREMAC, a Dutch company and world leader in offshore installation work, are major users of the Office's services and are currently discussing the provision of meteorological services worldwide. The Office earned much praise during recent installation projects including Piper Bravo, Lomond and Everest.

The work of the Science Support and New Product Development Groups

A Science Support Group was set up in 1992 to help develop Commercial Services activities. The section is concerned with the science of new services but may also be involved in applied research carried out under contract or the handling of the more unusual enquiries. Examples follow which illustrate the variety of work that has been undertaken.

A comprehensive analysis of wind data (hourly mean speeds, one-minute mean speeds and instantaneous gusts) from a number of sites has shown that the ratio of 1-minute speeds to hourly mean speed largely agreed with previous work, but that there was a geographic variation which was connected in a quantifiable way to the local surface roughness. This type of information is useful to the building industry particularly for design purposes.

A contract for British Rail (Regional Railways) investigated the weather-related factors involved in the deposition of leaves on tracks and the disruption it causes. The analysis of track failures showed that strong winds were the major factor. However, calm days with night frost or small amounts of rain in the previous week could enhance the effect of the wind.

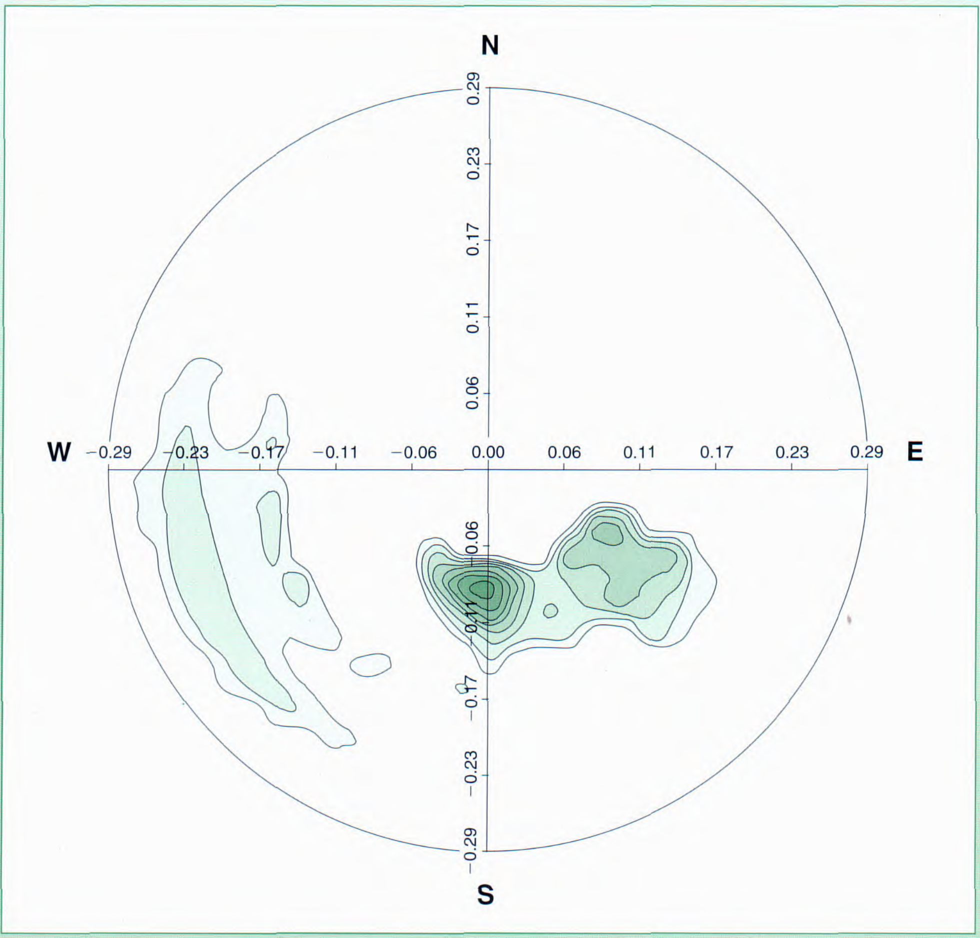


Figure 20. Two–dimensional wave spectrum example.

An exercise is currently underway to improve the Met. Office Rainfall and Evaporation Calculation System (MORECS). The model has been used in its present form since 1981, but developments since then in computing and agricultural science will allow changes to be made. For example the present model does not use hourly weather data and in some instances night-time conditions are derived from what happens during the day. The various crop models and soil information are at present rather basic and will be enhanced by using temperature sum models of crop growth and real soils data.

Services to the NESS (North European Storm Study) Group continued, with a major reorganization of the 25-year hindcast archive to enable data to be made available to users more efficiently. Three severe storms which have occurred since the end of the main study, and which are of interest because they caused considerable disruption to Offshore operations, were analysed to generate wind fields for input to the NESS wave and surge models.

The New Product Development Group provides the immediate technical support to Commercial Services and has been involved in many of the activities already listed. One innovative area under investigation in the past year has been the production of text automatically from numerical model output. In the cases being considered this involves taking one or more time sequences of numbers and sensibly grouping the data thereby identifying significant changes. These time-merged data are then put into a natural language processing system to generate the text. These processes, though easily stated, are difficult to implement. The work being undertaken is building upon the scheme developed by the Canadian Met. Service and the Department of Linguistics at the University of Montreal. Results obtained to date are very encouraging and it is likely that time critical products generated using this technique will appear in the coming year.

Forecasting Research

Overview

The Forecasting Research Division's task is to improve the various forecasting systems used by the Office. The main part of the work is concerned with improving numerical weather prediction on all space- and time-scales from global forecasts for a month ahead to UK mesoscale forecasts for a few hours ahead. Numerical weather prediction has to be supplemented by simpler techniques for very-small-scale and very-short-range forecasts, which have to be based more closely on direct observations.

Improvements in numerical weather prediction require the ability to use an increasing variety of new types of observation, and to extract the maximum possible information from existing observations. The cost of observations is very high, and it is proving difficult to maintain even the existing observing network. A key element in making progress is to use the forecast model to construct a best fit to observations made at different times. The model is also used to help interpret observations not directly related to model variables, such as satellite radiances. A major future development will be to use the model within a more advanced method of data assimilation which will construct a four-dimensional space–time best fit to the observations. This should allow much more information to be deduced from data which only measures a part of the atmospheric structure, for example, satellite measurements of surface winds over the sea and aircraft data measured at flight levels.

The numerical model used in all the Office's atmospheric forecast systems is the 'Unified' model introduced operationally in June 1991. A major task of the Division's work is the improvement of the model. This work is shared with the Climate Research Division. The use of the model on many space- and time-scales has proved very fruitful in identifying parts of the model which need improvement. A number of specific examples appear in this Review. Forecasts of sea state are provided from a separate wave model which is driven by the atmospheric model.

There are requirements for very-short-range high-resolution forecasts which it is not practicable to meet solely by numerical weather prediction. In the past, a number of separate stand-alone forecasting systems, such as FRONTIERS, have been developed to meet this need. The Nimrod project, described below, is intended to integrate these systems in a way which makes them easy to maintain and simpler for the forecasters to use.

It is also necessary to provide forecasting aids which can be used directly by the forecaster at a remote location. These are developed in the Atmospheric Processes Division, and an example, the 'air-mass transformation model' is described below.

The Division also carries out a number of major projects for individual customers. An ocean forecasting system is being developed for the Navy (see the Defence Initiatives section). This will involve assimilation of real-time data and making predictions of the upper ocean structure. A forecasting system for the immediate neighbourhood of major airports is being developed under contract to EUROCONTROL. This will use data from aircraft in the stacks and final approach paths. Work in evaluating the potential impact of new types of satellite instrument and of new types of satellite-derived products has recently been carried under contract to ESA and EUMETSAT.

Unified Model developments

Revised data assimilation

During the year, the operational data assimilation system has been revised so as to improve the analysis of small-scale features, particularly jet streams. It has been possible to fit aircraft data more accurately in the analysis. The wind analysis in the tropics has also been improved by using more information about horizontal divergence from the observations. Improvements have also been made to the analysis of fast-moving situations. A useful by-product of the changes was a substantial saving in time and cost.

The full package was tested in the parallel operational suite during October 1992. The objective verification showed a useful reduction in r.m.s. scores. We found r.m.s. scores for analysed temperature and wind fields reduced by typically 4%. In the short- and medium-range forecasts the average improvement is 3%. The figure shows the evolution of northern hemisphere 200 hPa r.m.s. vector wind error illustrating the improvement.

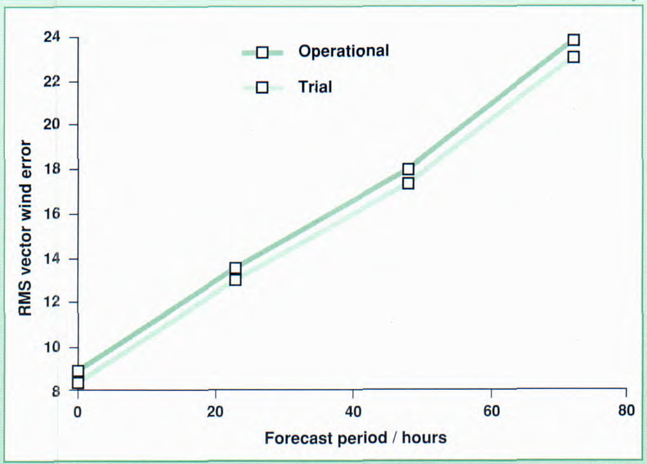


Figure 21. Evolution of the 200 hPa r.m.s. vector wind error against forecast time in hours.

The subjective assessment showed a clear, albeit modest improvement. Over the North Atlantic14 (out of 20) jet maxima were correctly identified as being stronger in the trial 24-hour forecasts. In terms of the forecast quality, 14 (out of 17) features at surface and jet levels over the North Atlantic sector were considered to be better forecast in the trial run.

Introduction of the mesoscale version

After a year of development and testing, a mesoscale version of the Unified Model became operational on 8 December 1992, replacing the previous system for producing short-period forecasts of weather over the British Isles.

The new model has 30 levels and a horizontal resolution of 17 km. It incorporates the latest representations of physical processes available to the Unified Model system, but with some modifications appropriate to its higher resolution.

After a preliminary trial of the new model on cases of 'mesoscale interest', it was found that the old model produced better surface wind forecasts. As a result, the specification of surface roughness in the new model was improved by using the formulation of the old model; after this wind forecasts from the two models were comparable. Roughness lengths in the new model were originally derived solely from a definition of vegetative cover, assumed to be mainly grass for the United Kingdom. The old model had larger roughness lengths which took account of lakes, grass, and fields, and, in mountainous regions, allowed for the effect of sub-grid-scale peaks and valleys. The roughness lengths for heat and moisture in the new model were also reduced relative to those for momentum, to be as in the old model.

The new model under-forecast convection over land. Several enhancements to the formulation of physical processes helped to correct this. These were developed first for use at climate-model resolution. A new version of the boundary-layer scheme was implemented, with a treatment of non-local mixing in which a proportion of the surface-layer heat and moisture fluxes is spread throughout unstable boundary layers. Also introduced was a version of the convection scheme which represents downdraughts, and a new formulation for the evaporation of rain and snow. The parameters specifying the buoyancy of convective parcels and their mass fluxes were revised from the values set for climate resolution, giving further improvements to precipitation forecasts.

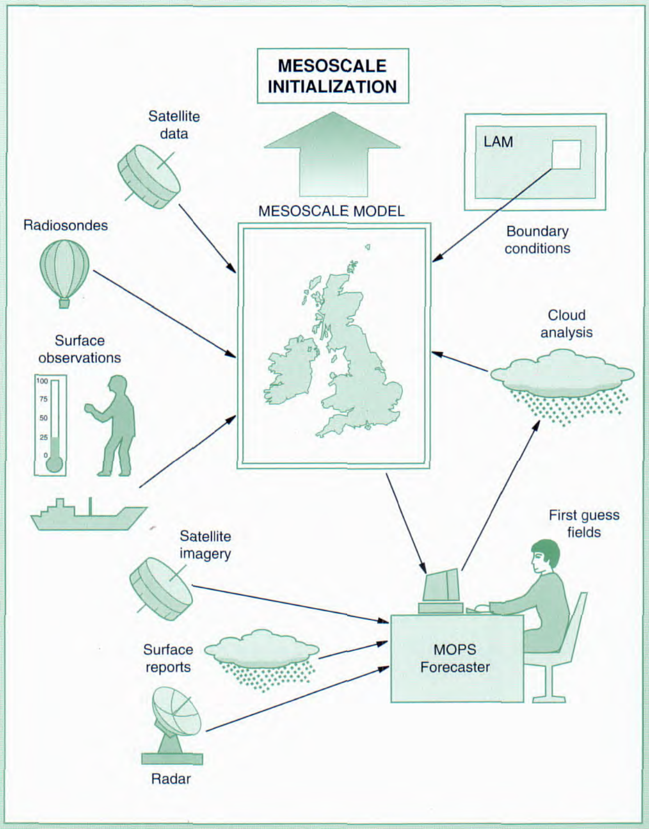


Figure 22. Assimilation scheme for the new mesoscale model.

The new model is initialized by a combination of data and analysis techniques drawn from the previous mesoscale model system, together with assimilation methods already in use for the larger-scale models (see figure).

The main difference between the old and new assimilation techniques lies in the way that data are inserted into the model. In the old system, analysed fields were imposed on the model instantaneously as initial conditions. The lack of consistency between different model fields emerging from this scheme caused a 'shock' to the model, which responded with spurious convection and cloud loss in the first few hours of the forecast. The new model remains closer to dynamical and physical balance, as it is 'nudged' continuously towards the data over two 3-hour cycles of integration forwards in time.

Surface data assimilated by the new model include hourly screen temperatures over land which are not used in the regional version of the Unified Model. The observations are adjusted, prior to analysis, for differences between station and model orographic height; they also supply increments to the model's soil surface temperature as well as to the lower layers of the atmosphere. Tests show that these data improve the accuracy of forecasts of screen temperatures, especially in anticyclonic conditions.

In the Moisture Observation Pre-processing System (MOPS), a 3-D cloud analysis is prepared from data sources illustrated in the figure. This analysis is converted into profiles of relative humidity, at every model grid-point, for assimilation by the model as 'pseudo-radiosondes'. The conversion is consistent with the model's cloud scheme.

Like its forerunner in the old mesoscale system, MOPS is a menu-driven system, operated by the forecaster on an interactive graphics workstation. The forecaster's main priorities are to detect any corrupt satellite imagery and monitor the cloud cover and cloud-top height analyses. Without intervention, these analyses can be grossly in error in situations where, with some straightforward intervention, the greatest benefit can be achieved from the data. For example, in the cloud-top height analysis, a cloud-top temperature derived from satellite imagery is assigned a height based on the model's first-guess temperature profile. In the presence of an inversion inadequately resolved by the model, often associated with stratocumulus sheets, this procedure may produce gross errors if run automatically. The forecaster can easily set a sensible cloud-top height. Research into automatic algorithms to cope with these problems is currently being pursued.

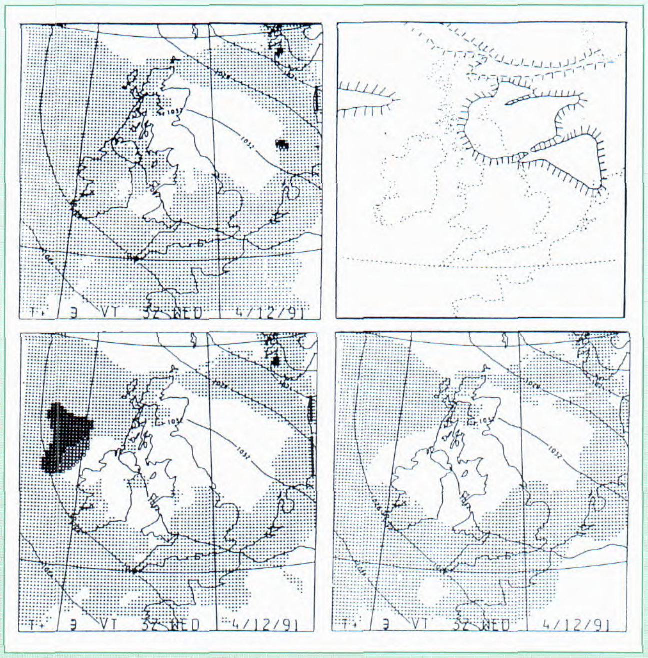


Figure 23.

