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OPENING OF THE RICHARDSON WING BY THE PRIME MINISTER

On the afternoon of 6 October 1972, in warm and sunny weather befitting the occasion, the Meteorological Office was honoured by a visit from the Prime Minister, the Rt Hon. Edward Heath, M.B.E., M.P., who came to perform the official opening of the new wing of the Headquarters building at Bracknell. The new wing, which houses the Central Forecasting Office, the Telecommunications Centre and the Computing Laboratory, has been named after Dr L. F. Richardson, F.R.S., the pioneer of numerical weather forecasting.

The ceremony was held in the flower-decked entrance hall of the Richardson Wing before an assembly of distinguished guests, including six members of the Richardson family, and about 350 members of the staff of the Office.

The Prime Minister was greeted on arrival at the main entrance of the FitzRoy Wing by Mr Antony Lambton, M.P., Parliamentary Under-Secretary of State for Defence for the Royal Air Force, and Dr B. J. Mason, F.R.S., Director-General of the Meteorological Office. After signing the Visitors' Book (Plates I and IV), and having been introduced to the senior directors, the Prime Minister proceeded to the entrance hall of the Richardson Wing (Plate II). Here an address of welcome was given by Dr Mason, in the course of which he recalled the achievements of Lewis Fry Richardson (Plate VI) and said that he was proud to name the new wing after this remarkable man, in the presence of his son and daughter.

In his reply the Prime Minister said that it had been a happy inspiration to name the new building after Lewis Richardson, and that the computer and other facilities that it contained were unrivalled in Europe. He hoped very much that the Government's offer to house the European Centre for Medium-Range Forecasts at Shinfield Park, Reading, would be accepted. After some appreciative remarks about the value of the forecasts he received as a yachtsman from the Meteorological Office, the Prime Minister unveiled a commemorative plaque (Plates III and V).

After a break for tea with official guests and senior staff, during which Dr Mason presented him with an inscribed copy of *Meteorology for mariners*

(Plate VII), the Prime Minister was escorted by Dr Mason and Mr P. J. Meade, Director of Services, round the new building. In the Central Forecasting Office (Plate XI) he was able to see how forecasts based on the new 10-level hemispheric model are made for up to three days ahead and extended to five days by more subjective methods. He was shown a striking selection of satellite photographs, the radar display, and ships being routed across both the Atlantic and Pacific Oceans. In the Telecommunications Centre (Plate IX) he was able to see the new facsimile switching centre (Plate X) and the computer-controlled message-switching system that will soon link Bracknell with Washington, Paris and Offenbach on the Main Trunk Circuit of the World Weather Watch. In the Computing Laboratory (Plates XII and XIII), the power of the new IBM 360/195 computer, which besides its main forecasting role, already handles about 2500 research and other tasks a week, was explained and Mr Heath saw how charts are plotted and drawn at very high speed on the cathode-ray-tube plotter.

The Prime Minister, who appeared to thoroughly enjoy his visit, showed a lively interest in everything he saw, and spoke to several members of the staff during the tour. He later wrote an appreciative letter to the Director-General which is reproduced in Plate VIII.

The unveiling of the plaque by the Prime Minister, film showing the operations and facilities in the new wing, and an interview with the Director-General were shown on BBC Television News at 7.30 and 9 p.m. on the same day.

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THE RICHARDSON WING*

The Richardson Wing forms the fourth side of a square around a grassed court, the other three sides consisting of the original building. It is a fine new building of five storeys designed and built by the Department of the Environment and houses the Meteorological Office operational centre containing the Computer Laboratory (ground floor), the Telecommunications Centre (first floor), and the Central Forecasting Office (second floor). Administrative offices occupy the third floor and heating, ventilating and electric plant the lower ground floor.

Air-conditioning plant maintains prescribed temperature and humidity conditions and the control system of the plant enables a fault to be located rapidly in the event of a failure.

An electrical passenger lift has been installed to all floors and there are also electric document-conveyors to suit operational requirements.

The Computer Laboratory. The development of a sophisticated 10-level atmospheric model and other projects requiring much larger computer power

* The main sections of this article were contributed by Messrs G. A. Howkins, D. McNaughton and C. Alderson respectively.

than was provided by the KDF9 computer (COMET) has led to the purchase in 1971 of an International Business Machines (IBM) 360/195 computer. The IBM 360/195 is one of the most powerful computers in the world, capable of about 10 million instructions per second, and currently only three such computers are installed in Europe. The Bracknell installation, including its air-conditioning plant and power supplies, occupies the whole of the ground floor and a substantial part of the lower ground floor of the new Richardson Wing.

The computer system is based on the IBM 360/195 central processor with 1 million characters of main storage and over 1200 million characters of fast on-line disc storage. A wide variety of standard input/output peripherals are included, such as card readers/punches, paper-tape readers/punches, line printers and magnetic-tape drives. The computer configuration provides a substantial degree of protection against peripheral failures which might interrupt operational forecasting schedules. In addition to the standard peripherals, there are a Calcomp computer output on microfilm system for plotting and line-drawing functions, two IBM 2250 graphic cathode-ray-tube (CRT) display units and several IBM teletypewriters and CRT alpha-numeric terminals providing remote job-entry facilities.

The new system was installed in October 1971, only three weeks after the planned installation date, and after trials supervised by the Ministry of Technology was handed over to the Meteorological Office shortly before Christmas 1971. A work load of over 1000 jobs per day had been absorbed by the New Year and, in spite of interruptions to electrical power supplies, a hemispheric version of the new 10-level model was implemented operationally on 1 August 1972. Also routine computations of the new fine-scale 10-level model for the British Isles are made twice daily.

Meteorological Telecommunications Centre. For many years the main 'tools' of communication have been teleprinters operating at comparatively slow speeds either by means of land-line links or through radio transmissions. The Bracknell Telecommunications Centre still relies heavily on these machines and, for purely internal communications between the U.K. outstations and Bracknell, will continue to do so for some years to come. But the picture is changing and Bracknell, in common with similar large centres in other parts of the world, has embarked on a programme of automation which will lead before long to the replacement of many of the slow-speed teleprinter channels by which information is received from Europe, North America and farther afield, by a new and very sophisticated computer-controlled message-switching system. In the new Automated Complex two Marconi *Myriad II* digital computers are already controlling the flow of meteorological traffic at speeds up to about 50 times that of a conventional teleprinter along the new 'main highway' provided by the Main Trunk Circuit which links Bracknell with Washington in the west and Paris and Offenbach in the east. Soon after this article is published the first part of the system will become operational and there will be a significant speeding up of the reception of information from a very wide area. Later, the extension of the Main Trunk Circuit through Moscow, New Delhi, Melbourne and Tokyo to encircle the globe, the implementation of various regional branches and circuits and the introduction of more automation in the Telecommunications Centre, providing (amongst other refinements) a 'preferred order' system for domestic teleprinter broadcasts and an electronic interface with the IBM 360/195 which produces forecasts, will still further improve and speed up the services provided.

Apart from the raw material of meteorological exchange there is an important requirement for the distribution of processed information both actual and forecast in various pictorial forms, e.g. charts of contours, isotachs and isotherms at various levels in the atmosphere. The Facsimile Section meets this requirement and operates four facsimile broadcasts almost continuously. One provides a service by land-line to most meteorological offices in the United Kingdom and consists mainly of support for their forecasting activities from the resources of the Central Forecasting Office. Two radio-facsimile broadcasts meet agreed international requirements for processed charts from Bracknell and a number of other important centres (including Moscow and Washington) for the general support of meteorological services, including those devoted to maritime and aviation activities. A further land-line service transmits charts produced by the IBM 360/195 direct to the large aviation offices at London/Heathrow Airport and the Headquarters of Strike Command and No. 46 Group, RAF. Bracknell arranges for the receipt of facsimile products from a number of other countries, and the exchange of similar products (alternately with alphanumeric data) will have an important place in the Main Trunk Circuit. There are also extensive arrangements for recording on magnetic tape so that charts can be accepted as they become available and fed into the various parts of the system when they are required.

Already the Telecommunications Centre receives and transmits more than 1½ million groups of weather information a day, as well as some 1000 facsimile weather charts and a very large number of plain-language forecasts and messages. As the volume and speed of traffic increases and as new methods and procedures are introduced the Telecommunications Centre will vary its facilities and services to meet changing needs. The new accommodation provided in the Richardson Wing will make a significant contribution to this development.

Central Forecasting Office. The Central Forecasting Office (CFO) entrance vestibule has a comfortable waiting area, decorated with a very fine series of cloud studies by R. K. Pilsbury, F.R.P.S. There is a Visitors' Room with a permanent display of information and of the charts used in CFO. The work of CFO is usually described to parties of visitors in this room. Met O 2b, who provide operational numerical forecasting program support, occupy the western end of the floor, together with the Storm Tide Warning Service and the *Daily Weather Report* office.

The forecast room and adjoining offices are air-conditioned and are completely carpeted. Benches and light-tables were specially designed and are grouped into convenient working units. The senior forecaster and deputy, and the medium-range and British Isles forecasters occupy one unit, ships' routeing section another and upper-air forecasters and plotters a further set of units. Surface plotters and the supervisors have their own sets of benches, as also has the Sea Ice Section. Along one wall are the warning display boards. These are made of stainless steel, with outlines of countries and warning areas etched in, and magnetic plastic characters are used to mark up the warnings state.

Adjoining the upper-air section is an IBM 2250 graphic display unit which is linked directly to the main computer on the ground floor. It is intended to use this unit in a number of ways including some control aspects of the numerical forecast program suite. Immediately in front of the senior forecaster is a weather radar display; this is transmitted via closed-circuit television from the radar display which is housed in a room which is also used for the conversion of satellite pictures into nephanalyses and for adding the geographical co-ordinates to such pictures.

Another room off the main forecast area houses the photo-reproduction equipment, which comprises an ADMEL PD 600 copier, used for making copies of charts, for distribution in the forecast room and to other branches and other government departments, and a Rank Xerox 1824 universal printer, which enlarges and prints, from 35-mm film produced by the Calcomp 1670 housed in the Computer Laboratory, upper-air analyses and prognostic charts which are subsequently broadcast on facsimile.

In the corner of the forecast room are lifts, connecting with the Meteorological Telecommunications Centre (Met TC) and the Computer Laboratory, which are used to pass information both to and from CFO. There is also a hand hoist, which connects directly with the facsimile area of Met TC, and from the Editing Room a conveyor bringing teleprinter data for plotting on the working charts by the assistant staff.

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THE METEOROLOGICAL OFFICE 360/195 COMPUTING SYSTEM

By G. A. HOWKINS, M.B.E.

Summary. The article is in three parts. The first part outlines the main data-processing functions to be fulfilled by the new computer and the second part outlines progress made prior to installation and during the first year of operation. The last part outlines, with the minimum of technical terms, some of the differences between the three computers used by the Meteorological Office and describes several of the more important features of the new configuration. A technical comparison of the three systems is made in an Appendix.

Introduction. A review of Meteorological Office computing requirements for the next decade was completed in 1968. The review revealed that, of 16 branches already involved in computing, 14 expected only a modest increase in their computing activities and much of this increase would depend on extended facilities for data archiving and retrieval. However, 2 branches, Met O 11 — Forecasting Research — and Met O 20 — Dynamical Climatology — were heavily involved in atmospheric modelling and foresaw the need for a major increase in computing power. Also the Telecommunications Branch, Met O 5, and Operational Instrumentation Branch, Met O 16, who were not at that time involved in computing, planned extensive automation of the telecommunications functions and the upper-air sounding networks, but this new work would be done by means of dedicated computers which would place little or no demands on the main computer serving the rest of the Office.