Top right: *Schematic analysis of cloud edge at 03 UTC, 4 December 1991, based on satellite imagery and surface observations.*

Top Left: *3-hour cloud-cover forecast for the same time from the mesoscale unified model, after assimilation of MOPS cloud data prepared with human intervention.*

Bottom Left: *As top left, but with MOPS data prepared automatically. The light grey tone indicates low cloud; the patch of denser grey tone indicates higher cloud, which in this case is unrealistic.*

Bottom right: *As top left, but after assimilation without MOPS data.*

The figure shows a case where the new model's 3-hour forecast of low stratocumulus cloud benefited significantly from assimilation of MOPS data. The experiment with automatically prepared MOPS data gave worse results than the standard run in which the MOPS data were prepared with intervention to cope with the cloud-top height assignment problem.

In the coming year, effort will be concentrated on improving the new model's skill in forecasting low cloud and fog. With this in mind, a configuration with higher vertical resolution near the surface will be tested and screen-level relative humidity data will be added to the assimilation system. The frequency of daily operational forecast runs may be increased from two to four.

Improving the rainfall forecasts from the regional model

The forecasting of rainfall during the summer is sometimes a severe test of the ability of current models, particularly when large-scale dynamical forcing is weak and convection is more important. Whilst the detailed prediction of the location of showers cannot be expected using the limited-area model with a resolution of 50 km, it can indicate the likelihood and probable intensity of showers. The prediction of showers by the limited-area model has been improved by the inclusion of a representation of the downdraughts which occur in deep convective clouds. The downdraughts are initiated by evaporation of precipitation. Previously the evaporation of cloud condensate was restricted to the region below cloud base. The treatment of the evaporation has been revised in the light of observations which show that snow generally evaporates more readily than rain. The turbulent mixing within the unstable boundary layer has also been revised, allowing mixing to a greater depth in a model time-step; this results in less intermittent convection occurring at individual grid points. The guidance on the distribution and occurrence of showers can be substantially better with the new scheme, as shown in the example; in this case predicting the showers over England and Scotland that were completely absent from the forecast made without the inclusion of downdraughts. A further improvement is a better indication of frozen precipitation (hail and graupel) with cold unstable air masses.

Improvements to the global forecasts

The following changes have been made to the global model since its operational introduction in June 1991. Limited vertical diffusion is now applied to the winds in the tropics between 500 and 150 hPa to remove small-scale inertial noise that occasionally develops. Revised long-wave transmissivities based on ECMWF data are used for the clear air which reduces the cooling at upper tropospheric levels and the model's systematic cold bias. The top model level was lowered from 2.5 hPa to 4.6 hPa to avoid the stratopause and so reduce the possibility of model instability due to excessive winds of the polar-night jet. The horizontal diffusion of moisture was revised from second order to fourth order, which is more scale selective. The tendency of the model atmosphere to be too moist was much reduced and the upper tropospheric cold bias was also improved, as illustrated in figure 25.

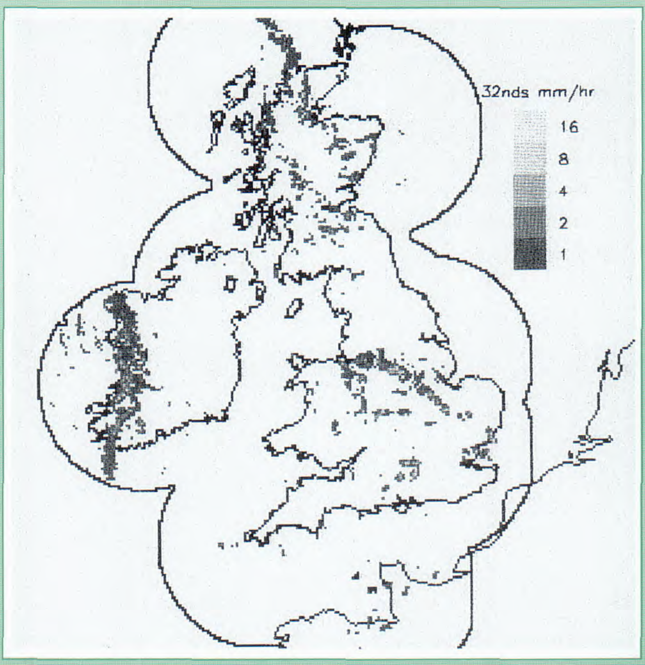
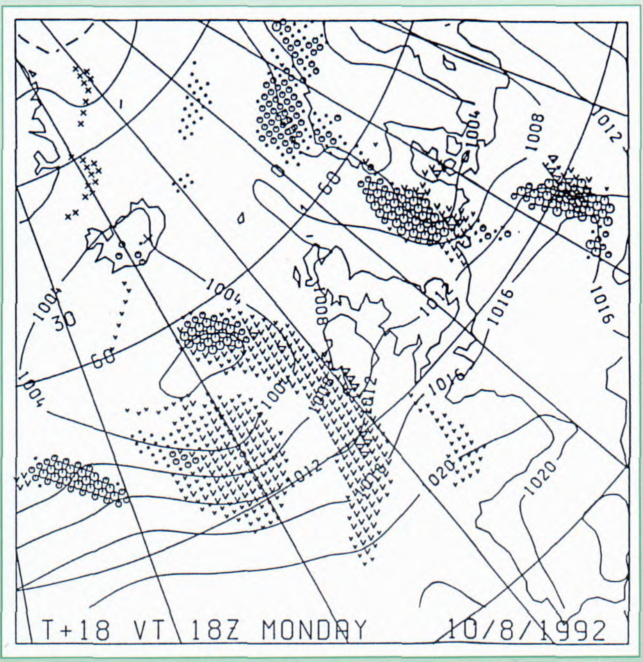
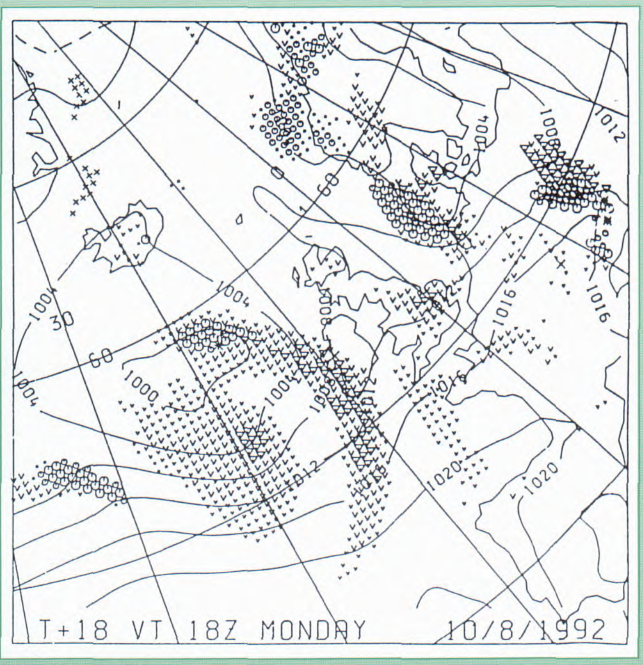


Figure 24. (a) Composite radar rainfall for 1800 UTC on 10 August 1992.



(b) 18-hour operational regional model forecast for same time.



(c) 18-hour forecast with improved physics as described in text.

Improving the model dynamics

The model includes a grid-scale filter to eliminate errors due to the finite difference representation of the equations. This tends to mix quantities, such as moisture, along the model's coordinate surfaces. In practice, the specific humidity is strongly stratified, and mixing along coordinate surfaces parallel to model orography is unrealistic. The effect of modifying the grid-scale filter to operate horizontally is illustrated. The cross-section in figure 26 is from central Asia through the Himalayas to southern India. On the northern side of the mountains the moisture is more correctly confined to lower levels. There is a similar, but smaller, confinement of the moistest air at the southern end of the cross section.

Making the Unified Model portable

The Unified Model and its associated software system have been modified in order to make the code easy to port to any Unix environment supporting FORTRAN 77 and ANSI C. This has been achieved without impacting on the efficiency of the model on the Cray Y-MP8 when it is used for operational numerical weather prediction or climate modelling. It is planned that the portable nature of the model will be maintained from now on.

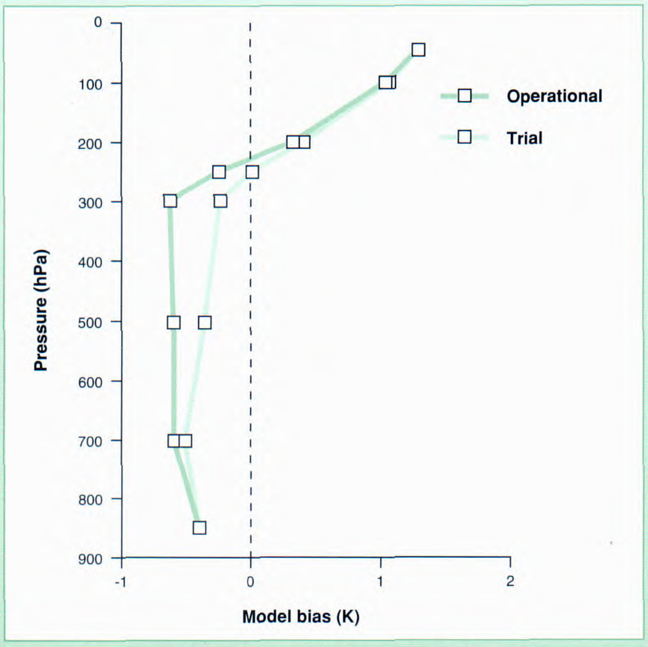
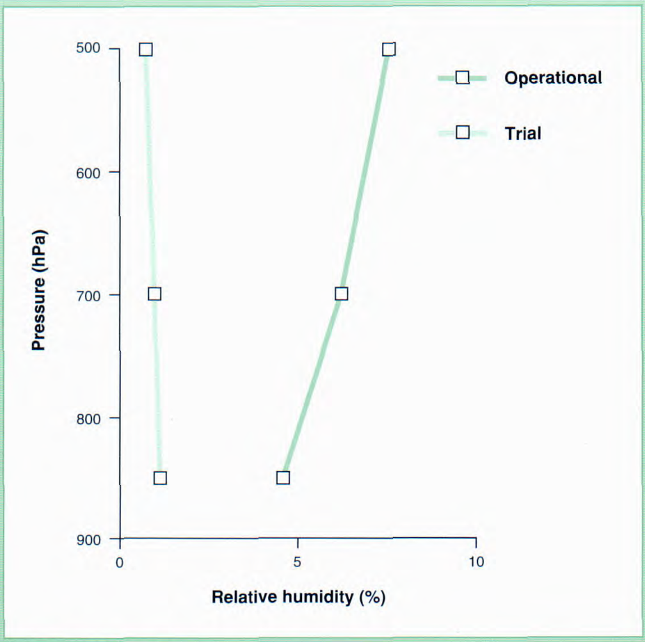


Figure 25. Vertical sections of global model bias in 72-hour forecasts, averaged over the northern hemisphere: (a) temperature (K)



(b) relative humidity (%).

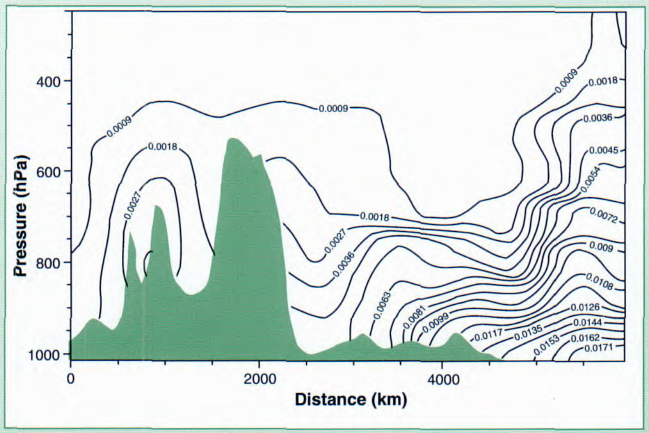


Figure 26. Cross-section of specific humidity from a 5-day prediction with the global forecast model.

This achievement now opens up a range of possibilities for the further use and development of the model.

(i) It is planned that data and software will be made available to collaborating institutes through a Met. Office computer node freely attached to national and international networks. New releases of the model will also be made available, once they have been accepted by internal users.

(ii) The portable nature of the model will enable easy transfer of the code to other large-scale scientific computers. The current code structure can then be tested and developed for efficient running on massively parallel computer systems. This should allow the code to evolve gradually into a more parallel form, making the transition to the next computer system reasonably transparent.

(iii) Of particular interest is the ability to run the model on workstations. This may represent a cost-effective way of developing and running low-resolution versions of the model in the future.

The original design of the model recognized the need for portability. Most occurrences of Cray specific code were identified and alternative code provided in standard FORTRAN via a software switch: nevertheless, substantial changes were required.

(i) Random access input–output is used by the model. This is a non-standard feature of Cray FORTRAN. Alternative C routines have been written to provide the same functions.

(ii) Source code management relies on a Cray-specific utility called UPDATE. When used on non-Cray systems, this has been replaced by an equivalent facility which has been developed in-house.

(iii) Memory management within the model uses a FORTRAN 77 extension to allocate and free workspace automatically. This feature is supported by FORTRAN 90, but is not yet widely available on other computer systems, so a utility was written to identify the use of dynamic memory within the model, and automatically replace the code by a call to standard C memory allocation routines.

(iv) The model control scripts were altered so as to make those sections containing Cray specific commands, such as the compilation step, more modular. Alternative, machine-specific modules may now be substituted easily.

(v) A simple, but rudimentary, substitute for the User Interface has been provided, which relies on the editing of a text file. The User Interface allows scientists to design and set up new experiments easily. It corresponds to over 200 menu-driven panels and runs on the Hitachi Data Systems front-end to the Cray Y-MP8s. The conversion of the User Interface into a fully portable form will require further substantial effort.

Observation developments

New observations

Greater emphasis is being placed on researching how to use new types of observations within the numerical weather prediction models (NWP). Over the years the Met. Office has made a great contribution to the science behind the use of satellite sounding data. The approach employed is to use the forecast model fields both as a background atmospheric state, and as a first guess in a radiative transfer model of the atmosphere. Solutions to the satellite-observed radiances are found by iteration until, with a knowledge of the observation and background errors, the most probable atmospheric state is determined. This approach has been expanded during the year to cover, not only temperature and humidity profiles, but also information on cloud, ozone and even volcanic aerosols. The technique shows even greater promise for the future, with access to larger volumes of satellite data, of increasing spectral resolution, spanning visible, infrared and microwave regions of the spectrum.

There is also a need to develop other processing systems for specific instruments or variables. Work continued in evaluating and preparing for operational assimilation of data from the European Remote sensing satellite ERS-1, in particular the scatterometer, the radar altimeter and the Along Track Scanning Radiometer.

Precipitation, an important variable for both forecast and climate models, is one of the most difficult to observe, particularly over the oceans. Satellite platforms offer the potential to observe globally but there are many problems in attempting to make accurate estimates with present day sensors; many of the techniques observe a variable (such as cloud-top temperature) which is only loosely linked to precipitation, and there are problems associated with sampling features that vary rapidly in space and time. Within the Global Precipitation Climatology Project (GPCP), a number of algorithm intercomparison projects (AIPs) have taken place. The second one of these was organized by the Met. Office, and covered northern Europe for a two-month period.