The main data-processing functions.

Atmospheric modelling. Lewis Fry Richardson[1] first conceived the idea of computing forecasts 50 years ago but no real progress could be made in this field until electronic digital computers had been developed. The Meteorological Office first started research into such schemes in the early 1950s, hiring time on suitable computers, and regular experiments were mounted on the first Meteorological Office computer — a Ferranti *Mercury* (METEOR) installed in 1958. Regular operational forecasts were introduced when the more powerful English Electric-Leo KDF9 (COMET) replaced METEOR in 1965. COMET was used from 1966 to 1972 to compute forecasts twice daily using a 3-level 'dry' atmospheric model, a 24-hour forecast taking about 20 minutes to compute (about 1 hour if data input, analysis and printing of results are included). Meanwhile the Forecasting Research Branch (Met O 11) began experiments on a more complex 10-level 'moist' model potentially capable of quantitative forecasts of precipitation. Computations for this model were first done on the International Computers Limited *Atlas* computer at Manchester University and subsequently on the *Atlas* computer at the Science Research Council establishment at Chilton. The *Atlas* computer is about 5 times faster than COMET but the new model required about 40 times more instructions than the 3-level model and a 24-hour forecast took several hours to compute on *Atlas*. While Met O 11 were experimenting with the 10-level model for short-range forecasting, Met O 20, the Dynamical Climatology Branch, were developing models to compute experimentally changes in hemispheric circulation taking place over a period of about 3 months. A large amount of computing was involved in each experiment because the forecasting interval was necessarily long and the area covered large. The computing capacity required by Met O 20 was at least as great as that required by Met O 11 for the new 10-level short-range forecasting models.

The encouraging results obtained on the Chilton *Atlas* provided the main reason for the purchase of a new high-speed computer system which had to be at least 10 times faster than *Atlas* to complete the development of the Met O 11 and Met O 20 models and to run the Met O 11 model for operational forecasting.

The operational numerical forecasting suite. Logically an operational numerical forecasting suite consists of four main groups of programs which :

(a) check and store the observations which form the basic data,
(b) produce analyses,
(c) compute forecasts,
and (d) output results.

The last step involves not only the presentation of results in the forms required by forecasters but also a considerable amount of computation to derive results such as tropopause data, and wind speeds and directions for pressure levels and along specified aviation routes, none of which are produced directly in computing the forecasting model.

In the KDF9 forecast suite, based on the 3-level 'dry' atmospheric model and written jointly by Met O 2, the Central Forecasting Branch, and Met O 11, the Forecasting Research Branch, data handling was confined to those items required specifically for the production of the analysed fields from which the forecast is computed. Other data, e.g. weather types, visibility, were not stored. In the new forecast suite, data handling was undertaken by Met O 12, the Data Processing Branch, and a more general approach was taken because it was expected that in the future more time-critical applications would be made of all types of synoptic data (e.g. for automated chart plotting). This led to the concept of a synoptic data bank in which all types of data received through the telecommunications channels in the past 60 hours would be stored 'on-line' to the computer on magnetic discs. While on disc, recognized data would undergo quality controls in several stages. Also generalized retrieval routines would be written to enable users to select and retrieve data to suit their requirements. After 60 hours residence on-line to the computer, all data, whether sorted into code types or not, would be stored on magnetic tape for permanent retention in archives. Thus the synoptic data bank is designed to provide the maximum amount of reliable data for time-critical projects run at various times of day and, to realize the full potential, data should be received continuously from the telecommunications channels.

The early versions of the synoptic data bank programs were written to provide only the essential data for known projects, such as the operational forecasts, but the design was such that additional programs could be introduced as the need arose. Also all data, whatever the code, were preserved and it will be possible to re-examine the stored data using later programs to extract more data.

In addition to retention in archives as a permanent synoptic data bank of quality-controlled observations, the data will be used by Met O 22, the newly formed Systems Development Branch, as one of several sources of data for a permanent climatological archive of data stored as time series for each each reporting station.

Because of this general approach adopted by Met O 12 for the synoptic data bank, Met O 2(b), the numerical-forecasting section of the Central Forecasting Office (CFO), wrote routines to select from the data bank those meteorological data required by the analysis programs, i.e. to set up the basic analysis data sets (BADS). The Met O 11 analysis programs are not very different in concept from those in the earlier 3-level suite but humidity analyses were required and because of the finer structure of the new model extra care was necessary to obtain 3-dimensional consistency in the analyses for the 10 levels. Met O 11 developed two forecast suites, both based on the 10-level atmospheric model. The 'octagon' forecast suite covers an octagonal area centred on the North Pole and extending over most of the northern hemisphere north of about 15°N. The octagon suite is designed to fulfil the functions of the 3-level model in providing forecasts for civil and military aviation and guide-line forecasts for weather over the CFO area of responsibility up to 72 hours ahead. The octagon model employs a grid of about 3000 points at approximately 300-km intervals at 60°N and the time step used to compute a forecast is 400 seconds. The finer-scale rectangle forecast suite, designed primarily to produce quantitative precipitation forecasts over the British Isles and near-European areas, covers about one-tenth of the area covered by the octagon and includes much of the North Atlantic Ocean and western

Europe. The distance between grid points is 100 km and the time step used is 150 seconds. As there are about the same number of grid points in the two versions of the 10-level model, the time taken for computation depends on the time step chosen, the rectangle taking about 35 minutes and the octagon 13 minutes for a 24-hour forecast on the 360/195.

Met O 2(b) operational output routines convert the forecast results to fields of data for standard pressure surfaces. The printed results are broadly similar to those from the 3-level model including a considerable amount of derived data such as that on the tropopause from the Brady modelling technique,[2] and wind speeds and temperatures for standard pressure surfaces along certain aviation routes and at major airports. Winds and temperatures for routes are punched directly to paper tape for teleprinter transmission to London/Heathrow Airport and Prestwick Airport where these data are fed into flight-planning and flight-control computers. Most of the output for standard pressure levels is produced on fast 2000-line-per-minute printers and is printed as contours in the form of 'zebra' prints on special continuous stationery with a chart background. These charts display isopleths of wind direction, wind speed and temperature, which are used as the basis of flight-planning documents for both civil and military aviation.

Data archiving and retrieval. The 1968 review of requirements showed that archiving and retrieval of data would increase steadily as new or expanding projects such as the Dee Valley rainfall study[3] and medium-range and seasonal forecasting studies generated new data banks or as new applications were developed for the large volumes of synoptic data already collected daily from much of the northern hemisphere. In particular, extended automation of time-critical functions such as line drawing and plotting of synoptic charts and preparation of the daily, monthly and annual publications would lead to increased use of a wider range of data than that currently used for operational numerical forecasting with the 3-level 'dry' atmospheric model. However, the processing power required for such functions is very small by comparison with the power required for computing atmospheric models for operational numerical forecasting and any processor capable of the latter would easily cope with archiving functions if sufficient fast on-line storage and archival storage were provided.

General computing service. In addition to the data archiving, atmospheric modelling and operational forecasting functions already described, there was a requirement for a general computing service covering the work of 16 of the 22 branches in the Meteorological Office. This embodies a whole spectrum of work from the short development jobs with little or no data or storage requirements to the very long and complex runs for proving a new operational forecasting suite. It is comparatively easy to provide a quick 'turn round' for jobs which require few facilities and take only a short time to compute but difficult to provide an acceptable service for jobs requiring a large share of the facilities and taking a long time to compute.

Pre-installation facilities and the first year of operation.

Pre-installation. An operational requirement for a new computing system was drawn up in 1968 and negotiations with several major manufacturers culminated in the ordering on 31 December 1969 from International Business

Machines Ltd (IBM) of a configuration based on the IBM 360/195 central processor. After the order had been placed the company made available programmer training facilities at Sudbury and by December 1971 when the computer was installed at Bracknell, 160 staff had been trained in the 'high-level' language FORTRAN IV and 70 were also trained in the 'low-level' IBM language known as ASSEMBLER. The company also made available facilities for program development at their Customer Test Centre (CTC) at Croydon, mostly on an IBM 360/65 computer, and at Poughkeepsie (U.S.A.), mostly on an IBM 360/195. The former, although much slower than the 360/195, belongs to the same series and programs written for the 360/65 will run on a 360/195. From October 1970 to December 1971, when the new system was available at Bracknell, a total of 240 hours of computer time were used at Poughkeepsie by Met O 2, 11 and 12 to develop operational forecasting suites based on the new 10-level model and by Met O 20 for their hemispheric model. All 16 branches involved in computing made use of the Croydon facilities to convert projects already running on COMET and to start new work for the 360/195.

Three methods were used : most jobs were delivered to CTC by a security service van for computer processing at night and return to Bracknell by road early on the following morning, others were taken to Croydon by individual programmers and, with effect from October 1970, day-time runs could be obtained for all but the largest programs by submission through a card-reader/line-printer terminal installed at Bracknell and linked by telephone line to Croydon. By the time that the 360/195 was available at Bracknell the weekly total of Meteorological Office jobs run at Croydon had exceeded 1000 and it was imperative that the new installation at Bracknell should absorb this work load smoothly and over a short period of time to avoid delaying the work of all branches. During the pre-installation period, and to the present date, IBM provided systems engineers at Bracknell to assist branches, as required, in the development of their new programs.

The first year of operation. The 360/195 was installed in the new Richardson Wing in October 1971 (see Plate XII), passed its acceptance tests by mid-December and by the end of that month was carrying the full work load from Croydon, together with some of the large jobs from Poughkeepsie. During the first four months, despite power problems and teething troubles generally, Met O 2, 11 and 12 made every effort to bring the development and testing of the new 10-level forecasting suites to an operational state. Both the octagon and rectangle suites were run twice daily on most days from March onwards. Met O 2 also had the responsibility of completing the development of a program to simulate the functions of the KDF9 COMET on an IBM 360/195 machine using a 'simulator' program purchased from the Nuclear Power Group, Knutsford, for the purpose of running the 3-level program suite on the 360/195. The simulator makes it possible to run programs written in USER code for KDF9 on an IBM 360 series computer without reprogramming in IBM ASSEMBLER code. This method, although very slow in computation, avoided reprogramming the complex 3-level suite which was only required for a short period in the new 360 system.

Apart from a few short breaks of service the 360/195 was operated 14 hours per day seven days per week from 18 December 1971 to 21 March 1972, when full 24-hour operation was introduced. Full 24-hour operation, including operation of the 3-level forecasting suite, also continued on COMET until the end of April 1972, after which COMET operations were reduced to 14 hours per day. The 3-level suite also ran on the 360/195 under the simulator program from 21 March and on 1 May the output from the new computer system assumed the operational role.

By the middle of 1972 the 10-level octagon suite was judged to be sufficiently developed for it to replace the 3-level suite as the main operational model and operation of the latter ceased on 31 July. Met O 11 are continuing the development of the 10-level rectangle model, which is intended primarily for quantitative precipitation forecasts, and forecasts are computed twice daily from the same data as those applied to the operational octagon suite.

It had been planned to transfer synoptic data between the telecommunications computers and the 360/195 by means of a high-speed electronic interface but it became clear that the telecommunications computers would not be available when the 360/195 was installed and it was necessary to develop programs to process data from 5-hole Murray-code tape punched in the telecommunications centre. The method is slow and cumbersome and poses serious problems which must be overcome as more frequent time-critical and data-dependent operations such as chart plotting are introduced.

Although the main emphasis in the first year has been on the development and introduction of the new forecasting models, the work of other branches has progressed well and the total of development jobs has risen from 1000 per week at installation to about 2500 per week by November 1972.

The new hardware and control programs. In digital computers the binary forms of characters and numbers are represented by strings of electrical impulses (Sumner[4]) and the ultimate constraint on computer operating speeds is the time required to transfer these impulses between the components of the processor. The Ferranti *Mercury* (METEOR) installed in 1958 was a first-generation machine based on thermionic valves which were physically large and well separated to disperse the generated heat. The English Electric-Leo KDF9 (COMET) installed in 1965 was a second-generation machine employing closely packed transistors with low power consumption and achieved operating speeds about 10 times that of METEOR. The IBM 360/195 is a third-generation machine based on solid logic technology which achieves a very high packing density by means of layers of miniature printed circuits mounted one on top of the other. It is one of the fastest third-generation general-purpose machines available commercially and is 50 to 100 times faster than COMET. A comparison of the three systems is given in the Appendix.

All modern general-purpose digital computer systems include the following :

(a) Central processing unit, where the instructions which make up a program are carried out.

(b) Main storage, where programs and data reside while the former are executed.

(c) Input devices, such as paper-tape or card readers, for entering programs and data, and output devices, such as line printers, for printing results.

In addition most systems have one or more types of backing store, where programs and data may be stored on-line to the computer ready for transfer to main store and program execution. Backing stores, although slower than the main store, are much faster than input/output devices and therefore contribute greatly to the overall through-put of work.

Although computing speeds are very dependent on central processor design, the operating speeds of the early computers were constrained by the speeds of the devices used to input programs and data because programs were submitted serially and each one ran to completion before the next was submitted. Nowadays most medium-to-large systems, including most second-generation machines, use a control program (variously called 'operating system', 'supervisor' or 'director') which ensures that other work is started if the program currently being executed has to wait for any reason. This philosophy has been extended to the hardware design in the latest machines. Special stored-program computers (IBM 'channels') are used to connect the input and output devices to the main computer. When input or output is required, the main computer 'instructs' the appropriate channel to undertake the work and the main processor is halted from its main task of computing only long enough to start or stop the channel. Once started the channel completes the data transfer unaided by the main computer.

The control program or operating system also includes a number of facilities such as system 'readers', 'writers' and job 'initiators' which can be stopped and started at will by the operator in charge at the console. Readers and writers control respectively the inflow from devices such as card readers and paper-tape readers to on-line discs and the outflow from discs to line printers or microfilm devices. Initiators may be started for each class of job defined for the system or for several classes to be selected in the order defined by the operator when the initiator is itself selected. Initiators allow the operator to create a mix of work which makes maximum use of all the facilities on the system or to ensure that work which has priority or is time-critical takes precedence when required.

The 360/195 gains much of its speed from a feature known as a high-speed buffer which is linked through a control unit to the main storage and the elements which undertake the computation. The buffer operates at a much higher speed than main storage and blocks of programs (about 20 instructions) or data are copied from main store as the program is executed. Most parts of a program and the related data are required in sequence and hence on almost all occasions the next instruction is waiting with its related data in the buffer and can be transferred very rapidly to the appropriate part of the central processing element (see Figure 1). A 'fetch' of the next block of instructions takes about 20 times as long as a transfer from the buffer but is required only when the next instruction to be obeyed (normally the next in sequence) is not already in the buffer, i.e. when all the immediately usable instructions already stored in the buffer have been obeyed.

The central processing element includes several parts, each of which executes a certain type of instruction, and all parts can operate concurrently with each other. Also, most instructions involve several actions in sequence but the next instruction can be analysed and started before its predecessor is completed.

During 1971 IBM announced a new series of peripherals including new magnetic tapes, discs and alphanumeric cathode-ray-tube peripherals suitable for the 360/195, but these were not available when the new system was installed in December 1971 and the initial configuration included older types on hire until the new devices became available. The installation is now complete and is shown diagrammatically in Figure 1.

Most peripherals are duplicated on separate channels and automatic two-channel switches are provided for the disc storage devices so that data can be read from or written to discs through the alternative channel if the normal channel is not available. The fixed-head disc, which is a very fast storage device of particular importance for operational numerical forecasting, is not duplicated because of its high cost, but alternative forecast programs have been developed which rely on the moving-head disc drives operating at about half the speed of the fixed-head device.

Five other types of device also deserve special mention. Two KDF9 magnetic-tape drives have been attached through special hardware, thus providing the means of transferring data to and from COMET and also the capacity to read any of the several thousand KDF9 magnetic tapes written during the lifetime of COMET.

The two IBM 2250 graphics display units consist of a cathode-ray tube for the display of characters, numerals and curved or straight lines. Each is equipped with a light-pen (see Plate XIII), alphanumeric keyboard and function keyboard. Programs, which are activated by the function keys, are under development to display data, plot diagrams, including tephigrams, and plot synoptic data to a variety of scales and a selection of areas on a map background. Options are selected by means of the light-pen. One display unit is installed in the Central Forecasting Office (CFO) for experiments on time-critical applications.

The Calcomp 1670 computer output on microfilm (COM) system may be operated off-line, using a 9-track magnetic tape, or on-line to the 360/195. It is a very high-speed incremental plotter which displays data on a very high-resolution $4\frac{1}{2}$-inch cathode-ray tube with an addressable matrix of 16 384 points in the x and y directions, but only $\frac{1}{4}$ of the points can be resolved. There are facilities to superimpose backgrounds, such as coastlines, optically by means of a forms projector — alternatively backgrounds may be produced by program. It takes only about 5 seconds to plot and record on film a British Isles surface chart or to draw the isobars, but about 10 minutes are required to develop film and to produce the first print ($14 \cdot 5 \times$ magnification) of a series by means of a Xerox printer in CFO.

Six IBM 2741 typewriter terminals are attached to the system, five in various branches in the headquarters main building and one at a remote site by means of a telephone line; a second remote unit will be installed at the Meteorological Research Flight, Farnborough. The terminals are similar to a standard electric typewriter and operate under a program known as Conversational Remote Job Entry (CRJE). They are used primarily to create and edit stored programs and data, but programs can be started from the terminals and output routed to the high-speed printers in the computer room or, if the amount is small, the user can receive it on his own slow-speed typewriter. Four cathode-ray-tube alphanumeric terminals with a supporting line printer are being installed in a special area near the computer room for use by all branches and will operate under CRJE, providing much the same facilities as the typewriter terminals.

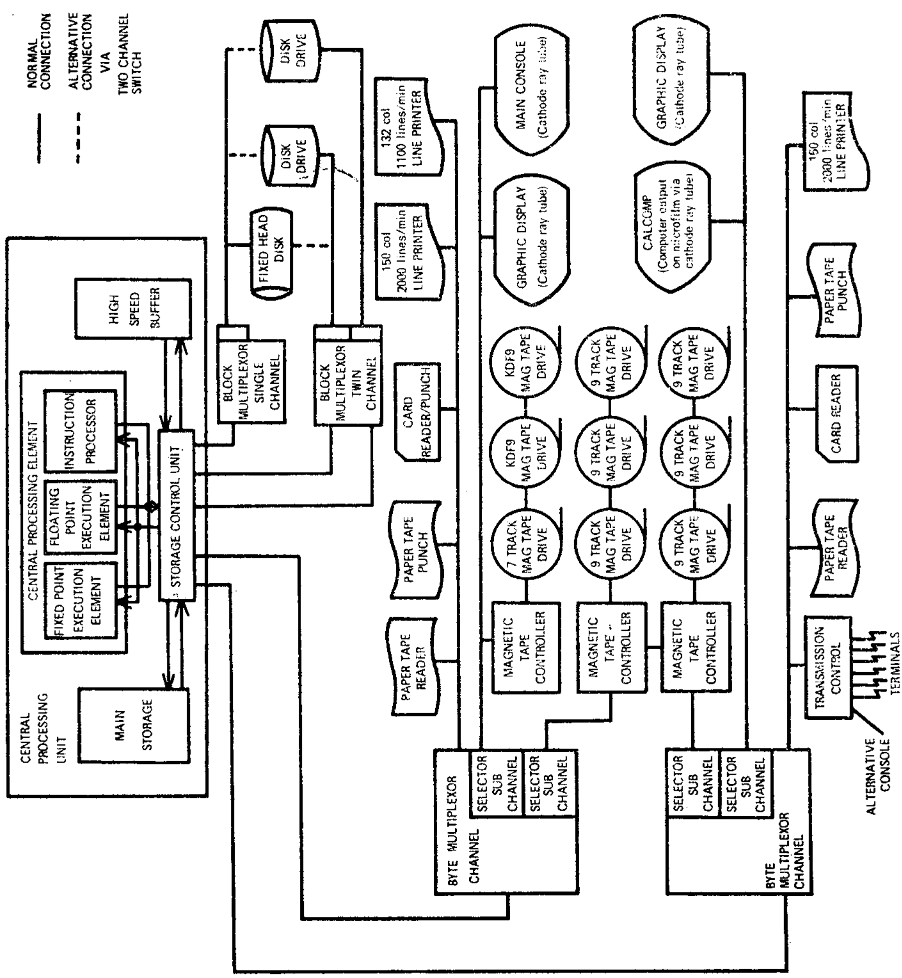

FIGURE 1—METEOROLOGICAL OFFICE IBM 360/195 COMPUTER SYSTEM

Concluding remarks. The planning and implementation of the new system demanded sustained efforts not only from several branches of the Meteorological Office but also from other government departments, such as the Department of the Environment, in providing the new accommodation with its many ancillary services, and the computer branches of the Ministry of Defence, Civil Service Department and Her Majesty's Stationery Office, in the planning, selection and procurement of the computer equipment. It was no small achievement on the part of everyone and of IBM to complete the installation within 3 weeks of the planned date. Now, less than 12 months from hand-over, the computing laboratory is handling about 1200 jobs per week for operational forecasting purposes and about 2500 other jobs per week for all branches. This is in no small measure due to the hard work done in Met O 12 by systems planning and operating staff who had almost no opportunity to gain practical experience before the equipment was installed and who were faced with the difficult task of absorbing immediately a heavy work load from Croydon and Poughkeepsie while, at the same time, introducing and developing a suitable operating system. The 360/195 is the most powerful computing facility serving any meteorological service in the world and a great deal of work has been done in the first year of operation. Nevertheless, further efforts will continue to improve the software and operating system to cope with the continually rising work load and consideration is being given already to some increase in the hardware facilities.

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3. HARDING, J.; Rainfall measurement by radar — Dee Weather Radar Project. *Bull Wld Met Org, Geneva,* **21**, 1972, pp. 90–94.
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APPENDIX

Comparison of METEOR, COMET and IBM 360/195

	METEOR	COMET	IBM 360/195
(a) Operating speeds (microseconds)			
Basic machine cycle	60	6	0·05
Access to high-speed buffer store			0·16
Access to main store	120	7	0·81
Addition and subtraction — fixed point		1	0·05
— floating point	180	10	0·11
Multiplication — fixed point		15	0·49
— floating point	300	17	0·16
Division — fixed point	3800	37	1·94
— floating point	3800	37	0·54
(b) Major storage capacities (1024 bytes)			
High-speed buffer			32
Main store	5	144	1 024
Magnetic drum or fixed-head disc	80	240	11 470
Discs			1 170 000

(c) Input/output speeds	METEOR No.	METEOR Speed	COMET No.	COMET Speed	IBM 360/195 No.	IBM 360/195 Speed
Magnetic-tape units			6	40 000 bytes/s	6	120 000 bytes/s
Paper-tape readers	1	300 ch/s	3	1000 ch/s	2	500–1000 ch/s
Paper-tape punches	1	33 ch/s	3	110 ch/s	2	120 ch/s
Card readers			1	600 cards/min	2	1000 cards/min
Card punches					1	300 cards/min
Line printers	1	150 lines/min	1	1000 lines/min	2	2000 lines/min
					1	1000 lines/min

ch = characters

551.509.334

FORECASTING SEASONAL RAINFALL AND TEMPERATURE FOR ENGLAND AND WALES IN SPRING AND AUTUMN FROM ANOMALOUS ATMOSPHERIC CIRCULATION OVER THE NORTHERN HEMISPHERE

By R. MURRAY

Summary. Monthly mean pressure data over the northern hemisphere for nearly 100 years are analysed and simple indices of anomalous circulations in the three months of winter and summer are derived and related to seasonal rainfall and mean temperature over England and Wales in spring and autumn respectively. The prediction rules can be applied in an objective manner. Except in a minority of cases, very useful seasonal forecasts can generally be made.