Satellite imagery data from this AIP have been collected and distributed to 22 international groups who are using their algorithms to estimate precipitation. The current problem being tackled involves establishing a 'ground truth' against which these estimates may be assessed. Over much of Europe, radar and rain-gauge data are available, but there are a number of problems in their use.

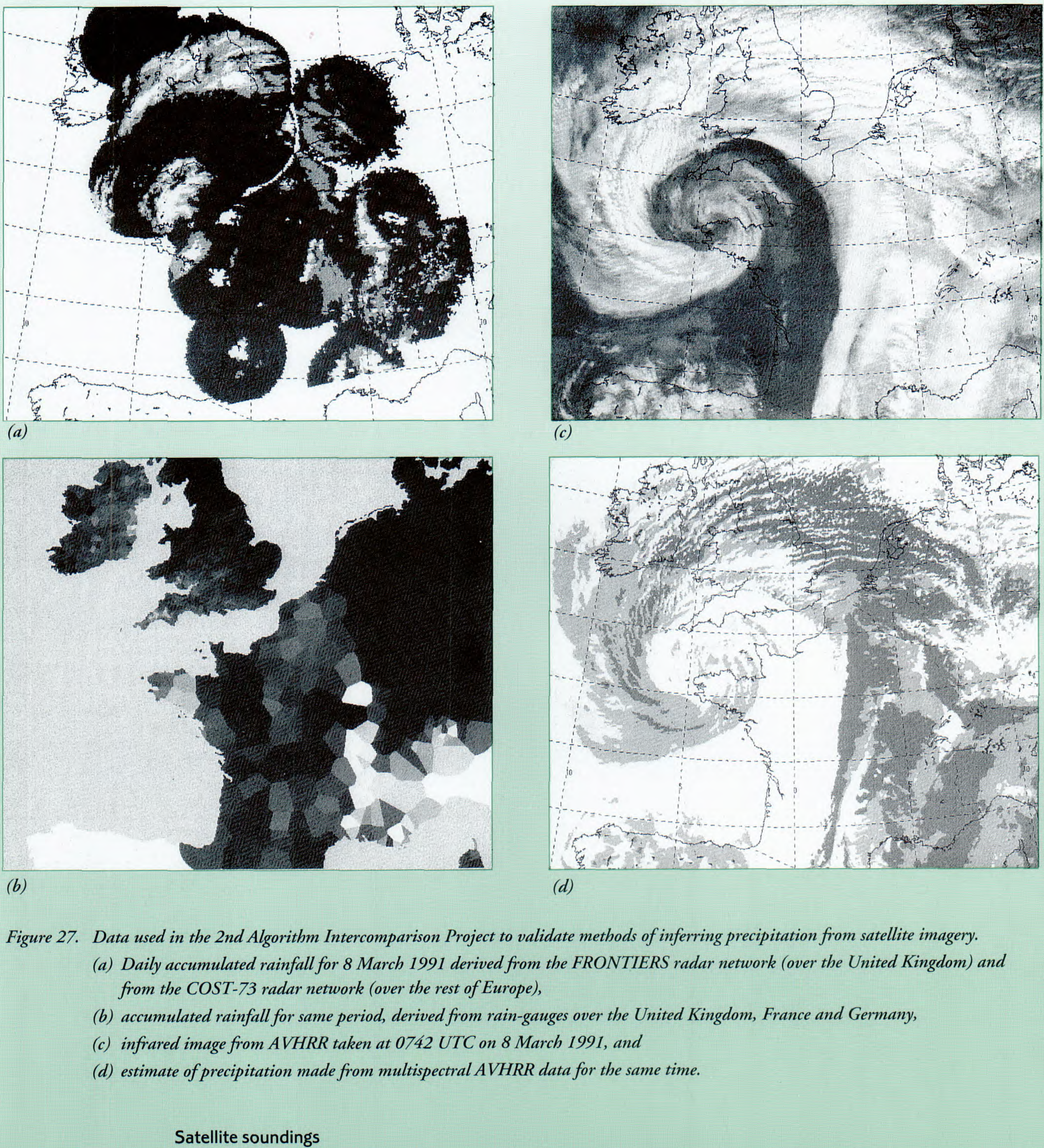


Figure 27. *Data used in the 2nd Algorithm Intercomparison Project to validate methods of inferring precipitation from satellite imagery.*

(a) Daily accumulated rainfall for 8 March 1991 derived from the FRONTIERS radar network (over the United Kingdom) and from the COST-73 radar network (over the rest of Europe),

(b) accumulated rainfall for same period, derived from rain-gauges over the United Kingdom, France and Germany,

(c) infrared image from AVHRR taken at 0742 UTC on 8 March 1991, and

(d) estimate of precipitation made from multispectral AVHRR data for the same time.

Satellite soundings

Sounding instruments carried on polar-orbiting satellites are important sources of information on the temperature and composition of the atmosphere. The significance of this information for NWP has long been recognized. More recently, its value for climate studies has also become clear.

The special value of these soundings is that they provide a consistent global coverage. With two operational polar-orbiting satellites, data for a given region are provided four times a day, as required for NWP.

The current generation of operational satellites carry a package of sounding instruments collectively known as the TIROS Operational Vertical Sounder (TOVS). There are 22 channels in all, sensing infrared radiation, of these 18 are designed for temperature sounding purposes, three for humidity and one for ozone. In addition, there are four channels sensing microwave radiation, again for temperature sounding. The primary emphasis on temperature sounding is evident, but because the weighting functions overlap in the vertical, the number of independent pieces of information on the temperature profile is considerably smaller than the number of channels.

In cloudy regions, the vertical resolution of the current instruments is drastically reduced since only the microwave channels can provide any information below the cloud top. With the Advanced TOVS (ATOVS), due to fly in 1996, this position is improved through the use of a combination of 15 infrared and 15 microwave channels for temperature sounding. Advances in NWP have led to an increased priority on humidity information from satellite soundings. Studies of the TOVS data have shown that only two independent pieces of information on the humidity profile can be expected even in cloud-free fields of view. This situation will be improved in the ATOVS package by the inclusion of the AMSU-B instrument, provided by the United Kingdom, with its five microwave channels designed for humidity sounding.

For a number of years, the Office has operated a Local Area Soundings System (LASS). Temperature and humidity data are retrieved by processing the TOVS measurements received directly from the satellites when they are in line-of-sight of the receiving station at Lasham. Background profiles from NWP play an important role in the processing of the satellite measurements. The derived temperature data are assimilated into the NWP models and also presented in chart form to the Central Forecasting Office.

An improved version of the LASS processing is now being run routinely. This includes a more complete treatment of the mathematical inversion required to infer temperature and humidity profiles from TOVS measurements. An important feature is that cloud information can now be retrieved along with temperature and humidity information. Cloud cover and cloud-top pressure are retrieved, and, in experiments, there has been encouraging success in obtaining cloud reflectivity information as well. In certain respects, for example in detecting semi-transparent cirrus cloud, the sounder data provides an important complement to the cloud data derived from the imaging instruments on the operational satellites. To support this, a number of theoretical studies concerning the scattering of radiation from clouds and aerosols have also been undertaken. A study of scattering by sulphuric acid aerosol has led to an investigation of the global distributions and mass loading of this aerosol following the Mount Pinatubo eruption in 1991 using two TOVS channels. Prompted partly by an expected requirement for monitoring information on stratospheric ozone, the TOVS retrieval system has been extended to include total column ozone.

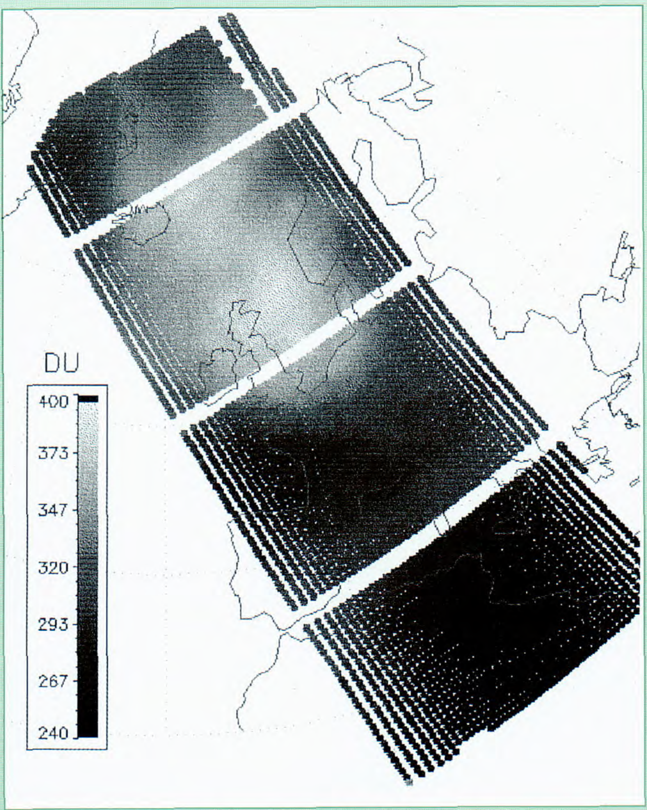
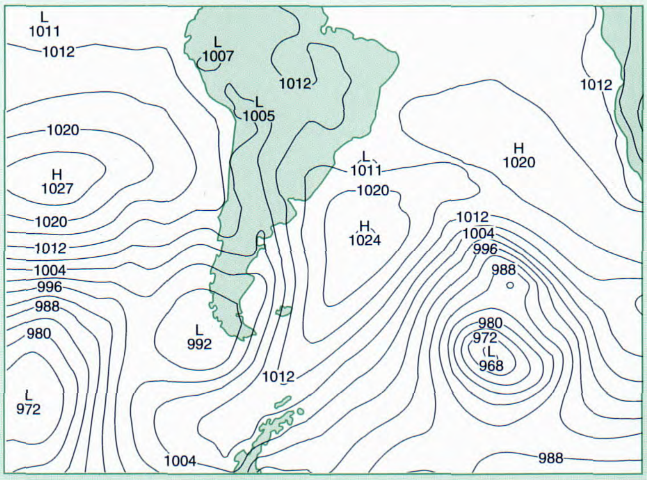
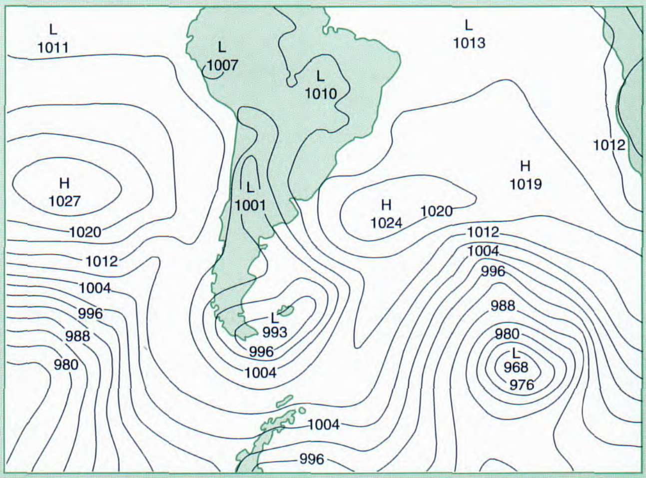


Figure 28. Total column ozone in Dobson Units as retrieved in LASS from a single satellite pass over the United Kingdom. Superimposed on the general latitudinal variation are patterns which are correlated with synoptic-scale meteorological features. The high values over the United Kingdom are associated with an upper-level trough and a low tropopause height.

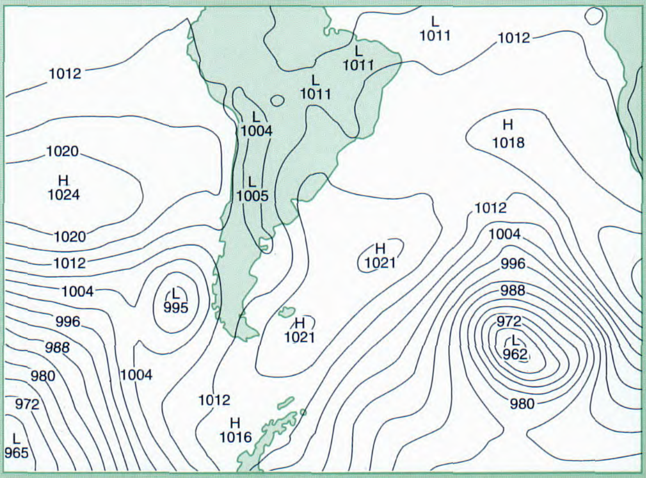
Figure 29. An example from the GLOSS trial in February 1993.



(a) T+72 hour forecast from an analysis using GLOSS data.



(b) T+72 hour forecast from the operational model, same time as (a). The main area of difference between (a) and (b) is around Tierra del Fuego and the Falklands.



(c) The Operational model analysis for the same time and, although there are differences, shows that the GLOSS forecast was substantially correct. Overall forecast accuracy during the trial is still being evaluated.

A major new piece of work has been the development of a Global Soundings System (GLOSS) using TOVS data received from Washington. Temperature and humidity profiles are retrieved with an important role being played by background data from the Bracknell NWP model. During February 1993, a two-week parallel run of analyses and forecasts was carried out comparing forecasts that used GLOSS data with the operational results. The operational system makes use of the same satellite data but in this case the observational processing has been carried out by NOAA/NESDIS using climatology, rather than a NWP model, as the first guess.

Whilst the satellite soundings research now in progress has the aim of improving the quality of the products derived from the TOVS data, care is being taken to ensure that the methods adopted are also appropriate to the ATOVS data when they become available. Collaboration with the satellite-data group at ECMWF, and involvement in relevant EUMETSAT activities, are important to ensure that we are prepared to exploit the data from future sounding instruments.

Cloud images

Satellite image data contains much information that is used by forecasters to help interpret the meteorological situation. The current challenge for researchers is to find ways of making use of these data as input to NWP models. The mesoscale model already uses Meteosat data as one of a number of inputs into a semi-automatic, 3-D, cloud analysis which is then used to produce relative humidity profiles to assimilate into the model. Research has started into ways of using other satellite image data to correct the humidity fields in the regional model. Figure 30 shows an infrared satellite image generated from AVHRR data by the Met. Office image processing system, AUTOSAT-2. Techniques have already been developed within AUTOSAT-2 to determine the radiating temperature of totally cloudy pixels, making use of the multispectral information available from the satellite instrument.

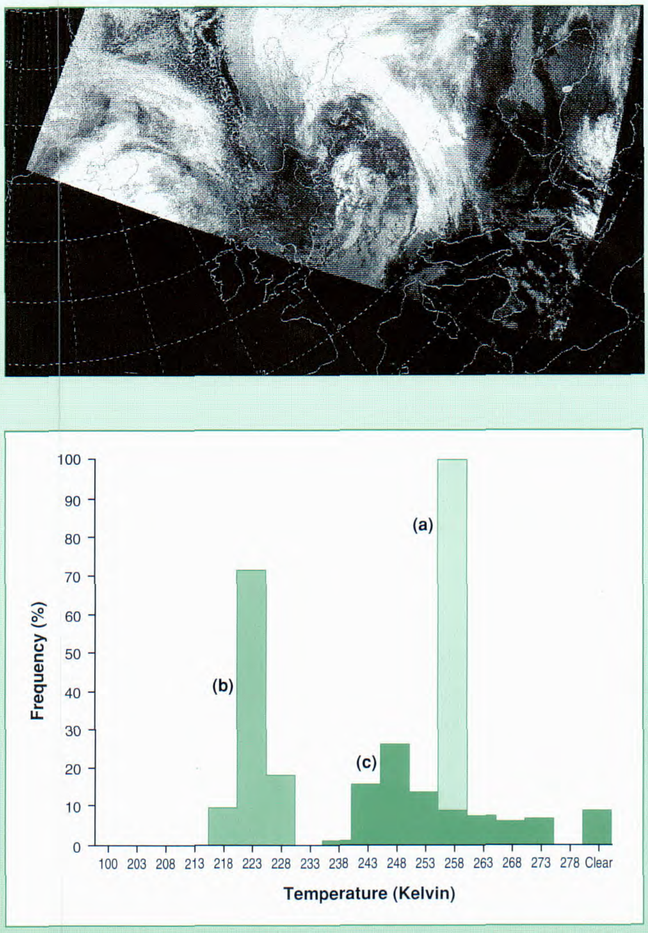


Figure 30. An infrared image obtained on 19 February 1993 from NOAA AVHRR data and processed by AUTOSAT-2. This example histogram show the distribution of cloud-top temperature within grid boxes of the regional model and the percentage of cloud-free pixels.