Introduction. The long series of monthly mean pressure data for the northern hemisphere (1873 to 1969) on magnetic tape have been analysed in searching for possible circulation parameters in key areas of the hemisphere during the three months preceding 'wet' or 'dry' and 'cold' or 'warm' springs and autumns. In this context the terciles of seasonal rainfall over England and Wales and the quintiles of mean temperature over central England are employed. For the detailed procedure and data references two recent papers by Murray[1,2] should be consulted. However, the method may be briefly outlined by an example.

Figure 1(a) is the composite monthly mean pressure anomaly (PA) map for July preceding very cold (quintile 1) autumns in central England, obtained by averaging the PA in each of the 18 Julys which preceded autumns with mean seasonal temperature <9·1°C in central England. Similarly Figure 1(b) shows the composite map for July preceding very warm autumns (based on 20 cases each with autumn mean temperature >10·4°C). Areas where the PA is significantly different from zero at the 5 per cent level of significance are shown as broken lines in these figures. Figure 1(a) is broadly like Figure 1(b) with the signs of the anomalies reversed. Composite maps such as Figure 1 suggest that anomalous circulation in certain areas, generally indicated by significant PA, might be related to subsequent circulation developments leading to cold or warm autumns. The PA at selected points, usually near the centre of areas suggested as significant on the composite maps (or the difference between the PA at two points when this procedure appeared more relevant) were computed for each winter (or summer) month and related to the subsequent spring (or autumn) mean temperature. The ranked PA were examined to see whether they showed worthwhile association with the following spring (or autumn) mean temperature, and classified provided the following objective criteria were satisfied :

(a) The class must contain at least 15 years.

(b) If both ends of the distribution of ranked pressure data appear to have an association with autumn temperature then for each class $SS \geqslant 1{\cdot}2$, where SS is the Sutcliffe Score (see Murray[1]).

(c) If only one end of the distribution of ranked pressure data appears to have an association with autumn temperature then $SS \geqslant 1{\cdot}4$.

(d) The pressure class was taken so that the critical pressure anomaly boundary was a whole number (e.g. PA > 3·0 mb) provided also that (a) and either (b) or (c) were satisfied.

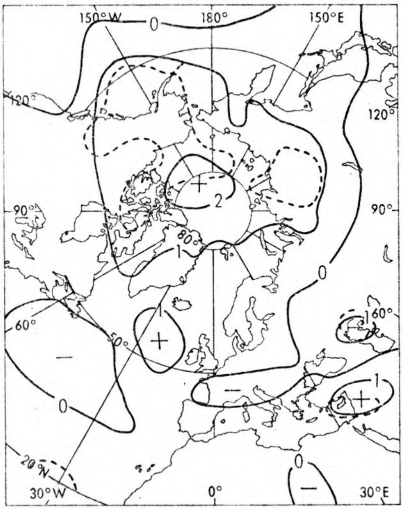

FIGURE 1(a)—MEAN PRESSURE ANOMALY PATTERN IN JULY PRECEDING VERY COLD (QUINTILE 1) AUTUMNS OVER CENTRAL ENGLAND.

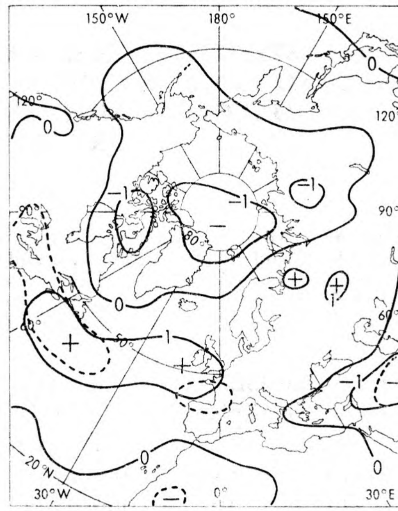

FIGURE 1(b)—MEAN PRESSURE ANOMALY PATTERN IN JULY PRECEDING VERY WARM (QUINTILE 5) AUTUMNS OVER CENTRAL ENGLAND

Pressure anomalies (1-mb intervals) from 1873–1968 average. Broken lines enclose areas where anomalies are significantly different from zero at 5 per cent level according to *t*-test.

Whenever the PA (or PA differences) were derived for nearby places and obviously represented the same anomalous features of the circulation, one was generally selected as representative.

The same procedure was employed to obtain the basic rainfall predictors except that terciles and upper and lower ten-percentiles of rainfall were used instead of quintiles.

Forecasting spring rainfall. Table I contains basic information on simple indices of anomalous circulation in December, January and February associated with dry or wet springs to follow.

The basic predictors in Table I cannot all be satisfied in a particular year, but often a preponderance of predictors of either dry or wet springs is in evidence. A simple discriminant procedure was adopted in the two recent papers by Murray.[1,2] Equal weight was given to each of the basic predictors in Table I; whenever the critical anomaly criteria are satisfied the differences between the number of rules predicting dry and the number predicting wet were related to the rainfall terciles of the following springs. Different weights could of course be given to different basic predictors in different months, but the simplest type of assumptions have in fact been made and the results shown in Table II appear to be satisfactory.

Table II shows that rather weak indications of spring rainfall are in evidence from December data. More useful predictions are likely to be available at the end of January, shown under (b) and (d). Finally when

PLATE I—THE PRIME MINISTER, THE RT. HON. EDWARD HEATH, M.B.E., M.P., SIGNING THE VISITORS' BOOK ON ARRIVAL AT THE METEOROLOGICAL OFFICE, BRACKNELL, ON THE OCCASION OF THE OPENING OF THE NEW RICHARDSON WING ON 6 OCTOBER 1972

The Director-General, Dr B. J. Mason, F.R.S., is on the left.

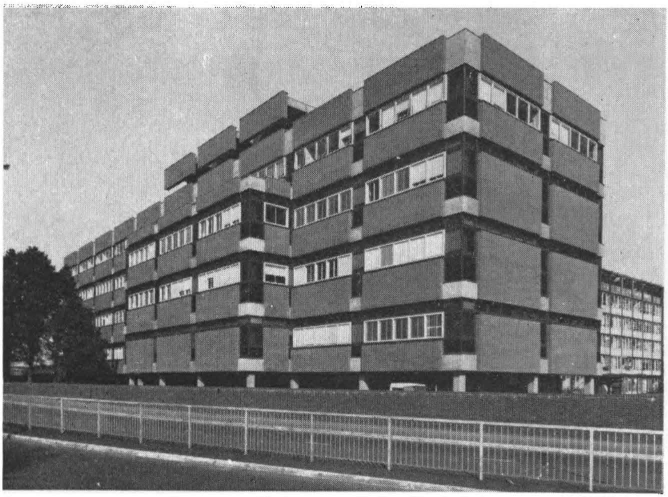

PLATE II—RICHARDSON WING OF THE METEOROLOGICAL OFFICE HEADQUARTERS, BRACKNELL, SEPTEMBER 1972

PLATE III—THE PRIME MINISTER UNVEILING THE PLAQUE IN THE RICHARDSON WING

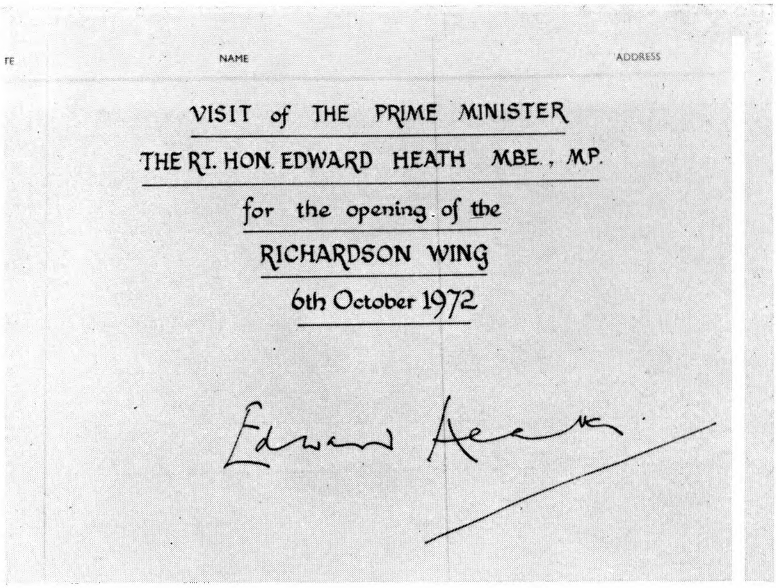

PLATE IV—THE ENTRY IN THE VISITORS' BOOK

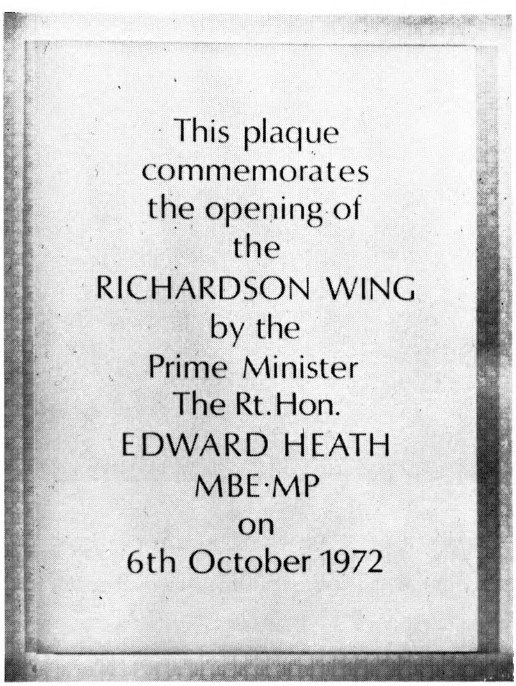

PLATE V—CLOSE-UP OF THE PLAQUE

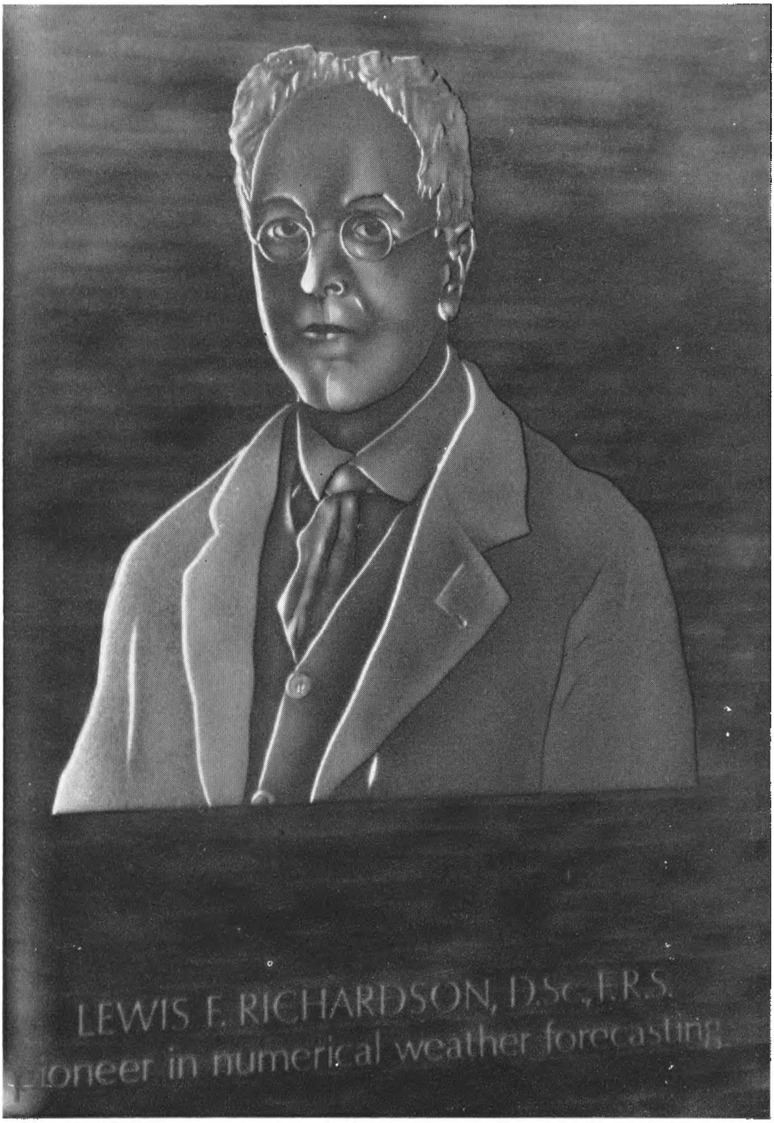

PLATE VI—PORTRAIT IN GLASS OF L. F. RICHARDSON, D.SC., F.R.S.

The portrait is set in the wall of the entrance hall to the new wing.

PLATE VII—THE PRIME MINISTER EXAMINING THE PRESENTATION COPY OF *Meteorology for mariners*

The Director-General is on the left.

10 Downing Street
Whitehall

16 October, 1972

Dear Director-General

It was a great pleasure for me to be able to visit Bracknell on Friday, and to open the new Richardson wing. I was much impressed by the work of the Meteorological Office under your direction and the facilities which are now available to it to carry out that work, and I should like to send to you and to all concerned my thanks for an interesting visit and my good wishes (not entirely unselfish) for a continuing steady improvement in the accuracy of your forecasts.

I should also like to thank you and your staff for presenting me with a copy of <u>Meteorology for Mariners</u>; I hope that this will enable at least one of your customers to make even better use of your forecasts than he already does.

With best wishes
Yours sincerely
Edward Heath

Director-General of the Meteorological Office.

PLATE VIII—LETTER OF APPRECIATION FROM THE PRIME MINISTER TO THE DIRECTOR-GENERAL

PLATE IX—PART OF THE MANUAL TELECOMMUNICATIONS CENTRE IN THE RICHARDSON WING

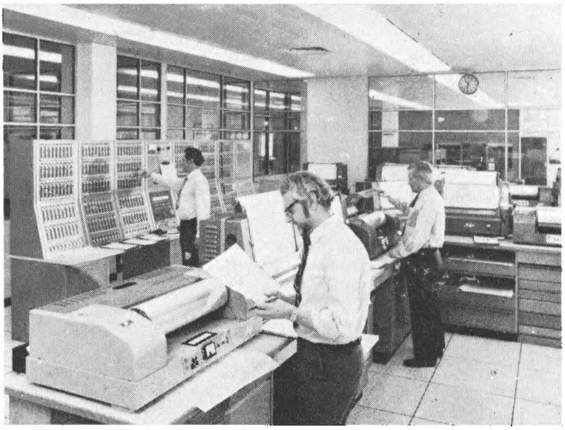

PLATE X—PART OF THE FACSIMILE ROOM

In the foreground are two facsimile transmitters and behind to the left are the switching panels whereby any transmission or reception can be relayed to any outgoing channel.

PLATE XI—CENTRAL FORECASTING OFFICE—THE UPPER-AIR SECTION

To face page 17

PLATE XII—THE COMPUTER ROOM

The seated staff member farthest from the camera is controlling the machine from the main console. Plate XIII is a close-up. The two staff members in the right foreground are controlling magnetic-tape units. The one in the centre foreground is manipulating a paper-tape reader and the one towards the left is attending one of the three line-printers.

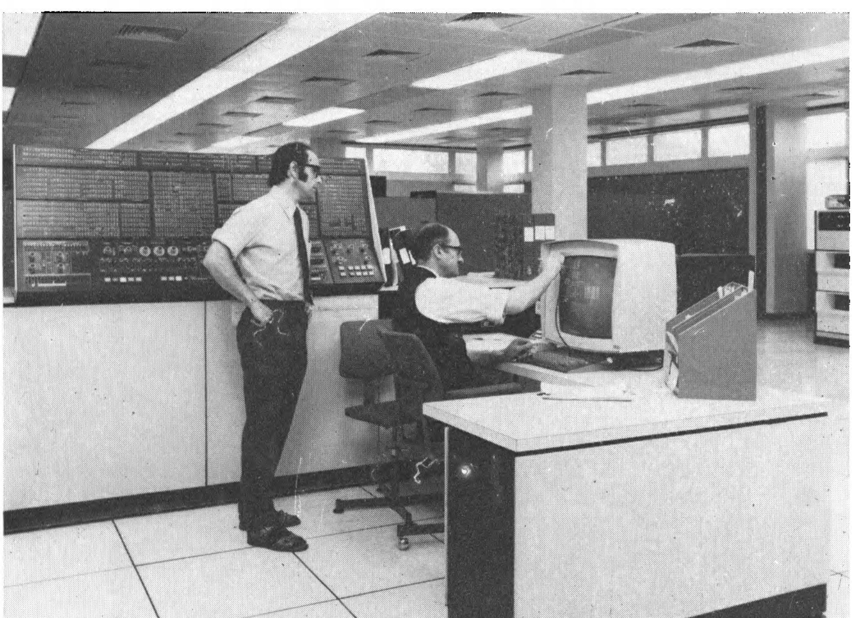

PLATE XIII—MAIN OPERATING CONSOLE WITH CONTROLLER USING LIGHT-PEN

TABLE I—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCES AT KEY AREAS IN DECEMBER, JANUARY AND FEBRUARY RELATED TO SPRING RAINFALL IN ENGLAND AND WALES

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Spring rainfall (terciles)			Bias
		millibars		1	2	3	
(a) December							
1	PA(60 60E)	1019·3	< − 5	2	7	13	wet
2	PA(40 10)	1020·2	> 4	3	3	11	wet
3	PA(45 10) − PA(65 20)	1017·5 − 999·8	> 6	6	8	17	wet
(b) January							
4	PA(60 20E)	1012·4	> 5	4		14	wet
5	PA(60 70E) − PA(60 20E)	1020·8 − 1012·4	> 5	14	6	5	dry
6	PA(70 40)	1004·8	< − 7	3	5	10	wet
7	PA(70 40) − PA(60 10E)	1004·8 − 1011·6	< −10	3	4	9	wet
8	PA(35 130)	1020·3	> 3	1	7	7	wet
9	PA(65 140)	1018·0	> 7	2	4	9	wet
10	PA(65 140) − PA(60 50)	1018·0 − 998·9	< − 8	10	2	4	dry
11	PA(65 140) − PA(60 50)	1018·0 − 998·9	> 2	6	11	17	wet
(c) February							
12	PA(80 20E)	1009·1	> 7	10	2	3	dry
13	PA(45 60)	1011·8	> 4	11	8	3	dry
14	PA(60 30)	1001·5	< −10	10	5	3	dry
15	PA(80 20E) − PA(60 30)	1009·1 − 1001·5	< − 5	4	10	17	wet
16	PA(80 20E) − PA(60 30)	1009·1 − 1001·5	> 6	11	9	2	dry
17	PA(55 20E)	1015·0	⩾ 4	15	5	5	dry
18	PA(30 70)	1019·5	< 0	7	11	21	wet
19	PA(60 30) − PA(55 20E)	1001·5 − 1015·0	< − 8	14	10	3	dry
20	PA(60 30) − PA(30 70)	1001·5 − 1019·5	< − 4	15	11	5	dry
21	PA(60 30) − PA(30 70)	1001·5 − 1019·5	> 12	4	3	9	wet
22	PA(60 30) − PA(40 00)	1001·5 − 1018·4	< − 9	15	10	4	dry

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Spring rainfall terciles, based on period 1874 to 1963, are : $R_1 \leqslant 160$ mm; $160 < R_2 < 193$ mm; $R_3 \geqslant 193$ mm.

TABLE II—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN DECEMBER, JANUARY AND FEBRUARY OVER THE NORTHERN HEMISPHERE AND SPRING RAINFALL OVER ENGLAND AND WALES

Period	Predictor	Spring rainfall (terciles)			Totals	*SS*
		1	2	3		
(a) December	$N_w \geqslant 1$	7	12	27	46	1·7
	$N_w = 0$	25	16	9	50	1·2
(b) January	$N_d - N_w \geqslant 1$	14	4	3	21	2·1
	$N_d - N_w \leqslant -2$	5	10	19	34	1·6
(c) February	$N_d - N_w \geqslant 2$	23	13	3	39	2·0
	$N_d - N_w \leqslant -1$	5	10	24	39	1·9
(d) December +January	$^*N_d - N_w \geqslant 0$	22	7	4	33	2·1
	$N_d - N_w \leqslant -2$	6	16	25	47	1·6
(e) December +January +February	1. $N_d - N_w \geqslant 2$	22	9	1	32	2·6
	2. $N_d - N_w \leqslant -2$	1	11	28	40	2·7

* This contains 9 years when $N_d = N_w = 0$.

N_d and N_w are the number of individual predictors (see Table I) which indicate dry (R_1) and wet (R_3) springs respectively. *SS* is the mean Sutcliffe Score. Tercile boundaries are given in Table I.

the anomalous circulation in February is known (usually on the last day of February) the two operational rules at (e), based on the circulation in the three winter months, give strong indications of dry (R_1) or wet (R_3) springs on some 72 per cent of occasions. If the latter rules are not applicable then the rules at (c) or (d) should be examined, and if none applies no prediction can be issued by this method. However, in the vast majority of years some positive prediction should be possible.