The histograms show the distribution of cloud-top temperature within three, example, model grid boxes; the percentage of totally cloud-free pixels is also indicated. There are just a few areas, as in histogram (a), that show totally uniform cloud over the model grid-box. For this grid-box, the cloud-top temperature is unequivocally determined, but no information can be derived about the thickness of the cloud layer from the IR image.

Histogram (b) comes from an area which is completely covered by frontal cirrus cloud radiating at fairly cold temperatures. The cloud-top temperature is clearly defined, but there is little information on the depth of the cloud layer. Histogram (c), however, comes from an area of convective cloud in which the cloud cover is not total. Some cloud-free pixels are observed, and there is a wide range of cloud-top temperatures which are associated with clouds at different stages of development. For this region, there is potential for determining the depth of convection. Various options are being investigated to make use of these cloud-top temperature histograms and develop a satellite 3-D cloud analysis including:

(1) ensuring that the humidity at levels above the highest cloud level are sufficiently dry;

(2) changing the humidity at levels where cloud is observed to be consistent with the cloud amount, taking some account of the obscuration of higher-level clouds.

The analysis should take account of the possible errors, which would include those due to interpolation of values on model levels, and in estimating the cloud beneath other clouds. Clearly these are first attempts at directly using satellite images in NWP models. More-sophisticated approaches could be investigated which could take account of textural information and temporal evolution.

Nowcasting developments

Development of a new integrated short-range forecast system

Over the past 20 years, The Met. Office has taken two approaches to providing guidance for very-short-range forecasting. In FRONTIERS, high-resolution analyses and extrapolation forecasts of precipitation are based on radar and satellite imagery. Human intervention permitted rapid progress with unreliable data. In the mesoscale model, the successful techniques of synoptic-scale numerical weather prediction are adapted for finer space- and time-scales. For these scales, the Interactive Mesoscale Initialization was developed to enable a human analyst to extract detailed moisture information from inadequate and unreliable data.

Both systems achieved rapid progress by harnessing human analysis skills through interactive processing. However, both now suffer from the limitations of those analysis skills, and are expensive to operate and maintain. In the meantime, the data sources have improved and become more reliable, and techniques are becoming available for automating many of the interactive techniques.

The success of FRONTIERS has led to pressure for its application to other variables, notably cloud. However, it is also recognized that model predictions will offer better guidance beyond a few hours ahead. There is a need, therefore, to establish appropriate extrapolation techniques for variables other than rainfall, and to find ways of merging these techniques with the model products.

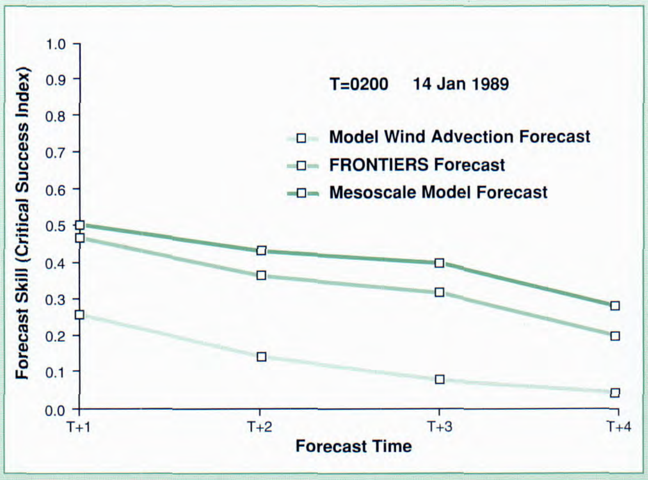


Figure 31. Comparison of precipitation forecasts made by different techniques for 14 January 1989.

The Nimrod project will take up these challenges. Its object is to determine, and implement, (a) the optimum method of generating analysis and forecast guidance in the time range 0–6 hours for the United Kingdom and immediately surrounding areas, and (b) the optimum method of producing cloud and rainfall fields for use in initializing the mesoscale model.

During the past year, work has proceeded in parallel on two aspects of the project. Firstly, the requirements and overall design have been established in order to ensure that the project results in real benefits to users of short-range forecasts. Secondly, substantial progress has been made in developing automated algorithms to replace the current FRONTIERS system. This work is described below.

In designing the system, it has been recognized that for some requirements, e.g. wind, pressure and temperature, the mesoscale numerical modelling system already provides a good basis; while for others like precipitation, cloud and visibility, more-substantial improvement is needed. This improvement will be obtained by applying linear extrapolation to detailed analyses of the observations in a similar way to that used in FRONTIERS, but with the addition of information on non-linear processes from the model. The coherence of the separate forecasts will be ensured by setting the whole system within the model forecast cycle.

Automating the FRONTIERS forecast

The new forecasting scheme incorporates several techniques to generate the forecast: linear extrapolation of the observed movement of the radar rainfall patterns, advection of the patterns with winds forecast by the mesoscale model, and direct use of the mesoscale model precipitation forecasts. Because the relative performance of these different methods varies from one situation to another, the automated scheme must choose, on each occasion, which method to use.

Different elements within the overall rainfall pattern move with different velocities, or are associated with winds at different levels. The automatic forecast scheme first segments the latest precipitation map into separate objects and then attempts to produce the best forecast for each of these in turn.

Velocities for linear advection are determined by using cross-correlation to find the horizontal displacements of objects in the current radar image that give the best match with precipitation in an earlier image. While the most suitable model wind to use, is determined by using forecast winds at various heights and times, to advect the earlier precipitation patterns forward to be compared with objects in the current image. Model precipitation forecasts for the current time (and neighbouring times, in case the model has a timing error) are also compared with each object in the current image to see how well they match.

The best forecast method is then applied to each object to produce a sequence of forecast positions, the overall precipitation forecast at each of these times being assembled by combining the forecasts for all the individual objects.

The automatic precipitation nowcasting system is designed to select the best forecasting technique on a given occasion. In figure 11, the middle curve shows the performance achieved by the existing interactive FRONTIERS system using linear extrapolation. On this occasion (data taken from 14 January 1989), the mesoscale model's precipitation forecasts were poor (bottom curve). However, by choosing the best wind field from all those produced by the model (at 3100 m height in this case) with which to move the frontal rainfall pattern, an improvement over the FRONTIERS forecast can be obtained.

Automating the FRONTIERS analysis

Good forecasts depend upon good observations, and the radar data are subject to a number of sources of error, corrections for which must be included in the automated system.

In some atmospheric conditions the radar beam is refracted downwards to such an extent that it encounters the ground, producing echoes that can be mistaken for showers. This is known as anomalous propagation or 'anaprop'. Anaprop echoes can seriously contaminate the forecast and must, if possible, be removed, but not at the expense of removing genuine rain. The automatic system will combine evidence from a variety of sources, such as maps of frequent anaprop occurrence, ray-tracing to predict the beam path, and satellite cloud observations. Doppler radar data are expected to be a good discriminator of anaprop echoes and will be incorporated as they become available.

The remaining steps of the FRONTIERS radar analysis to be automated involve correcting the radar rainfall-rate measurements to produce the best estimate of the surface value. The FRONTIERS analysis allows corrections to be applied for the bright-band effect, caused by enhanced returns from melting snowflakes, and for growth of precipitation under the radar beam at long range. With strong winds and high low-level humidity, significant growth of precipitation occurs within 1–2 km of the surface over mountains and hills. Such growth, known as orographic enhancement, is missed by the radars over most of the analysis area. Tables of corrections for orographic enhancement are available within FRONTIERS and these will be used in the automated scheme. The FRONTIERS forecaster chooses when and where to apply the orographic corrections and the automation of this selection process, using wind and humidity fields from the mesoscale model, is being investigated.

The proposed automatic correction scheme uses an idealized reflectivity profile, containing a representation of the bright band, orographic enhancement and the decrease in reflectivity between the bright band and cloud top. The profile is defined for each radar pixel using the local melting-level height, cloud-top height and orographic enhancement. The heights of the melting level and cloud top will be obtained from the mesoscale model.

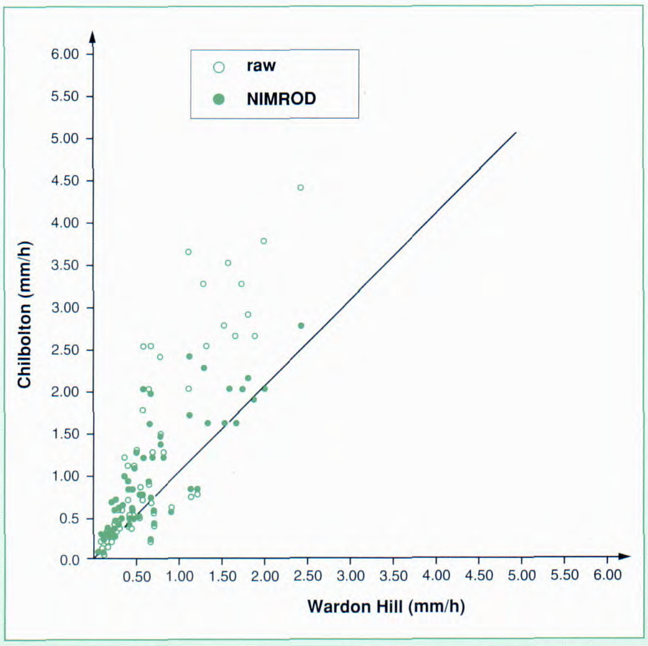
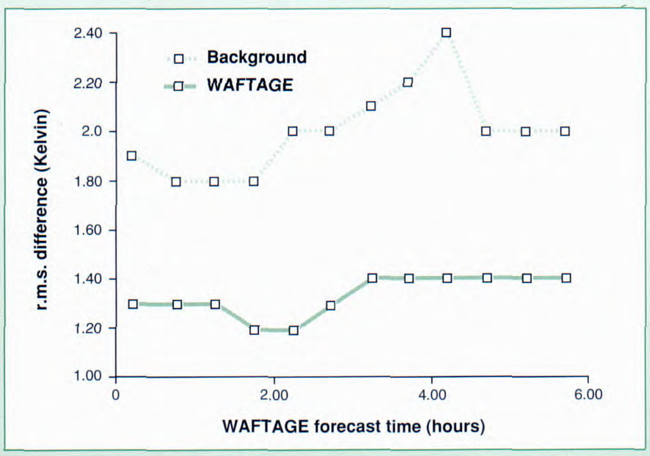


Figure 32. The rainfall rate from the Wardon Hill radar on 21 February 1991 1455–1800 UTC plotted against the Chilbolton estimate of surface rainfall rate. The open circles show the raw Wardon Hill data and the filled circles show the corrected data, which are much closer to the 1:1 line.

A key issue during the development of the scheme has been whether the intensity of the bright band depends on the underlying reflectivity (or rainfall rate), since there is conflicting evidence in the literature. Using an archive of high-resolution reflectivity profiles from the Chilbolton experimental radar, it has been established that the peak reflectivity in the bright-band region is highly correlated with the underlying reflectivity, and a relationship has been established between them for use in the correction scheme.

It is necessary to use an iterative technique to obtain the unknown underlying reflectivity because of the correlation with the bright-band intensity. An initial value of the underlying reflectivity is specified and this also defines the bright-band intensity. Using a parametrization of the beam power profile of the operational radars, an estimate of the measured reflectivity is computed and compared with that observed. The underlying reflectivity is then altered to reduce the difference, and the calculation repeated until there is close agreement between the calculated and observed reflectivity. The resultant best estimate of the underlying reflectivity is then converted to rainfall rate using the normal Z–R relationship.

The new scheme is under test using independent verification data from the Chilbolton radar. The reflectivity measured by the Chilbolton radar a few hundred metres above the surface is used as a measure of the true surface rainfall rate. An example of the results is shown in figure 32. The new radar corrections reduced the measurement error by approximately 50% in this case.



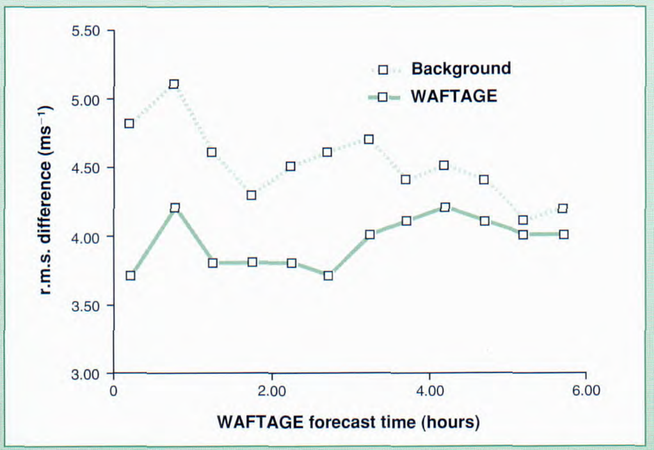


Figure 33. Verification of wind and temperature forecasts. The solid line shows the r.m.s. differences between WAFTAGE forecast and ACARS observations as a function of forecast time. The broken line shows the r.m.s. difference between the NWP forecast (used as background) and the ACARS observations.

Forecasting for air traffic control

The better data links planned for the next decade will give an opportunity to improve the quality of meteorological information for air traffic management. Work done under a contract placed by CAA has examined the requirements for short-term forecasts (typically 20 minutes ahead) for accurate trajectory prediction and for the avoidance of unsuitable flying conditions. The initial contract, completed this year, studied the operational requirements, reviewed the current and future data sources, and studied various options for the forecast modelling.

Conventional forecasting for aviation using NWP models suffers from two major disadvantages. Firstly, the forecast products are not ready for dissemination to the users until several hours after the observations have been made. Secondly, the root-mean-square (r.m.s.) vector wind errors at grid points are substantial around typical cruise altitudes. Monthly values over Europe are typically 8.5 m s^{-1} in a 24-hour forecast, 6.5 m s^{-1} in a 12-hour forecast, and 4.5 m s^{-1} in a 0-hour forecast. In connection with trajectory prediction, it is perhaps more informative to consider the r.m.s. error in the headwind component integrated along part of a flight path. Theoretical considerations indicate that this error is a decreasing function of the route length, and preliminary results give values between 5 m s^{-1} and 2 m s^{-1} depending on location and route length. Monthly r.m.s. temperature errors at grid-points over Europe are between 1.0 and 2.0 °C. These levels of accuracy. particularly for wind speed, are not good enough to satisfy the future requirement for air traffic management.

The approach advocated in this work is to make maximum use of the most recent observations to correct our forecast field. This has been carried out with a 4-dimensional data-assimilation scheme based on optimal interpolation together with a background field from an NWP model. The successive correction scheme developed is computationally efficient, using an iterative method instead of performing a large matrix inversion. It also exploits the sparse nature of the covariance matrix by limiting the number of observations affecting any grid point. Incorporated in the scheme is a quality control algorithm which allows for observations with a non-Gaussian error distribution. The model is named WAFTAGE which stands for 'Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe'.