The long-period mean surface pressure map for spring (i.e. March, April and May) is shown in Figure 2. In general, individual springs have mean

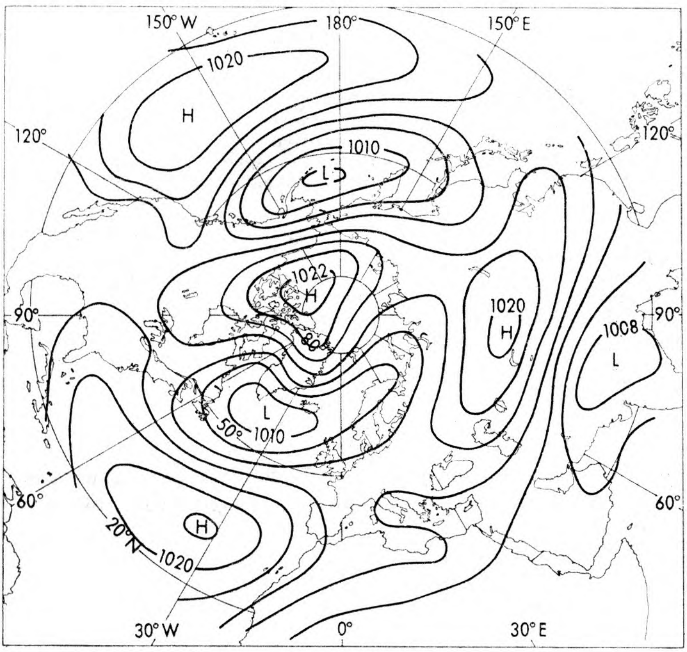

FIGURE 2—MEAN SURFACE PRESSURE IN SPRING, PERIOD 1873 TO 1968

pressure distributions which are different to a greater or less extent from the seasonal pattern in Figure 2. A composite of the mean pressure anomalies associated with the 32 springs in which the winter pre-conditions for dry springs given under (e)1 of Table II (i.e. $N_d - N_w \geq 2$) were satisfied, is shown in Figure 3. In this composite map the mean pressure in spring is significantly (at the 5 per cent level) above average over the British Isles and significantly below the seasonal average from the Russian Arctic to Greenland. A composite map (not shown) for the 40 cases which satisfied the criterion $N_d - N_w \leq -2$ (i.e. (e)2 of Table II) for wet springs is characterized by mean pressure which is significantly below average over the British Isles; mean pressure is above average in the Arctic, although only significantly so near southern Greenland. The composite pattern in the latter case is similar to that shown in Figure 3 if the signs of the anomalies are reversed.

Forecasting spring temperature. Table III contains the basic information from anomalous circulation in the winter months associated with cold or warm springs.

TABLE III—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCES AT KEY AREAS IN DECEMBER, JANUARY AND FEBRUARY RELATED TO SPRING MEAN TEMPERATURE IN CENTRAL ENGLAND

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Spring temperature (quintiles)					Bias
		millibars		1	2	3	4	5	
(a) December									
1	PA(60 40)	998·5	> 7	8	2	5	2	1	cold
2	PA(60 40) – PA(55 30E)	998·5 – 1016·5	< –12	1	2	5	4	6	warm
3	PA(60 40) – PA(50 90E)	998·5 – 1033·1	< – 5	1	5	3	7	9	warm
4	PA(60 40) – PA(50 90E)	998·5 – 1033·1	> 6	9	1	2	3	0	cold
5	PA(80 140E) – PA(65 40)	1019·6 – 1000·4	< – 5	12	1	6	5	0	cold
6	PA(70 120E)	1022·3	> 4	1	3	2	8	4	warm
7	PA(35 50E)	1020·7	< – 1	3	3	8	14	4	warm
(b) January									
8	PA(40 60)	1015·4	< – 3	3	1	6	3	11	warm
(c) February									
9	PA(75 20)	1010·7	< – 5	1	1	5	10	9	warm
10	PA(45 10E)	1016·9	< – 5	8	4	5	3	0	cold
11	PA(45 10E)	1016·9	> 3	4	1	5	11	10	warm
12	PA(75 120)	1021·7	> 4	3	10	5	3	1	cold
13	PA(35 30) – PA(55 00)	1020·3 – 1013·3	> 11	2	8	3	1	1	cold
14	PA(55 160) – PA(45 130)	1003·7 – 1015·8	< – 1	3	4	8	12	14	warm
15	PA(45 10E) – PA(55 50)	1016·9 – 1003·9	< – 8	6	6	4	2	1	cold
16	PA(45 10E) – PA(55 50)	1016·9 – 1003·9	> 7	3	0	1	10	6	warm
17	PA(45 10E) – PA(40 50E)	1016·9 – 1020·2	< – 5	9	8	5	1	0	cold
18	PA(45 10E) – PA(40 50E)	1016·9 – 1020·2	> 5	2	2	3	9	8	warm
19	PA(45 10E) – PA(75 160)	1016·9 – 1022·7	< – 8	6	5	4	1	1	cold
20	PA(45 10E) – PA(75 160)	1016·9 – 1022·7	> 6	3	0	5	8	8	warm
21	PA(45 10E) – PA(45 30)	1016·9 – 1012·8	< – 5	9	8	8	0	1	cold
22	PA(45 10E) – PA(45 30)	1016·9 – 1012·8	> 7	2	1	2	5	7	warm

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Spring temperature quintiles, based on period 1874 to 1963, are : $T_1 < 7{\cdot}5$; $7{\cdot}5 \leq T_2 < 8{\cdot}1$; $8{\cdot}1 \leq T_3 < 8{\cdot}4$; $8{\cdot}4 \leq T_4 < 8{\cdot}9$ $T_5 \geq 8{\cdot}9$°C.

The basic predictors which were satisfied in individual years were combined in the same way as for rainfall and the predictive rules for spring temperature contained in Table IV were obtained.

TABLE IV—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN DECEMBER, JANUARY AND FEBRUARY OVER THE NORTHERN HEMISPHERE AND SPRING TEMPERATURE IN CENTRAL ENGLAND

Period	Predictor	Spring temperature (quintiles)					Totals	*SS*
		1	2	3	4	5		
(a) December	$N_c - N_w \geq 1$	11	2	5	2	1	21	1·9
	$N_c - N_w \leq -2$	0	2	4	9	7	22	2·0
(b) December +January	$N_c - N_w \geq 1$	11	1	3	2	1	18	2·1
	$N_c - N_w \leq -2$	1	3	5	10	13	32	1·9
(c) February	$N_c - N_w \geq 2$	9	11	7	1	0	29	2·0
	$N_c - N_w \leq -1$	4	1	10	16	17	48	1·7
	(≤ -4)	(1)	(0)	(2)	(9)	(8)	(20)	(2·1)
(d) December +January +February	1. $N_c - N_w \geq 2$	11	10	4	1	0	26	2·3
	*2. $N_c - N_w = 1$ or 0 or -1	4	3	10	6	2	25	1·1
	3. $N_c - N_w \leq -2$	3	2	7	15	17	44	1·8
	(≤ -4)	(1)	(1)	(3)	(10)	(10)	(25)	(2·1)

* Neglecting one case when $N_c = N_w = 0$.

N_c and N_w are the number of individual predictors (see Table III) which indicate very cold or cold (T_1 or T_2) and warm or very warm (T_4 or T_5) springs respectively. *SS* is the mean Sutcliffe Score. Quintile boundaries are given in Table III.

Note : For a predictor value in brackets, the quintile distribution is shown in brackets.

It is clear from Table IV that quite useful indications of the probability of cold or warm springs are available at the end of December on about 45 per cent of years. January adds little extra information. However, the overall predictors based on the three winter months are likely to be applicable and useful on virtually all occasions. The rules (d)1 and (d)3 are particularly strong and they will probably be applicable on average in three out of four years. The figures in brackets refer to the cases when the more stringent pre-condition is satisfied. The final forecast should be based on rules (d)1, (d)2 and (d)3. If the pre-condition which is satisfied is (d)1 predict T_1 or T_2, if (d)2 predict T_3, if (d)3 predict T_4 or T_5. The choice between T_1 and T_2 or between T_4 and T_5 will generally depend on other considerations; in any case the temperature forecasts would be regarded as satisfactory even if the error were one quintile. In using (d)2 the prediction should normally be T_3, but it may be T_2 or T_4 if the (c) rules for February or other considerations (e.g. sea temperatures) suggest a slight bias.

It is of interest to see in Figure 4 the composite mean pressure anomaly map for the 26 springs in which the criterion $N_c - N_w \geqslant 2$ for predicting a cold spring (given under (d) of Table IV) was satisfied. The main features

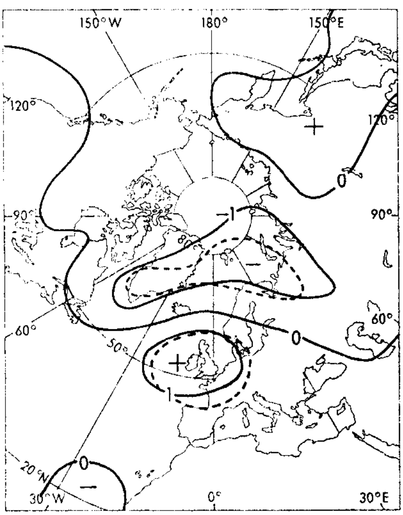

FIGURE 3—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN SPRINGS FOLLOWING WINTERS SATISFYING THE RAINFALL PREDICTOR $N_d - N_w \geqslant 2$ GIVEN IN TABLE II(e)1

See notes under Figure 1.

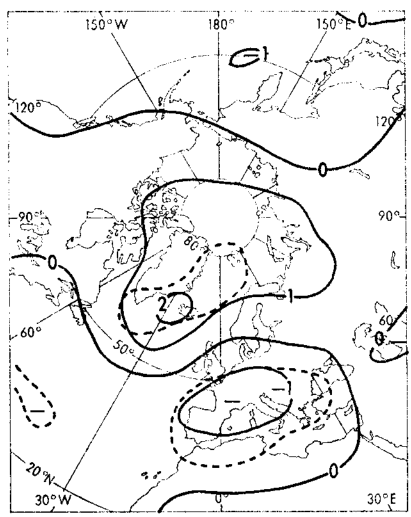

FIGURE 4—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN SPRINGS FOLLOWING WINTERS SATISFYING THE TEMPERATURE PREDICTOR $N_c - N_w \geqslant 2$ GIVEN IN TABLE IV(d)1

of Figure 4 are the extensive areas with below-average mean pressure over Europe and the Mediterranean and above-average mean pressure over Iceland, Greenland and the Arctic; in these two regions mean seasonal pressure is significantly different from average over large areas centred on France and on the Denmark Strait. Evidently blocking on an enormous scale is shown in Figure 4. Nor is it surprising that most of the springs were cold over central England in view of the north-east anomaly of flow indicated in Figure 4. The criterion for warm springs, $N_c - N_w \leqslant -2$, given as (d)3 in Table IV, was satisfied in 44 years; the composite pressure anomaly map (not shown) suggested anomalously strong westerly flow in the Atlantic sector, with the pressure near Iceland being significantly below average and the Azores anticyclone being stronger than usual.

Forecasting autumn rainfall. The basic predictions in June, July and August and the derived operational rules for forecasting autumn rainfall are listed in Tables V and VI respectively. No dry or wet predictor satisfying the pre-conditions laid down in the Introduction was found for July, but there were two related basic predictors which suggested average rainfall (see Table V).

TABLE V—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCES AT KEY AREAS IN JUNE, JULY AND AUGUST RELATED TO AUTUMN RAINFALL IN ENGLAND AND WALES

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Autumn rainfall (terciles) 1	2	3	Bias
		millibars					
(a) June							
1	PA(45 80)	1014·3	< -1	4	10	14	wet
2	PA(55 80)	1012·4	> 2	9	7	2	dry
(b) July							
3	PA(40 40E) −PA(65 20E)	1008·1 − 1010·4	> 2	4	15	4	average
4	PA(40 40E)	1008·1	> 1	5	16	4	average
(c) August							
5	PA(80 180)	1015·7	> 4	9	6	2	dry
6	PA(80 180) −PA(45 160E)	1015·7 − 1013·0	> 5	10	4	2	dry
7	PA(65 110E)	1010·3	> 2	11	7	1	dry
8	PA(65 110E) − PA(55 50E)	1010·3 − 1011·8	< -3	5	6	15	wet
9	PA(65 110E) − PA(55 50E)	1010·3 − 1011·8	> 0	20	17	5	dry
10	PA(55 160) −PA(75 160E)	1012·8 − 1013·6	< -3	12	9	3	dry

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Autumn rainfall terciles, based on the period 1874 to 1963, are : $R_1 \leqslant 234$ mm; $234 < R_2 < 305$ mm; $R_3 \geqslant 305$ mm.

TABLE VI—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN JUNE, JULY AND AUGUST OVER THE NORTHERN HEMISPHERE AND AUTUMN RAINFALL OVER ENGLAND AND WALES

Period		Predictor	Autumn rainfall (terciles) 1	2	3	Totals	*SS*
(a) June		$N_w=0,\ N_d=1$	9	7	2	18	1·5
		$N_d=0,\ N_w=1$	4	10	14	28	1·4
(b) July		$N_a=2$	1	12	2	15	2·8
(c) August	1.	$N_d-N_w \geqslant 1$	25	19	6	50	1·5
		$(\geqslant 3)$	(10)	(6)	(1)	(17)	(2·1)
	*2.	$N_d-N_w \leqslant 0$	8	13	26	47	1·5
(d) June	1.	$N_d-N_w \geqslant 2$	17	9	2	28	2·1
+August	2.	$N_d-N_w \leqslant -1$	3	9	17	29	1·9

* This includes 22 years with $N_d=N_w=0$.

N_d, N_a and N_w are the number of individual predictors (see Table V) which indicate dry (R_1), average (R_2), and wet (R_3) autumns respectively. *SS* is the mean Sutcliffe Score. Tercile boundaries are given in Table V.

Note : For a predictor value in brackets, the tercile distribution is shown in brackets.

On less than 50 per cent of occasions some indication of autumn rainfall can probably be given in June. In a small number of years the circulation in July will suggest that an average type of autumn will probably follow.

The August predictors can generally be invoked, but the forecast accuracy is likely to be high only in the more stringent case shown in brackets in (c)1. The operational rule (d) involving June and August should be used unless rule (b), based on the July mean circulation, suggests that the rainfall will be average. If neither rule (b) nor rule (d) is applicable, prediction should be based on rule (c) or on other considerations.

The long-period mean surface pressure map for autumn is given in Figure 5. Wet or dry autumns over England and Wales typically differ from

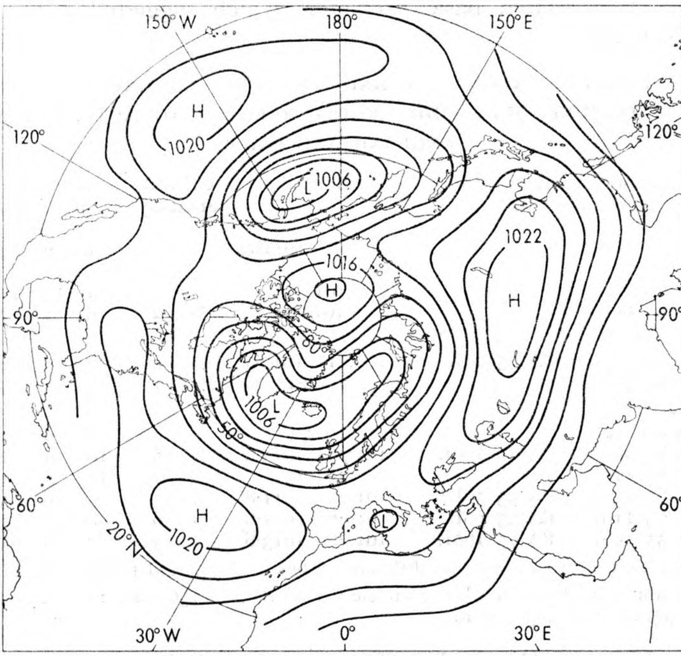

FIGURE 5—MEAN SURFACE PRESSURE IN AUTUMN, PERIOD 1873 TO 1968

Figure 5 and the anomalous circulation can of course be seen by examining seasonal pressure anomalies. The composite autumn pressure anomaly pattern which emerges when the criterion for a wet autumn is satisfied, namely $N_d - N_w \leqslant -1$ in (d)2 of Table VI, is depicted in Figure 6, where the main feature is the below-average mean pressure over the British Isles. The composite map for the dry autumns (not shown) associated with the predictive criterion $N_d - N_w \geqslant 2$ (i.e. (d)1 of Table VI) is roughly similar to Figure 6 with the signs of the anomalies reversed : the main difference is that the mean pressure is significantly above average from Mongolia northwards to the polar region and also over Hudson Bay.

Forecasting autumn temperature. Table VII lists the basic predictors in the summer months and Table VIII summarizes the rules for predicting autumn mean temperature.

Predictions of warm autumns are possible on less than 25 per cent of years at the end of June, as indicated by rule (a) of Table VIII. At the end of July fairly accurate predictions can be made much more often, either from rule (b) or rule (d) of Table VIII. August adds further information so that

TABLE VII—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCES AT KEY AREAS IN JUNE, JULY AND AUGUST RELATED TO AUTUMN MEAN TEMPERATURE IN CENTRAL ENGLAND

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Autumn temperature (quintiles)					Bias
		millibars		1	2	3	4	5	
(a) June									
1	PA(45 140E)	1008·8	>1	0	3	6	3	10	warm
2	PA(40 140)	1021·8	>3	3	2	0	10	5	warm
3	PA(40 140) − PA(70 140)	1021·8 − 1015·3	>4	3	2	2	10	4	warm
4	PA(45 50E) − PA(60 20)	1011·0 − 1011·6	>3	0	4	3	3	7	warm
(b) July									
5	PA(65 100E)	1008·0	>2	9	3	7	1	2	cold
6	PA(60 150)	1014·2	>2	11	1	5	3	1	cold
7	PA(45 00)	1017·4	<-1	6	10	6	4	1	cold
8	PA(40 50)	1020·8	<-1	7	9	8	3	2	cold
9	PA(40 50)	1020·8	>2	1	3	3	3	7	warm
10	PA(70 100) − PA(40 50)	1012·6 − 1020·8	<-3	2	2	4	6	8	warm
11	PA(70 100) − PA(40 50)	1012·6 − 1020·8	>2	10	7	11	1	2	cold
12	PA(60 40) − PA(40 40)	1010·7 − 1023·2	>5	4	5	6	0	1	cold
13	PA(35 170) − PA(70 100)	1023·1 − 1012·6	<-3	6	6	5	0	3	cold
14	PA(35 170) − PA(70 100)	1023·1 − 1012·6	>3	1	5	2	10	8	warm
15	PA(50 00) − PA(65 40)	1016·4 − 1011·0	<-4	5	8	5	3	1	cold
16	PA(35 50E)	1003·0	<-2	2	3	3	5	7	warm
17	PA(35 50E)	1003·0	>2	3	7	2	2	1	cold
18	PA(45 00) − PA(80 20)	1017·4 − 1014·3	<-4	4	6	5	3	0	cold
19	PA(45 00) − PA(80 20)	1017·4 − 1014·3	>3	1	1	4	6	6	warm
20	PA(45 80) − PA(70 100)	1014·6 − 1012·6	<-3	7	4	6	0	2	cold
21	PA(45 80) − PA(70 100)	1014·6 − 1012·6	>2	2	4	1	10	9	warm
(c) August									
22	PA(70 160)	1012·0	<-2	1	4	3	8	11	warm
23	PA(30 00)	1012·1	<-1	2	5	5	8	12	warm
24	PA(30 00)	1012·1	>0	14	10	9	3	3	cold
25	PA(70 160) − PA(45 150)	1012·0 − 1021·1	<-3	2	3	2	9	10	warm
26	PA(70 160) − PA(45 150)	1012·0 − 1021·1	>4	6	6	6	0	1	cold
27	PA(40 150)	1023·9	<-1	12	10	10	1	5	cold
28	PA(40 150)	1023·9	>2	3	3	4	9	9	warm

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Autumn mean temperature quintiles, based on period 1874 to 1963, are : $T_1<9{\cdot}1$; $9{\cdot}1\leqslant T_2<9{\cdot}7$; $9{\cdot}7\leqslant T_3<10{\cdot}1$; $10{\cdot}1\leqslant T_4<10{\cdot}5$; $T_5\geqslant 10{\cdot}5$°C.

TABLE VIII—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY MEAN PRESSURE ANOMALIES IN JUNE, JULY AND AUGUST OVER THE NORTHERN HEMISPHERE AND AUTUMN MEAN TEMPERATURE IN CENTRAL ENGLAND

Period	Predictor	Autumn temperature (quintiles)					Totals	*SS*
		1	2	3	4	5		
(a) June	$N_c=0,\ N_w\geqslant 2$	1	2	1	11	7	22	2·0
(b) July	$N_c-N_w\geqslant 4$	10	7	8	0	1	26	1·9
	$N_c-N_w\leqslant -1$	2	4	6	11	16	39	1·8
	$(\leqslant -2)$	(0)	(1)	(3)	(6)	(10)	(20)	(2·5)
(c) August	$N_c=0,\ N_w\geqslant 2$	0	4	3	10	10	27	1·9
	$N_w=0,\ N_c\geqslant 1$	13	10	10	1	1	35	1·8
(d) June +July	$N_c-N_w\geqslant 4$	9	6	7	0	0	22	2·1
	$N_c-N_w\leqslant -3$	0	0	3	10	12	25	2·7
(e) June +July +August	1. $N_c-N_w\geqslant 3$	14	9	9	0	1	33	2·1
	2. $N_c-N_w=2$, 1, 0 or -1	3	6	9	3	4	25	1·0
	3. $N_c-N_w\leqslant -2$	1	4	2	16	16	39	2·1
	$(\leqslant -6)$	(0)	(0)	(1)	(7)	(9)	(17)	(3·0)

N_c and N_w are the number of individual predictors (see Table VII) which indicate cold (T_1 or T_2) or warm (T_4 or T_5) autumns respectively. *SS* is the mean Sutcliffe Score. Quintile boundaries are given in Table VII.

Note : For a predictor value in brackets, the quintile distribution is shown in brackets.

the operational rules based on the three summer months shown under (e) of Table VIII enable very useful predictions to be made of the mean autumn temperature in central England. Rules (e)1 and (e)3 are clearly more reliable than rule (e)2. When the latter rule applies there is rather weak evidence for predicting T_3 but T_2 or T_4 could be forecast if either rule (c) or rule (d) suggests a bias to the cold or warm side of average temperature. Rule (e)1 strongly indicates that the autumn will not be warm; the best prediction in practice is T_1 or T_2. Rule (e)3 predicts a warm autumn (T_4 or T_5); if the more stringent criterion in brackets is satisfied the probability of a warm autumn is extremely high.