The model has been tested over North America where in addition to radiosonde observations there is a high density of aircraft reports (ACARS). As background, 6-, 12- and 18-hour forecasts from the global version of the Unified Model were input, linear interpolation being used to obtain values at the observation position and time. WAFTAGE has used the ACARS observations available between 06 and 12 UTC, and the radiosonde observations at 12 UTC, to provide its forecast for 12–18 UTC. The figure shows the r.m.s. differences between the ACARS observations at all levels and the WAFTAGE forecast for wind components and temperature for a 110-day period. For comparison, the r.m.s. differences between the Unified Model forecast and the ACARS are also shown. The figure indicates the level of improvement that has been achieved on both variables compared with using a NWP model alone.

Over the next few years the system will be developed to an operational status and attempt to forecast other variables of importance to air traffic management.

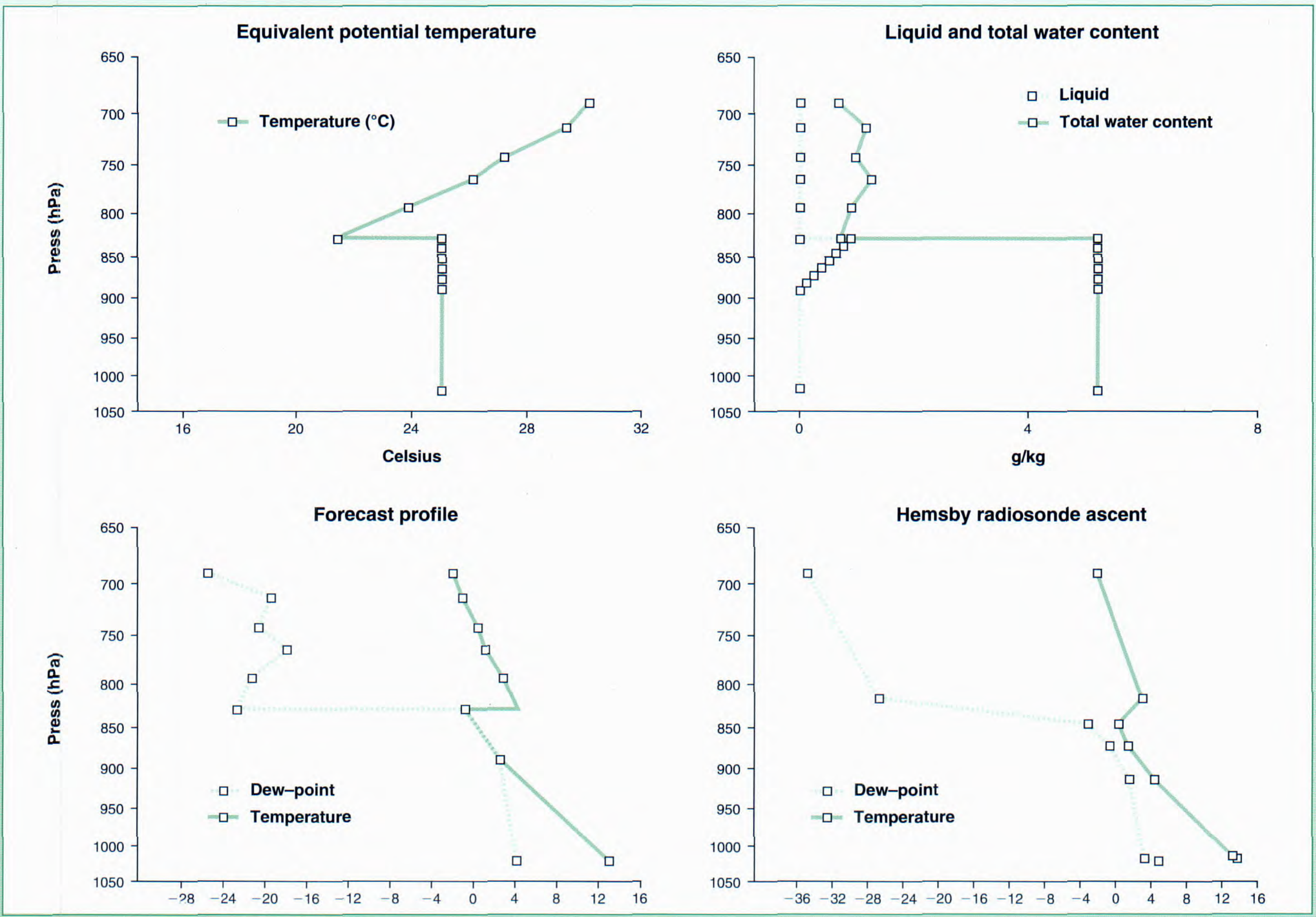


Figure 34. A 12-hour run of the AMT model, for Hemsby in an easterly airstream. The top two graphs show the forecast profile in terms of the conservative model variables, equivalent potential temperature and total water content. It can be seen that each remains constant in both saturated and unsaturated layers in the well mixed boundary layer. The lower graphs show the forecast and actual temperature and dew-point profiles. Hemsby reported Cu and Sc at 3000 and 4000 ft, respectively; the model diagnosed the cloud base at 3550 ft.

Air-mass transformation modelling

Although the operational numerical weather prediction models provide the most important guidance to outstation forecasters on likely weather developments for 24 hours and more ahead, they do not, as yet, have the resolution to help forecast local low-cloud base and fog development in the short term. A simple 1-dimensional numerical model of the atmospheric boundary layer has been developed to predict changes in temperature, humidity and cloud under conditions of fairly uniform air mass, for 12 hours or so ahead. This 'air-mass transformation' (AMT) model was provided in a basic, dry version by courtesy of the Dutch meteorological service (KNMI), and has been extended to include water vapour and cloud. In addition routines have been added which compute temperature changes due to solar and long wave radiation. The source of the air mass which will affect the station is identified by the calculation of back-trajectories, and the model's initial temperature and moisture profiles composited from representative radiosondes.

The model has been adapted to run on desk-top computers, and outstation trials will be carried out during 1993/94. The model will, inevitably, only approximate fluctuations in low cloud base etc., but it has the great strength that it can be run repeatedly, incorporating any modifications to the initial profiles which outstation forecasters consider helpful. With sensitivity studies of this kind they should be able to learn much about the potentialities and variability inherent in the situation. The figure is of a recent 12-hour forecast in a cloudy situation.

Atmospheric Processes Research

Introduction

More-detailed representation of atmospheric processes (clouds, radiation, convection, boundary-layer, pollution, etc.) within weather forecasting and climate models is becoming increasingly important, as the expectations and requirements of users grow. Devising effective ways of representing these processes and their interactions with one another requires a deep understanding of the physics involved. Because of the complexity of the scientific problems, increasing cooperation is being sought from universities and other research institutes so that basic research done elsewhere can be synergistically exploited and applied to practical problems related to improving numerical models of the atmosphere. The cooperation ranges from major international collaborative projects (such as those promoted by the World Climate Research Programme (WCRP)) to individual research contracts or contributions on precisely defined problems (for example Professor Leonard (University of Akron, USA) has visited on a number of occasions to work on advanced numerical advection schemes).

Facilities available for the research include the C-130 aircraft of the Meteorological Research Flight (MRF) based at Farnborough, boundary layer instrumentation based at Cardington, and state-of-the-art numerical models. The Natural Environment Research Council (NERC) has established an aircraft officer post at MRF to facilitate cooperation with university scientists; nearly half the flying in 1992/93 of the C-130 aircraft involved university participation.

Collaboration with the university community has also been strengthened by the enlargement of the Joint Centre for Mesoscale Meteorology (JCMM) at the University of Reading. Additional staff from the Met. Office and the University, and additional funding from NERC and the Met. Office have enabled the formation of four research groups: the mesoscale systems group (originally established in 1988) undertakes theoretical and observational studies; the mesoscale modelling group uses numerical models to investigate precipitation, land surface processes, and their representation in models; the cloud processes group is developing cloud resolving numerical models; and the radar and satellite observation group is developing algorithms to enable these observing systems to be used more effectively for studying mesoscale weather processes.

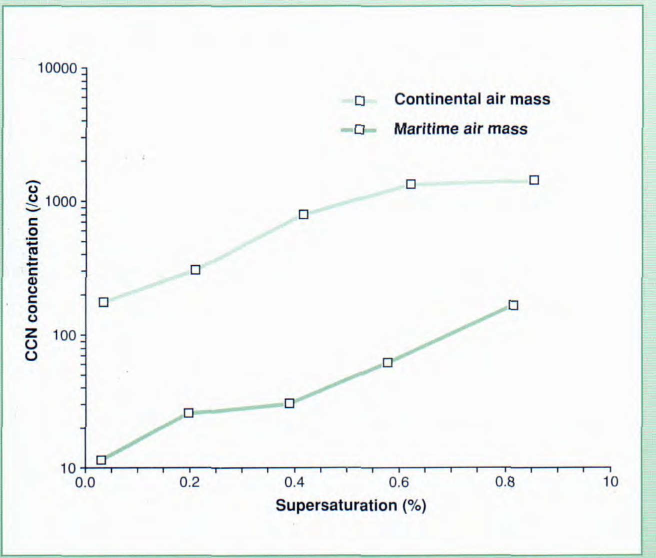


Figure 35. Cloud condensation nuclei (CCN) concentration plotted against supersaturation, measured during ASTEX in a continental air mass on 19 June 1992 at a height of 170 m, and in a maritime air mass on 14 June 1992 at 120 m.

Radiation and clouds

In June 1992 the C-130 aircraft took part in the Atlantic Stratocumulus Transition Experiment (ASTEX) in the Azores, together with aircraft from the US National Center for Atmospheric Research, the University of Washington and the National Aeronautics and Space Administration, to investigate the break-up of persistent stratocumulus. The main aims were to study how processes, such as cloud-top entrainment instability and diurnal variation of stratocumulus, contributes to the break-up. The most striking feature seen in the preliminary analysis was the almost total lack of well mixed boundary layers. In nearly all the flights the boundary layers were relatively deep (1500 m) and the surface was decoupled from the cloud layer. Moisture was being transported from the surface layer up to the stratocumulus layer through cumulus clouds which had their base at the top of the surface layer. At times highly polluted outbreaks of continental air from Europe were encountered. The aerosol concentrations in these air masses were surprisingly high considering the long sea tracks the air had travelled over. Figure 35 shows the differences between the cloud condensation nuclei (CCN) supersaturation spectra, as measured by the thermal gradient diffusion chamber carried by the C-130 aircraft, in typical maritime and continental air masses. The CCN concentrations were an order of magnitude higher in continental than in maritime air masses, at all supersaturations.

The sensitivity of warm stratocumulus cloud-albedo to changes in droplet concentration, termed cloud susceptibility, has been calculated using data obtained by the C-130 aircraft in the eastern Pacific, the South Atlantic, subtropical regions of the North Atlantic and around the British Isles (see Figure 36). A susceptibility of 0.01 cm^3 means that the increase in droplet density of one drop per cm^3 will increase albedo by 0.01. The range of susceptibility measured is large and maritime clouds (with low aerosol concentrations) are shown to have the largest susceptibility. These measurements highlight the high sensitivity of maritime clouds and the rapid reduction in sensitivity as the aerosol, and hence cloud droplet concentration, increases.

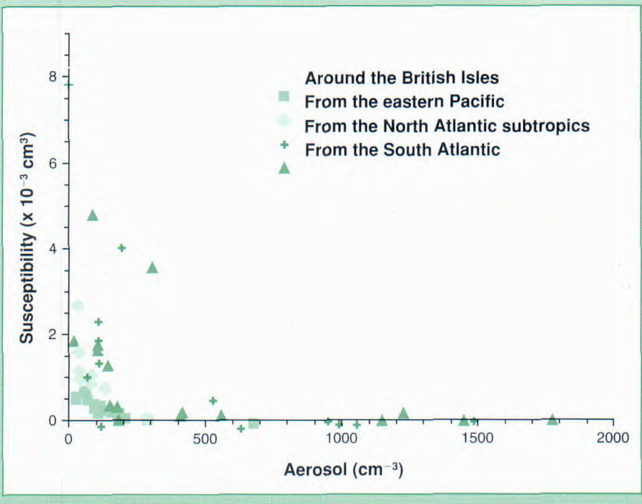


Figure 36. Cloud susceptibility as a function of aerosol concentration below cloud-base: + around the British Isles; X from the eastern Pacific; X from the North Atlantic subtropics.

Analysis of simultaneous measurements of the radiative and microphysical properties of several cirrus clouds (made by the C-130 aircraft during the International Cirrus Experiment) have shown that both the long-wave and short-wave radiative properties of cirrus may be parameterized in terms of the ice water content (IWC) and a suitably defined ice crystal 'effective radius' (*re*). Figure 37 shows how the ratio of the inferred long-wave absorption coefficient and the IWC shows a marked inverse dependence on *re*, in line with a relationship predicted from simple theoretical considerations.

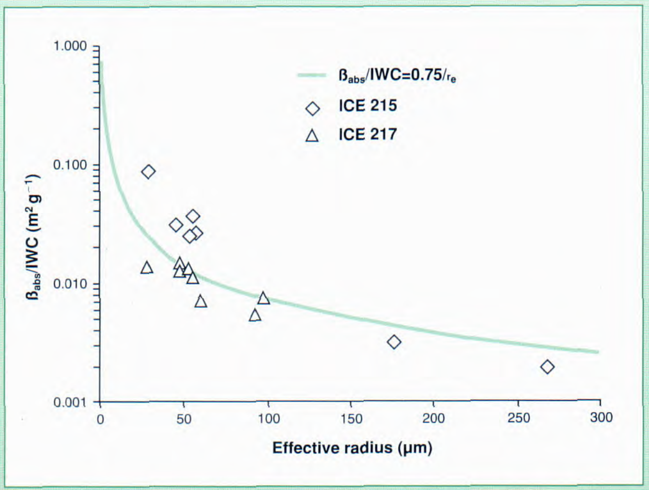


Figure 37. Inferred values of the ratio of the broad-band long-wave absorption coefficient (β_{abs}) and the ice water content (IWC) plotted against the effective radius (re) for two flights, ICE215 and ICE217. The full line is a simple theoretical relationship.

The marine boundary layer

The Tropical-Ocean Global-Atmosphere Programme's Coupled Ocean Atmosphere Response Experiment (TOGA–COARE) was devised, as part of the WCRP, to study energy exchanges between the atmosphere and ocean in the western Pacific warm-pool region, an area of great importance in modelling the ocean–atmosphere system. In early 1993 the C-130 aircraft joined four other aircraft from US universities and institutes and fourteen research vessels from a number of countries around the Pacific rim, to make meteorological and oceanographic observations. Eight flights were made to the north east of Papua New Guinea, primarily to estimate evaporation from the sea surface. The resulting data will be used to investigate the parametrization of evaporation in numerical weather forecasting and climate models.

The Internal Boundary Layer Experiment (IBLEX) was carried out over the sea areas around the UK to study the influence of sea-surface temperature gradients on the cloud-topped marine boundary layer. When air is being advected over a progressively colder sea there is potential for very stable layers to form close to the sea surface inhibiting the transport of moisture up to the stratocumulus layer which may cause it to thin or break up. Figure 38 shows a series of three profiles of potential temperature over the Irish Sea which was more than 2 K cooler on the eastern side than in the west. A stable surface layer is found which deepens from 180 m to 350 m as the air is advected from the west to the east. In profile (c), which is in the extreme west, a layer of stratocumulus was observed at the top of the boundary layer at 950 m. Further downwind this broke up completely and was not observed in either profiles (b) or (a).

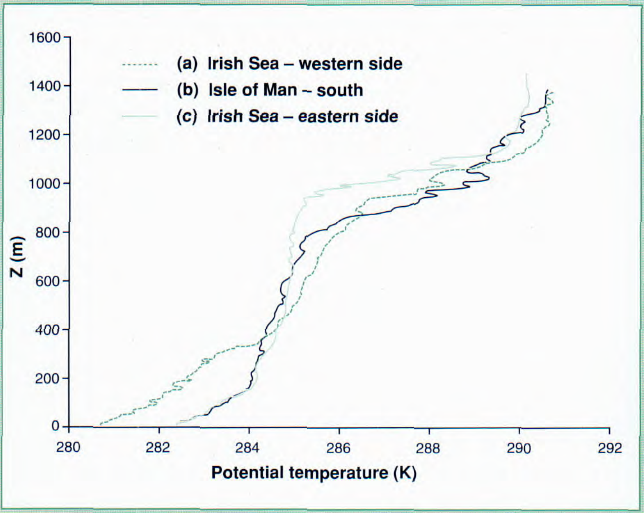


Figure 38. Aircraft profiles of potential temperature on 6 March 1990. Profile (a) is on the western side of the Irish Sea, profile (b) is to the south of the Isle of Man, and profile (c) is on the eastern side of the Irish Sea over the coldest water.

It has long been hypothesized that evaporative cooling associated with turbulent mixing across the top of boundary-layer cloud can sometimes cause an explosive growth in entrainment and rapid dissipation of cloud. Recent analytical work suggests a new, more restrictive criterion for occurrence of this instability. This is supported by results from a study using a very-high-resolution two-dimensional numerical model which shows a very rapid increase in the decay rate of the cloud as the governing parameter increases above its critical value of 0.7 (Figure 39).

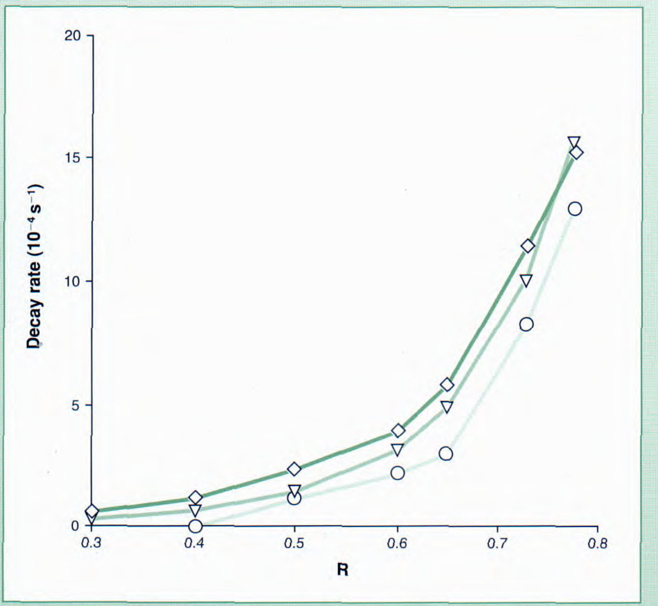


Figure 39. The variation, in different runs of the model, of the decay rate of a stratocumulus cloud-deck with the stability parameter R, which measures the relative size of the jumps in equivalent potential temperature and total water mixing ratio across the cloud top.

Boundary layer over land surface

Experimental studies have been conducted over land (using a tethered balloon and other surface-based instrumentation) to investigate the structure of the boundary layer, and exchanges between it and the underlying surface. At night the boundary layer is characterized by a stable temperature gradient and reduced turbulence favouring, for example, the formation of fog and the lessening of the dilution of atmospheric pollutants. The boundary-layer structure can be analysed using the gradient Richardson Number (*Ri*), defined as ratio of static stability to the square of wind shear. Joint studies with the University of Sheffield are complementing recent modelling results; preliminary experimental results have demonstrated that, in some stable boundary layers, turbulence cuts off at a value of *Ri* greater than the conventional 0.25 (Figure 40).

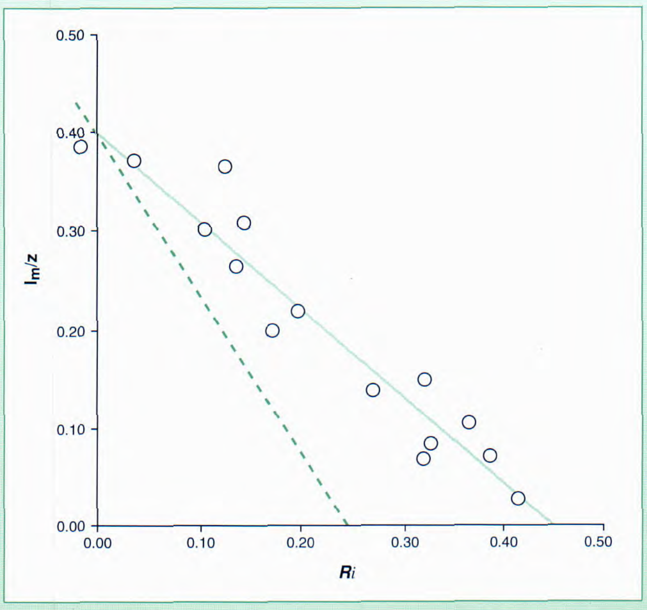


Figure 40. Mixing length (l_m), non-dimensionalized by height z, plotted against Richardson Number (Ri). The full line is the best-fit line and the dashed line is the parametrization based on the conventional value of the critical Ri of 0.25.

The effects of local heterogeneity, caused by different types of surface roughness such as trees and grass, on area-averaged vertical fluxes of momentum and heat have been investigated in observational campaigns over landscapes containing different scales and types of heterogeneity. Results obtained in 1991 show that the effective roughness length for momentum is markedly affected by adding a few trees to a grass terrain, whereas the effective roughness length for heat transfer varies more linearly with the fractional cover of trees. This is confirmed by early results from a second campaign in the autumn of 1992.

On a smaller scale, an experimental and modelling study is under way to improve the road-surface-temperature model used in the Office's 'OpenRoad' service. Preliminary analyses of meteorological data from the Cardington field site and of temperatures from an adjacent road surface suggest that model changes may be needed to improve the short-wave radiation scheme, and to account for the effects of advection.

A key modelling tool for boundary-layer studies is the 'large-eddy simulation' (LES) model; this has been adapted for near-surface turbulence studies, for investigations of flow over hills and for simulations of deep convection. Intercomparisons between LES models from Sweden, Germany and the Netherlands, have highlighted the sensitivity to different treatments of sub-grid processes. Our model is unique in including stochastic backscatter, where energy is randomly scattered back from sub-grid to resolved scales, and gives more realistic velocity profiles near the ground.

Atmospheric chemistry and pollution

The UK Atmospheric Dispersion System (UK-ADMS) (being developed in conjunction with the Cambridge Environmental Research Consultants and National Power) is a computer-based model for dispersion of pollution in the atmospheric boundary layer; it is designed for improving routine practical calculations of dispersion by incorporating recent advances in understanding. The first version of the UK-ADMS was released during the year, though several aspects are still in need of attention.

Experimental studies are important for developing and testing atmospheric chemistry models. The hydroxyl radical OH plays an important role in controlling the lifetime, and therefore the concentration of, greenhouse gases such as methane, HCFCs and HFCs, but because this highly reactive radical only occurs in very small concentrations it is difficult to measure directly. Measurements of a number of hydrocarbons in air samples collected by the C-130 aircraft in plumes from the burning Kuwaiti oil wells, some close (≈100 km) to the source and some for which the plume had been exposed to OH degradation for several days, have been analysed. By comparing the relative concentrations of different hydrocarbons, the OH concentration could be inferred from a knowledge of their reactivity with OH. Figure 41 indicates that, although significant variability existed, the data for all eight hydrocarbons indicate an OH concentration of about 1×10^6 molecules/cm^3, diurnally averaged over several days.

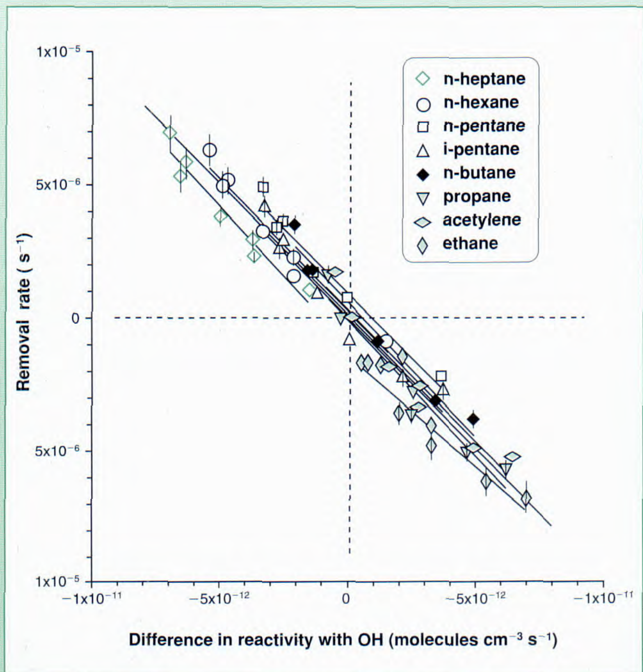


Figure 41. The removal rates of several hydrocarbons relative to reference hydrocarbons plotted against the corresponding difference in reactivity with OH.

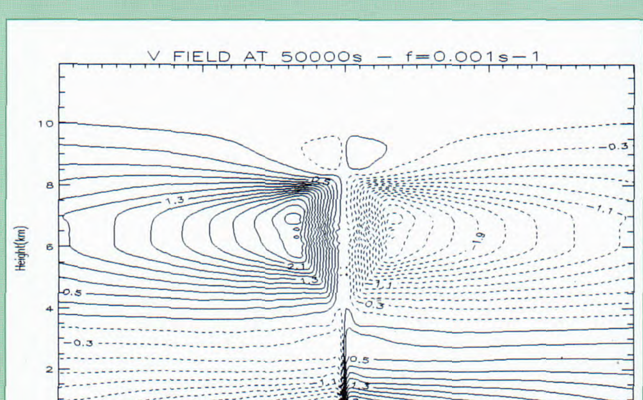


Figure 42. Balanced component of velocity (into the plane) in a numerical model after deep convection.

Deep convection and frontal structure

Air transported through deep convection eventually comes under the influence of the earth's rotation and evolves into organized balanced structures. A numerical modelling study of a single moist convective plume in an atmosphere rotating at an artificially high rate (to speed up the adjustment process and to reduce the scale of the final balanced state) demonstrates that the convective mass transfer creates a lens of zero potential vorticity at the neutral buoyancy level and a vertical shear at the surface (Figure 42). Typically, the maximum lens size produced by a simple theory based on this model is between 50 and 100 km; this may explain the observed size of mesoscale convective systems.

Cumulonimbus clouds redistribute heat, moisture and momentum and they generate gravity waves; these processes must be parameterized in large-scale models. Observations alone are not sufficient for the derivation of parametrizations and so a very-fine-scale numerical model that explicitly resolves the main dynamical features of convective clouds is being developed to diagnose their large scale effects. A bulk cloud microphysics scheme involving 5 species (cloud ice, cloud water, rain, snow and graupel) has been implemented within the convective cloud-resolving model, which has successfully simulated a multicell storm, and has been used to study momentum transport and gravity wave generation in idealized flows (see Figure 43).

In March and April 1992 the FRONTS-92 experiment was carried out by to investigate the mesoscale structure of frontal waves. The focus of the experiment was the use of the C-130 aircraft, with dropsonde and radar systems, to observe mesoscale patterns of wind and precipitation. Figure 44 shows a cross-section of the estimated vertical component of vorticity across the cold-frontal region of a wave observed during FRONTS-92. A double vortex structure is evident, accompanying a double cloud structure at the base of an extending trough and a split structure of the associated stratospheric descent.

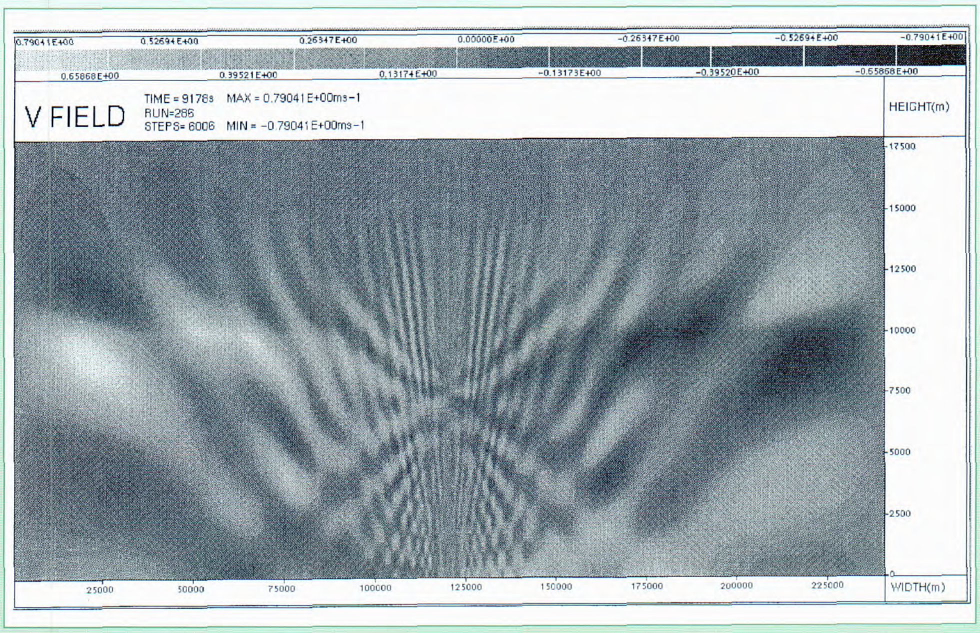


Figure 43. Velocities (into the plane) in a cloud-resolving model, revealing gravity waves generated by deep convection.

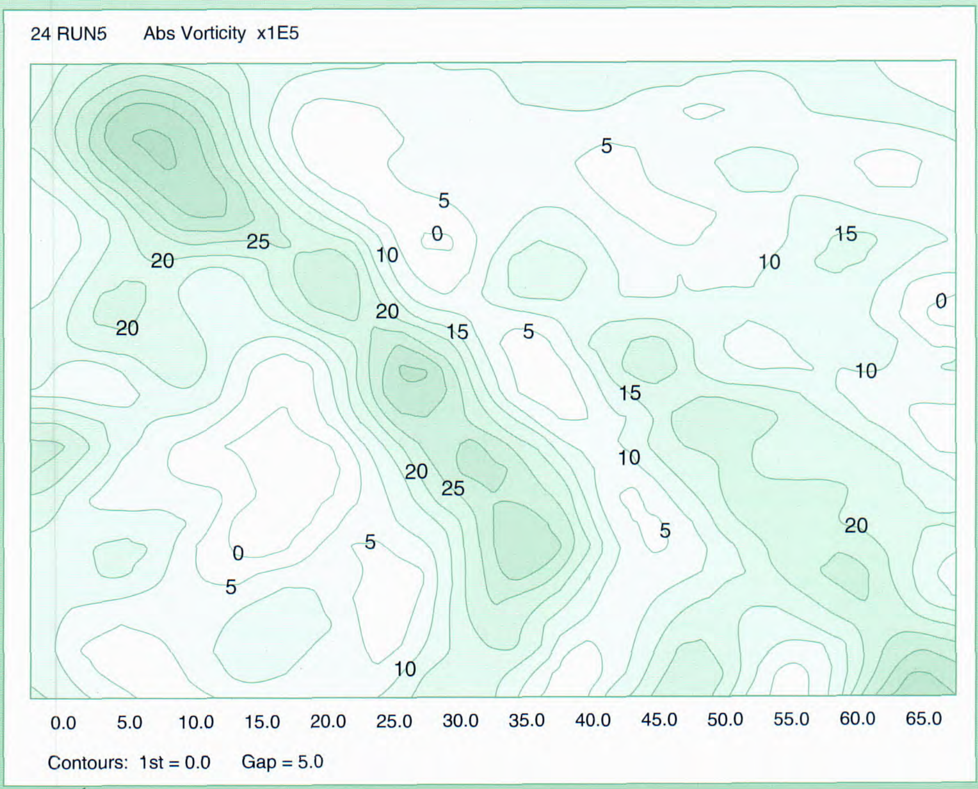


Figure 44. Cross-section of the estimated vertical component of vorticity across the cold -frontal region of a wave observed during FRONTS-92 (positions of dropsonde soundings are marked along the upper axis).

Climate variability and change

Introduction

Jointly funded by the Department of the Environment (DoE) and the Met. Office, the Hadley Centre is the main United Kingdom centre for research on prediction of climate change, a topic which continues to attract a high level of attention and public debate. The major objectives of the Centre are (a) to simulate the present climate, (b) to monitor and understand natural climate variability, (c) to understand the factors controlling climate change and (d) to predict global and regional climate change to the end of the 21st century. It aims to provide a focus for other national research programmes relevant to understanding, detecting and predicting climate change, in particular by incorporation of their results into predictive models of the atmosphere, ocean, land surface and sea ice.

Climate prediction requires these models to be run in coupled mode, which allows the interactions between the various components to be represented. A major facility for this task is provided by a DoE-funded Cray Y-MP8/864 supercomputer dedicated to climate research. Rapid and effective analysis of results is provided by a graphics workstation system.

Observed climate variability and change

The Centre analyses a number of key parameters for the study and monitoring of observed climate variability and change. Some of the work is carried out collaboratively with other institutions, in particular the University of East Anglia's Climatic Research Unit. Over the year, a start has been made on blending and improving global mean-sea-level pressure data sets for the period since the late l9th century and on collection and analysis of worldwide maximum (day) and minimum (night) surface air temperatures. Early results confirm the view that minimum temperatures have risen more than maximum temperatures over recent decades.

The first version of a 'globally complete' analysis of monthly fields of sea surface temperature and sea ice extent from 1871 to date was issued during the year, including an update incorporating satellite data from 1982 onwards. This data set is contributing to a modelling project now underway; the aim is to identify the effects of changes in sea-surface temperature and sea-ice extent on atmospheric variability over the last 100 years.

Simulation and prediction of climate change

Considerable interest was generated by the publication in August 1992 of a report (*The Hadley Centre Transient Climate Change Experiment*) summarizing the main results of the first Hadley Centre experiment to assess the effects of a gradual increase in greenhouse gas concentrations on climate. Such 'transient response' experiments require the ocean and atmosphere to be brought into mutual adjustment before running present-day climate ('control') and increased greenhouse gas concentration scenario ('anomaly') experiments. Considerable work has been carried out to improve the techniques by which this is done, and to optimize the coupling between atmosphere, ocean and sea ice in preparation for a second experiment, now underway, using the climate version of the new Unified Model.

Industrial activity over the last century has been accompanied by increased concentrations of atmospheric sulphate aerosols. Though the first transient experiment did not contain an explicit representation of these, estimation of their effects has been made through an energy balance model calibrated against the coupled model results. Their implied effect is to reduce the rate at which global warming takes place, particularly over land (Figure 45) so matching the observed land-temperature record more closely. An explicit representation of aerosols for use in the general circulation model is currently being developed.

Recent stormy winters over the UK and surrounding areas have led to speculation in some quarters that increases in greenhouse gases may lead to a more 'extreme' climate. A detailed study of an experiment to assess the equilibrium response to a doubling of carbon dioxide (CO_2), shows that the simulated storm tracks in the North Atlantic shift northward and extend eastward, but without any significant increase in intensity. However, an analysis of model output suggests an implied increase in the geographical extent, frequency and intensity of hurricanes in a doubled CO_2 climate.

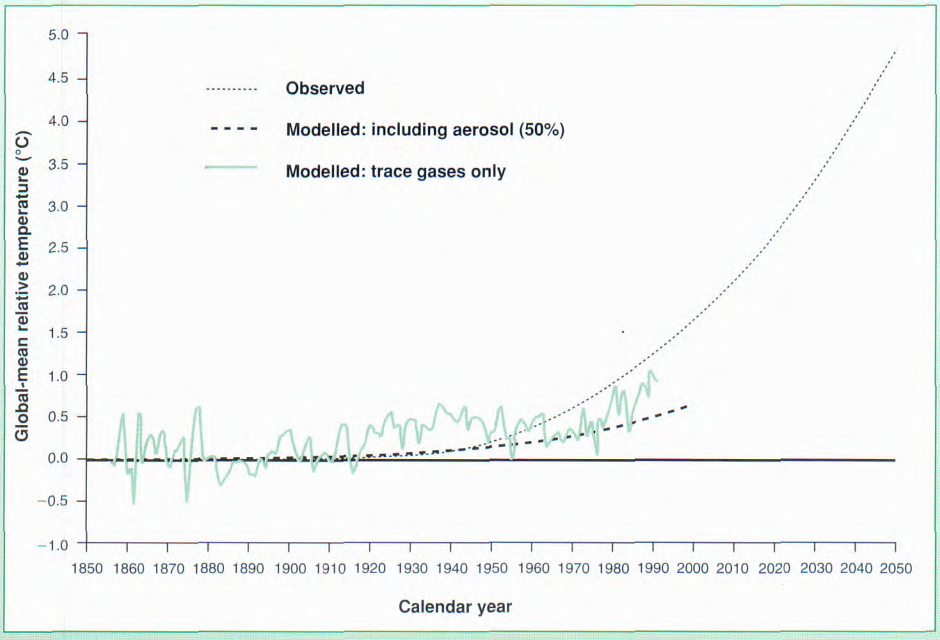


Figure 45. Simulated increase in the annual mean surface air temperature over land in an energy balance model with and without aerosols. Also shown is the observed variation of annual mean land-surface temperatures averaged over the globe.

Recently, a study has been made of the dependence of simulated climate sensitivity on the choice of cloud parametrization. Four experiments were carried out, each using a different cloud parametrization. When compared with earth radiation budget satellite data, differences between schemes were found to be small. However, equilibrium CO_2 doubling experiments carried out with each scheme showed a wide range of sensitivities. Increases in global mean surface temperature ranged from 5.2 °C to 1.9 °C, demonstrating the uncertainties still present in such experiments.

The comparison of numerical simulations and palaeoclimatic reconstructions of past climates may help to reduce the range of uncertainty in predictions of the future. Preliminary simulations for 6000 years ago, when Earth's orbit gave stronger heating in the northern hemisphere in summer, are in broad agreement with evidence for the period.

Atmosphere and land-surface models — development and validation

Radiation and clouds

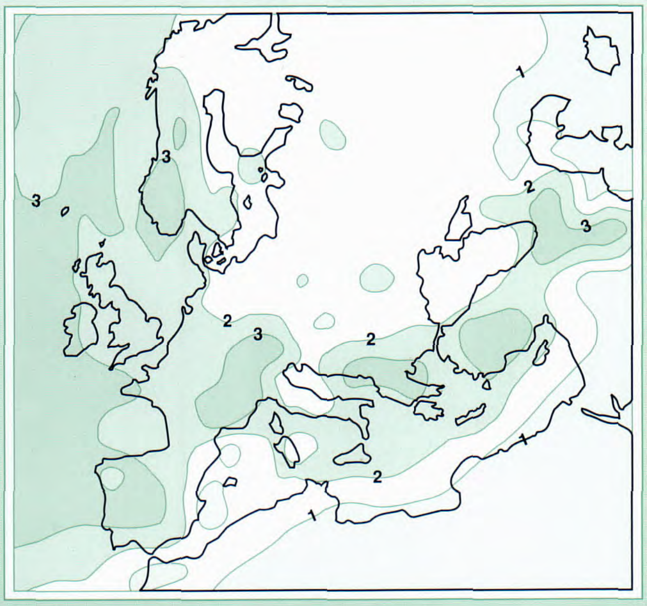
Development and refinement of the Unified Model radiation code have continued and a new radiation code (with variable spectral resolution in which the effects of atmospheric trace gases, aerosol and clouds can be incorporated) has been developed. It is now being tested in the Unified Model. Research on representation of the radiative properties of ice clouds and on inclusion of an interactive scheme for representation of cloud droplet effective radius has been carried out in collaboration with the Meteorological Research Flight and the University of Manchester.

The system for the Simulation and Analysis of Measurements from Satellites using Operational aNalyses (SAMSON) uses global analyses, produced by weather forecast centres, as the input to a detailed radiative transfer code to simulate atmospheric radiative fluxes and heating rates. Work using SAMSON has included simulation of the clear-sky outgoing long-wave radiation using ECMWF analyses and a study of the relationships between the clear-sky greenhouse effect and atmospheric temperature and humidity structure. SAMSON was also used to calibrate a new scheme for retrieval of clear-sky long-wave fluxes at the surface from satellite data.

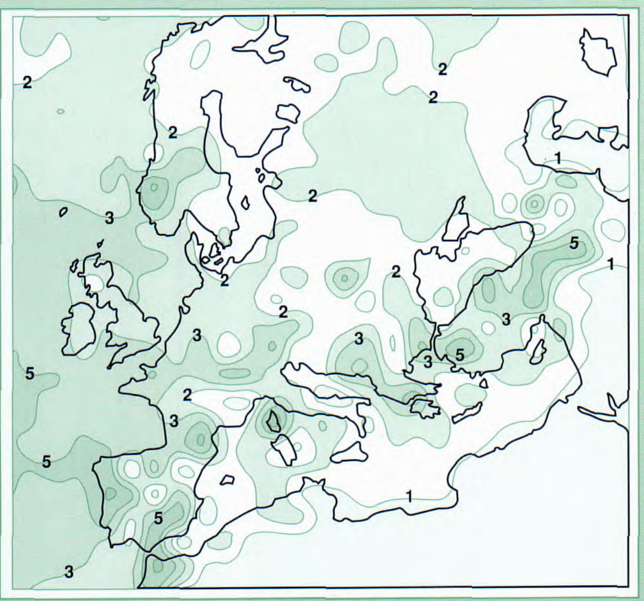
Surface, boundary layer and convective processes

A collaborative project (with the Universities of Reading and Sheffield, the Institute of Terrestrial Ecology (ITE), Edinburgh and the Institute of Hydrology, Wallingford) has been set up to develop the techniques to model vegetation and the terrestrial carbon cycle, and so represent the interactions between the climate and the land surface. Work so far has involved the coupling of a leaf photosynthesis and stomatal resistance model developed at ITE into a single-column version of the Unified Model. Simulations have been carried out to indicate the feedbacks associated with stomatal functioning. An important feedback has been shown to be the reduction of evaporation by the stomatal response to increased CO_2.

Figure 46. Rainfall over three winters
Contours at 1, 2, 3, 5 and 10 mm/day



(a) Global model
Area average = 2.0 mm/day



(b) Regional model driven by global model.
Area average = 2.4 mm/day

A multi-layer soil hydrology scheme has been written and tested in the Unified Model. It will be used in collaborative experiments with the Institute of Hydrology. The Hadley Centre is also involved in intercomparisons of a wide range of current hydrological schemes. Comparison is being made of the output values of variables such as run-off, evaporation and soil moisture to identify differences in performance and help in the design of more realistic schemes. A new snow model and permafrost/methane-emission model have also been developed, the latter in collaboration with the Scott Polar Research Institute.

Boundary layer turbulent mixing and convection are the main processes which link the surface to the troposphere. An improved scheme for distributing the heat and moisture from the surface, through an unstable, rapidly mixing boundary layer has been developed. Work has also started on the development of a new scheme for representing the form-drag effects of unresolved orography.

Introduction of downdraughts into the convection scheme has been found to bring substantial improvements in the simulation of precipitation. A start has been made on a further modification to provide better representation of convective stratiform clouds.

Model validation

Validation of the performance of the atmospheric model continues to be an important topic, and this work has been drawn together in a new project this year. Model validation is also a key theme of the Atmospheric Intercomparison Project (AMIP), sponsored by the World Climate Research Programme, in which the Centre is taking part. The AMIP run of the Unified Model is being compared with a variety of data, including analyses created from the weather forecasting models of ECMWF and the Met. Office and earth radiation budget data.

Regional climate modelling

Two approaches are being used to address ways of generating information at finer resolution on the regional scale than is possible with the current generation of global climate models (GCMs). The first is to use a nested high-resolution model within the GCM. Work on this has concentrated on using the configuration set up for operational forecasting. A year-long integration of the model on a 50 km grid, and driven by GCM boundary conditions, has demonstrated the stability of the model for such long integrations. The potential for a more realistic estimation of regional climate is illustrated by Figure 46 in which the precipitation and shadowing effects of mountains resulting from a much more realistic representation of orography in the regional model can clearly be seen.

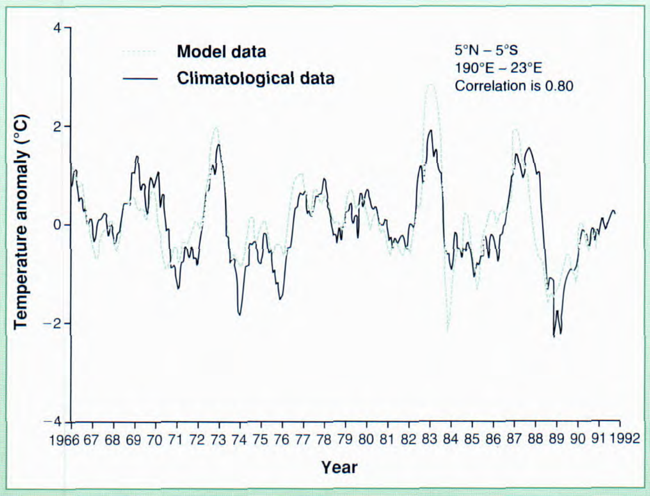


Figure 47. Sea-surface-temperature anomalies for January 1878 showing the well developed EL Niño. Black areas represent sea ice.

An alternative approach to regional climate prediction consists of developing statistical relationships between variables available from the GCM and locally observed weather. Tests of this technique have been made which demonstrate its viability.

Development of ocean and sea ice models and parametrizations, including the ocean carbon cycle

A version of the global ocean model on a 1.25° latitude–longitude grid with higher resolution (⅓° north–south) in the tropics has been developed and coupled to the global atmospheric model for future studies of climate variability, and eventual use in climate prediction. The first multi-decadal run of this coupled model has recently been completed. A limited-area version of the ocean model (covering 60° longitude × 70° latitude) has been used to investigate techniques of spin-up of ocean models and aspects of the representation of vertical diffusion. The present ocean model employs a vertical coordinate system with model levels at fixed depths. Isopycnic models, which use density as a vertical coordinate, provide an alternative approach. Differences between the two are being examined via intercomparison studies being carried out in collaboration with the James Rennell Centre for Ocean Circulation. Work has also continued on coding of a dynamical sea-ice model, now under test in the Unified Model.

An increasingly important component of studies of climate change is modelling the carbon cycle. An inorganic ocean carbon cycle model has been coded into the global ocean model and a simplified representation of ocean biology developed in collaboration with the James Rennell Centre and Plymouth Marine Laboratory.

A major part in the variability of the coupled atmosphere–ocean system on interannual time-scales, important for seasonal prediction, is that of the El Niño–Southern Oscillation (ENSO). It involves coupled interactions between the tropical ocean and global atmosphere. The response, of both 'reduced physics' and the full high-resolution tropical Pacific circulation models, to observed wind stress forcing has been studied for the period 1961 to 1992. Overall, the model results compare reasonably well with the observations. Runs of the full tropical Pacific Ocean model, coupled to the global atmospheric model, are currently in progress to investigate the ability of the coupled system to simulate ENSO events. A series of ENSO hindcasts (of which Figure 47 is an example) carried out using the reduced and full physics ocean models with an 'empirical' atmosphere, showed cold events to be generally well predicted: however this was less the case for warm events.

Seasonal variability and forecasting

Analysis of climate model experiments, indicating potential skill in the prediction of rainfall over much of tropical North Africa, have resulted in an extension of the Met. Office experimental forecasts for the Sahel to other areas of the North African region during 1992. Rainfall forecasts for four selected areas proved very skilful, as was the forecast carried out for North East Brazil. Much seasonal climate variability is now viewed as involving near-global-scale processes. Research, using global climate models with historical climate data sets, is revealing a tropic-wide pattern of summer (July to September) rainfall variability. A system has been developed for quantifying the relative importance, for atmospheric variability, of boundary forcing and internal atmospheric variations. This is being applied to identify further regions of potential predictability from atmospheric model ensemble integrations.

Middle atmosphere research

Research into the middle atmosphere is being given new impetus by measurements provided by the Upper Atmosphere Research Satellite (UARS). The Met. Office is contributing to the international UARS project by using a version of the Unified Model to provide analyses of available stratospheric data. These analyses are produced daily and supplied to the UARS science team via the NASA Goddard Space Flight Center.

Theoretical studies are helping with the interpretation of UARS observations. Measurements, from the HALOE instrument on UARS in October 1991, showed that mixing ratios of methane in the middle of the southern polar stratospheric vortex were as low as those found in the mesosphere. A recent numerical model simulation for the southern hemisphere winter of 1991 calculated trajectories of over 40 000 particles showing the systematic transport of air. In Figure 48 the descent of mesospheric air into the stratosphere in south polar latitudes can clearly bee seen, as can the absence of air of stratospheric origin above 30 km and poleward of 70° S. This provided striking confirmation of a hypothesis that the low mixing ratios were due to the descent of mesospheric air into the centre of the stratospheric vortex.

Further computer experiments have been used to study the response of the Arctic stratosphere to a doubling of CO_2. These showed that the consequent stratospheric cooling may increase the possibility of wintertime Arctic ozone depletion under certain meteorological conditions.

External liaison

Strong links are maintained between the Hadley Centre and other groups involved in research on climate change both in the UK and throughout the world. Some of these have already been indicated above, and there is an active programme of exchange visits, in particular as part of the DoE-funded Climate Prediction Programme within the Centre. Active involvement with other European groups is maintained especially by participation in the Commission for the European Community (CEC) Environment Programme and in the newly established European Climate Support Network.

Intergovernmental Panel on Climate Change (IPCC)

The Hadley Centre hosts the Technical Support Unit for the Scientific Assessment Working Group (WGI) of the IPCC. The unit, which is funded by the DoE, coordinates the planning, preparation, review and publication of the periodic IPCC reports. It also provides a central reference point for IPCC activities.

In April 1992, the Supplementary Report to the first full IPCC assessment of 1990 was published, timed to coincide with the United Nations' Conference on Environment and Development. Since then, the unit has been coordinating work on IPCC guidelines of national inventories of greenhouse gases. This has been done in collaboration with the Organization for Economic Cooperation and Development. Plans are also being made to produce, in 1994, a further interim report on radiative forcing of clouds. A full Scientific Assessment Report will follow in 1995.

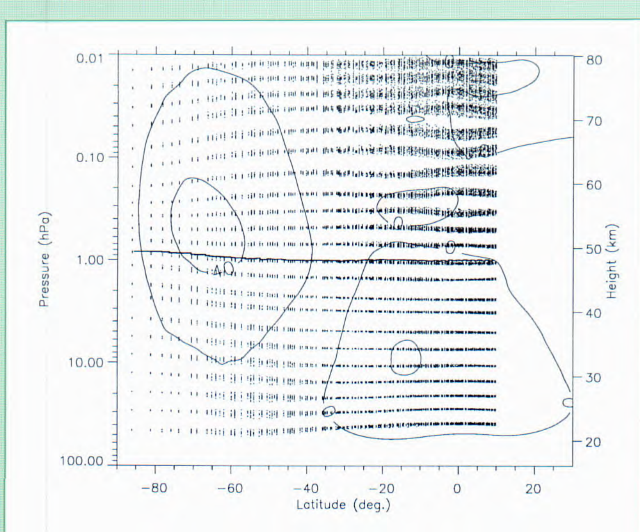
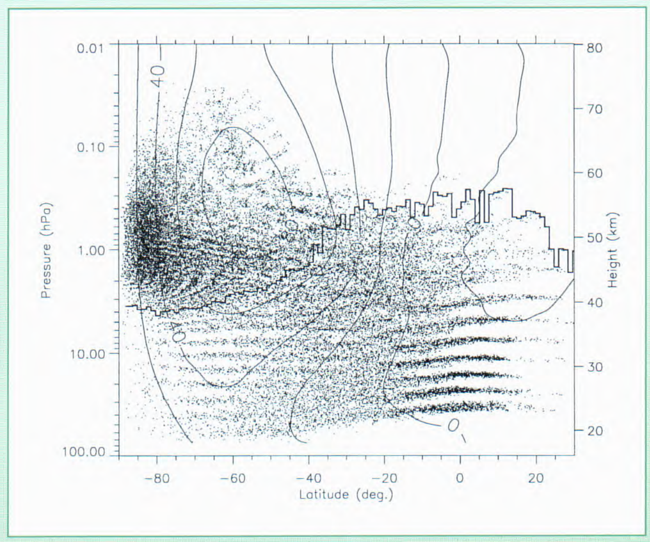
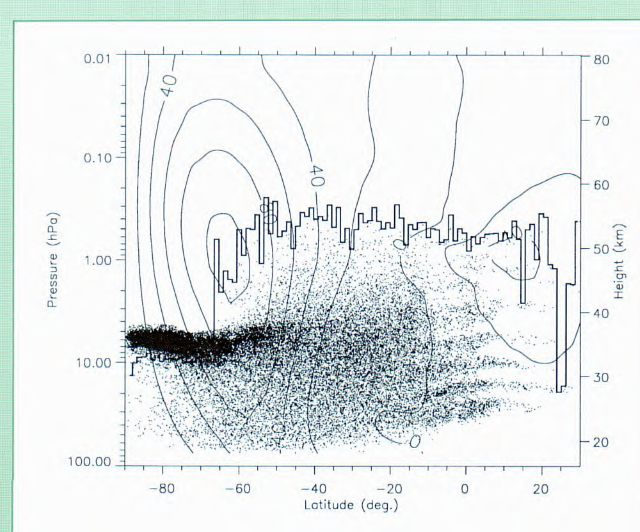


Figure 48. Particle locations from a numerical model simulation for:

(a) an initialization date of 1 April,



(b) 31 May,



(c) 29 August 1991.

Contours show modelled mean westerly wind speed.

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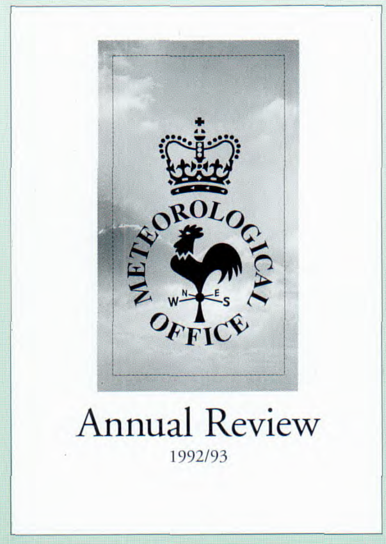
List of acronyms used in this report

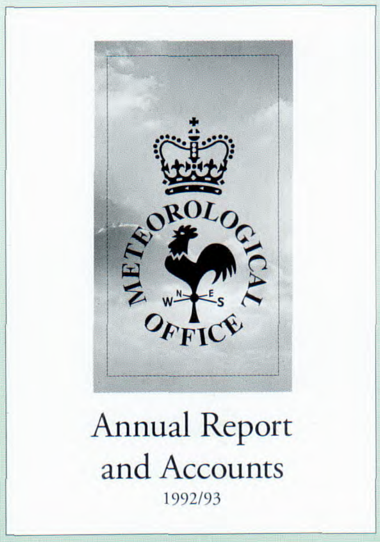
A&AEE	Aeroplane and Armament Experimental Establishment
ACARS	AirCrAft ReportS
AIP	Algorithm Intercomparison Projects
ALFENS	Automated Low Flying Enquiry and Notification System
AMIP	Atmospheric Intercomparison Project
AMPA	Advanced Mission Planning Aid
AMT	Air Mass Transformation
ASTEX	Atlantic Stratocumulus Transition EXperiment
ATOVS	Advanced TOVS
CCN	Cloud Condensation Nuclei
CEC	Commission for the European Community
CFO	Central Forecast Office
CGM	Computer Graphics Metafile
CBS	Commission for Basic Systems (WMO)
CIIS	Customer Information and Invoicing System
COSMOS	Met. Office's central computing complex
CRDN	Civil Rented Data Network
DEC	Digital Equipment Corporation
DMF	Data Migration Facility
DoE	Department of the Environment
DRA	Defence Research Agency
DTI	Department of Trade and Industry
ENSO	El Niño—Southern Oscillation
FAMIS	Finance and Accounting Management Information System
FCMS	Finance and Contract Management System
FDDI	Fibre Distributed Data Interface
FLIR	Forward Looking InfraRed
FOAM	Forecasting Ocean Atmosphere Model
GCM	Global Climate Models
GLOSS	Global Soundings System
GPCP	Global Precipitation Climatology Project
GUI	Graphics User Interface
HORACE	HQSTC OASYS Replacement and CFO Enhancement
HUD	Head-Up Display
ICE	International Cirrus Experiment
IBLEX	Internal Boundary Layer Experiment
IDMS	Integrated Database Management System
IMS	Inventory Management System
IPCC	Intergovernmental Panel on Climate Change
IREPS	Integrated Refractive Effects Prediction System
ISDN	Integrated Services Digital Network
ITE	Institute of Terrestrial Ecology
IWC	Ice Water Content
JCMM	Joint Centre for Mesoscale Meteorology
KNMI	Dutch meteorological service
LAM	Limited-Area Model
LAN	Local Area Network
LASS	Local Area Soundings System
LES	Large-Eddy Simulation

Met. TC	Meteorological Telecommunications Centre
MIST	Meteorological Information Self-briefing Terminal
MRF	Meteorological Research Flight
MOPS	Moisture Observation Pre-processing System
MORECS	Met. Office Rainfall and Evaporation Calculation System
MOS	Model Output Statistics
NAME	Nuclear Accident ModEl
NERC	Natural Environment Research Council
NESS	North European Storm Study
NRP	National Response Plan
NVG	Night Vision Goggles
NWP	Numerical Weather Prediction
OCP	Outstation Communications Processor
ODA	Operational Decision Aid
ODS	Outstation Display System
OPUS	Outstation Production Unified System
O−B	Observation-minus-Background
PEM	Parabolic Equation Method
P&EE	Proof and Experimental Establishment
PoP	Probability of Precipitation
RAFC	Regional Aviation Forecast Centre
RAL	Rutherford Appleton Laboratory
RIMNET	Radioactive Incident Monitoring NETwork
RMU	Remote Monitoring Unit
SAMSON	Simulation and Analysis of Measurements from Satellites using Operational aNalyses
SIGWX	Significant weather charts
SMS	System Managed Storage
TCC	Technical Co-ordination Centre
TDA	Tactical Decision Aids
TOGA-COARE	The Tropical-Ocean Global-Atmosphere Programme's Coupled Ocean Atmosphere Response Experiment
TOVS	TIROS Operational Vertical Sounder
TROPICS	Transmission and Reception of Observational and Product Information by Computer-based Switching
UK-ADMS	UK Atmospheric Dispersion System
UARS	Upper Atmosphere Research Satellite
WAFC	World Area Forecast Centres
WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe
WCRP	World Climate Research Programme
WGI	Scientific Assessment Working Group
WIN	Weather Information Network
WIS	Weather Information System

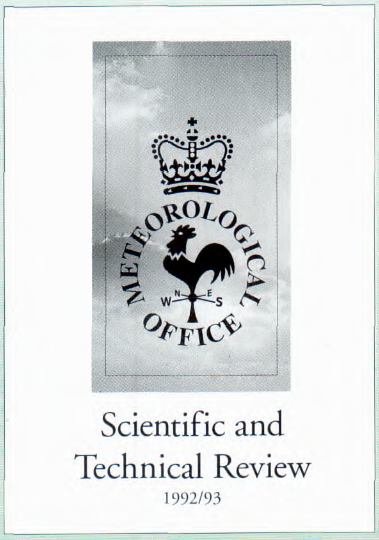
The Met. Office publishes its annual reports in three booklets, the *Annual Review, Annual Report and Accounts,* and *Scientific and Technical Review.*



The Annual Review *gives a summary of all the Met. Office's activities during the year. It covers new developments in public services, defence and commercial services and gives a résumé of research and development work, as well as providing a focus on our international interests and quality procedures. Its broad view of the Met. Office is of particular interest to those who do not specialize in meteorological science, but who have an interest in the use of weather intelligence.*



Full details of the Met. Office's accounts are provided in the Annual Report and Accounts, *which gives the Income and Expenditure Accounts, accounting procedures, and performance against targets, as required by the Treasury as a result of the Met. Office's status as an executive agency.*



The Scientific and Technical Review *gives a more-detailed account of the research work currently being carried out at the Met. Office. Among the many topics it covers are forecasting research, numerical models, use of new satellite data, plume dispersal, etc. It describes progress being made in climate change research at the Hadley Centre and the Met. Office's contribution to the IPCC. The* Scientific and Technical Review *contains a detailed bibliography of papers published by scientists at the Met. Office over the last year, and is a valuable guide for everyone engaged in research into physical and numerical processes in weather and climate.*

You can speak to our Enquiries Officer on the number below, or leave a recorded message out of normal office hours. You can also ask for leaflets giving details of all our services, including where you can hear the latest forecast on radio or television, by phoning your local weather centre (listed on the back cover) or the Enquiries Office. You can find details of our public services in programme magazines, newspapers and telephone directories under "Weather". We want to hear your views, and learn whether you are satisfied with the services we provide.

Copies of the Met. Office's *Annual Review, Annual Report and Accounts* and the *Scientific and Technical Review* for 1992/3 are available free of charge from the Enquiries Officer, The Met. Office, London Road, Bracknell, Berkshire RG12 2SZ. Telephone 0344 854455

Copies of the Report and Accounts are also available from HMSO.

Data Protection Act

If you DO NOT wish us to retain your address (so that we can send next year's Reviews as soon as they are published), please state this explicitly in any communication.

For services available in your area contact your nearest Weather Centre

Aberdeen Weather Centre	0224 210574
*Belfast Climate Office	0232 328457
Belfast Weather Centre	08494 22339
Birmingham Weather Centre	021-717 0570
*Bracknell Enquiry Bureau	0344 856207
Bristol Weather Centre	0272 279298
Cardiff Weather Centre	0222 397020
*Edinburgh Climate Office	031-244 8362
Glasgow Weather Centre	041-248 3451
Leeds Weather Centre	0532 451990
London Weather Centre	071-831 5968
Manchester Weather Centre	061-477 1060
Newcastle Weather Centre	091-232 6453
Norwich Weather Centre	0603 660779
Nottingham Weather Centre	0602 384092
Plymouth Weather Centre	0752 251860
Southampton Weather Centre	0703 228844

* These offices provide past weather and climatological information services only

International Marine and Offshore services enquiries:
Aberdeen Weather Centre +44 (0)224 211840

International Commercial Enquiries:
Bracknell Head Office +44 (0)344 856283

Recruitment:
Mrs. Kimberley Turner 0344 856038

National Meteorological Library: Bracknell Head Office
0344 854843

Enquiries Officer:
Mr. Martin Allwright 0344 854455

Head Office:
The Meteorological Office, London Road, Bracknell
Berkshire RG12 2SZ

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