The typical anomalous circulation in autumn associated with predictions based on the criterion $N_c - N_w \leqslant -2$ for June, July and August (i.e. (e)3 of Table VIII) is shown in the composite map in Figure 7. The south-west

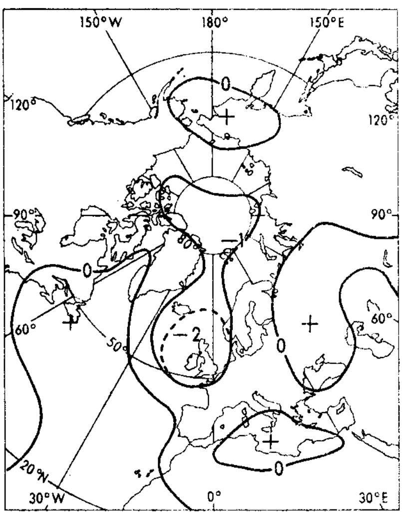

FIGURE 6—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN AUTUMNS FOLLOWING SUMMERS SATISFYING RAINFALL PREDICTOR $N_d - N_w \leqslant -1$ GIVEN IN TABLE VI(d)2

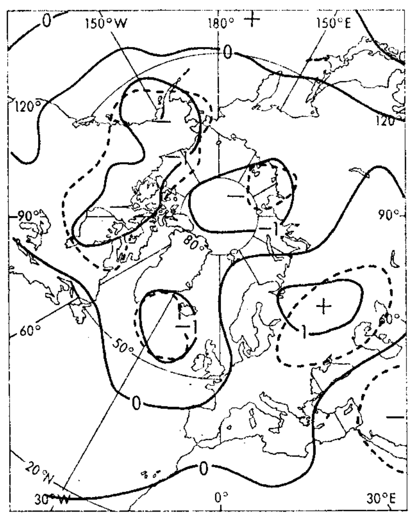

FIGURE 7—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN AUTUMNS FOLLOWING SUMMERS SATISFYING THE TEMPERATURE PREDICTOR $N_c - N_w \leqslant -2$ GIVEN IN TABLE VIII(e)3

See notes under Figure 1.

anomaly of flow over England is of course characteristic of many warm autumns. The circulation anomalies in Figure 7 are on a very large scale; mean pressure is significantly below average over most of Canada, the north-east Atlantic and near the Siberian Arctic and significantly above average over Russia. In contrast the composite map (not shown) associated with the years in which the predictive criterion $N_c - N_w \geqslant 3$ (i.e. (e)1 of Table VIII) is satisfied shows mean pressure significantly above average over Alaska, much of Canada, and the north-east Atlantic but significantly below average in an area north of the Caspian Sea and in the North Pacific south of the Aleutian Islands; the composite map in this case is like Figure 7 with the signs of the anomalies reversed.

Discussion. The qualitative arguments for the use of monthly mean pressure anomaly data over the northern hemisphere in developing objective rules for predicting seasonal rainfall and mean temperature have been given in two recent papers[1,2] and need not be restated here.

The empirical rules in this paper have been derived from data covering nearly 100 years during which time longer-period changes in seasonal temperature and rainfall have taken place, but the writer has not noticed that the overall rules based on the three months before the season in question are significantly different in the accuracy of their predictions in the different epochs. For instance in the decade 1960 to 1969, the spring rainfall rules (e) of Table II and the spring temperature rules (d) of Table IV gave mean Sutcliffe Scores of 3·0 and 2·8 respectively. In the same decade, the autumn rainfall rules (d) of Table VI and the autumn temperature rule (e) of Table VIII gave mean Sutcliffe Scores of 1·8 and 2·2 respectively. In this recent decade there has been a noticeable trend to warm autumns. In fact there were no very cold autumns in central England and only two T_2 (quintile 2) autumns, namely 1962 and 1965. The predictor $N_c - N_w$ was equal to 4 in 1962 and 1 in 1965; rules (d) of Table VIII predicted T_1 or T_2 for the 1962 autumn and T_3 for the 1965 autumn. In the other 8 cases the pre-condition $N_c - N_w \leqslant -2$ ((e) of Table VIII) was satisfied; in other words, warm autumns were indicated and in fact the mean temperatures in these 8 autumns were quintiles 5, 4 and 3 on four, two and two occasions respectively. Thus a recent trend in autumn temperature was satisfactorily handled by the predictive criteria.

The years 1970 to 1972 were not included in the data from which the various rules were derived. In predicting the spring rainfall for 1970 and 1971 the rules in Table II in the individual months were conflicting. In each case the overall rules based on the three months indicated that the seasonal rainfall was unlikely to be tercile 1 or tercile 3. In such cases either tercile 2 (average) or no forecast should be given; in the event both seasons had average rainfall. At the end of February 1972 rule (e)2 in Table II was satisfied and a wet spring was correctly predicted. The autumn rainfall in 1970 was correctly predicted as average on the basis of the rule (b) in Table VI. However, no basic rule was applicable from any of the summer months in 1971, so that no forecast could be given. As regards the temperature forecasts (see Table IV) the spring rule (d)1 was satisfied in 1970 so that a cold spring was predicted and T_2 occurred; in 1971 the rule (d)2 applied, thus an average (T_3) spring was expected and in the event the mean temperature was T_3: in 1972 an average (T_3) spring was expected from rule (d)2 and the mean spring temperature was actually T_4. The autumns of 1970 and 1971 were very warm (T_5); in each case the predictive rule for warm or very warm autumns, given as (e)3 in Table VIII, was satisfied ($N_c - N_w = -9$ in 1970 and $N_c - N_w = -3$ in 1971). Thus in these recent years of independent data the predictive rules have proved very successful.

There is not yet in sight any numerical procedure, based on physical laws, which will allow seasonal weather predictions of practical value to be made. With all its limitations an essentially empirical approach to seasonal forecasting, such as has been presented in this paper and in the two recent papers to which reference has been made, gives useful, practical results. In the course of time, it is very likely that a marriage between this type of empirical work and physically based numerical researches will produce substantially more reliable seasonal forecasts. In the meantime forecasts of seasonal weather over England and Wales can generally be made with a high expectation of success, although on a minority of occasions forecasts will not be possible or will be seriously in error.

Acknowledgement. I wish to express my appreciation of the help of colleagues, especially Mr P. Collison and Mr M. J. Weller, in processing data.

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TROPOSPHERIC WINDS AND THE OCCURRENCE OF RAINFALL NEAR THE EQUATOR

By D. E. PARKER

Summary. Mean winds at tropospheric levels over Gan, Nairobi, and the Seychelles were found for wet days and for dry days up to three days before and after wet days. Mean winds at tropospheric levels over Gan were also found for dry days in general. The most significant finding was a reduction in easterly flow in the vertical-shear zone beneath the northern summer upper-tropospheric easterly jet over Gan on wet days in comparison with the flow on surrounding dry days or with the overall mean flow.

Introduction. The interaction between tropical convection and the surrounding large-scale flow is an important element in the dynamics of the tropical atmosphere. An indirect method of studying this interaction is to look for statistical relationships between tropospheric winds and occurrence of rainfall in the tropics. The relationship between upper-tropospheric winds and rainfall during the south-west monsoon over India has in fact been investigated by George,[1] who explained many features in terms of vorticity advection associated with variations in the upper-tropospheric easterly jet. The present work is concerned with winds and rainfall near the equator over the western half of the Indian Ocean and over East Africa, but vorticity considerations are beyond the scope of the work because upper-wind data were readily available from only three stations.

Procedure. The stations used were Gan (00° 41′S, 73° 09′E), Port Victoria (04° 37′S, 55° 27′E) on Mahé Island in the Seychelles group, and Nairobi (01° 18′S, 36° 45′E). The stations were treated separately. Most of the calculations were for Gan where orography plays a very small part.

Days were classified as either dry or wet, the criterion for wet days being either $\geqslant 1$ mm or $\geqslant 4$ mm total rainfall.

Mean zonal and meridional wind components at each level were calculated for Gan for dry days in general (U_d and V_d), and for each station for wet days (U_w and V_w) and for dry days up to three days before and after wet days (U_{w+j} and V_{w+j}, $j=-3, -2, -1, 1, 2, 3$ days). For this purpose it was necessary to allow for occasions when wet days were separated by five dry days or less. For these occasions dry days were used with the nearest wet day, those dry days midway between two wet days being excluded. Any dry days up to three days before the start of the first year of an analysis or up to three days after the end of the last year were not used.

Results. Table I gives U_w, U_d and U_w-U_d at each level over Gan for the mid-season months, using data for 1960 to 1964 and taking the 1-mm criterion for wet days. There were consistent slight excesses of westerly component at the surface and 900 mb, and consistent deficits of easterly component between 400 mb and 200 mb, on wet days. The latter effect was most marked in July when the upper-tropospheric easterlies were strongest. There were no consistent patterns in V_w-V_d.

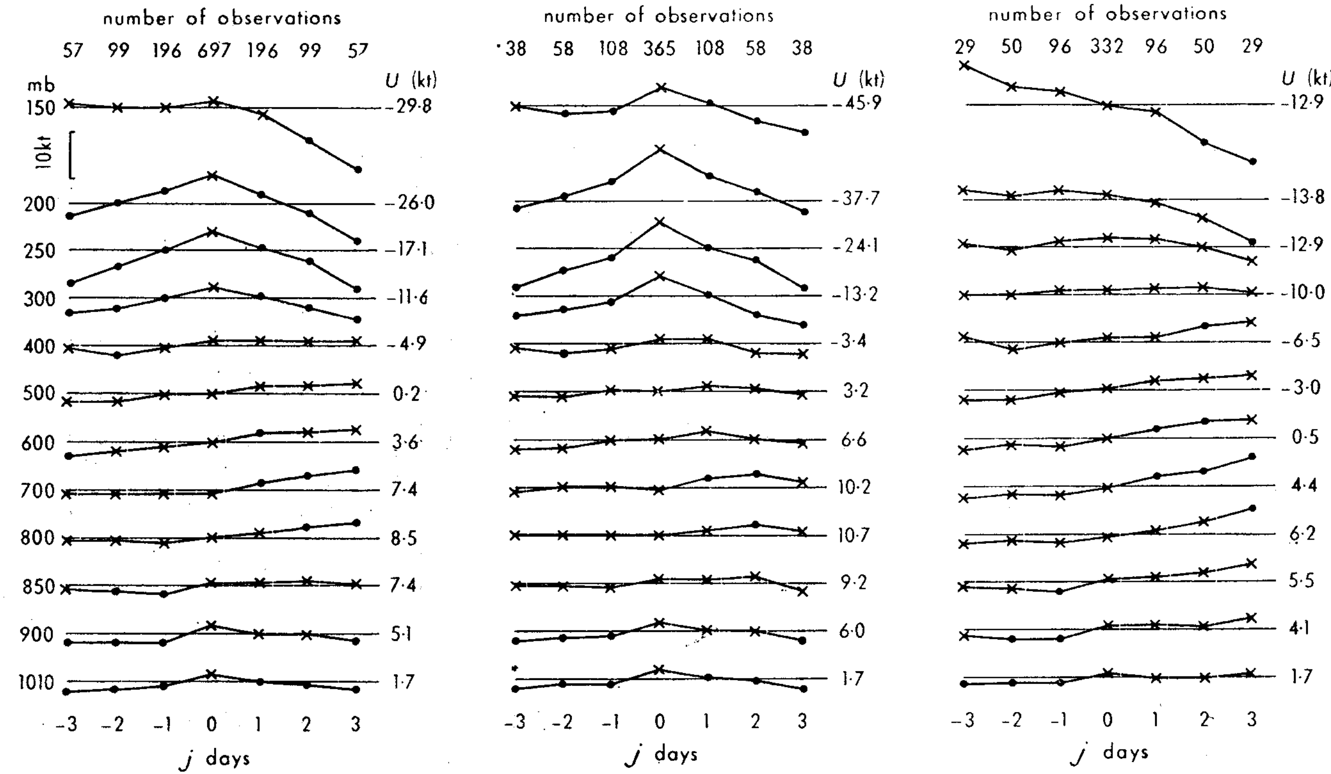
Figure 1 compares U_{w+j} with U_w and the all-days mean U for Gan, using the 1-mm criterion. The most notable feature was at 200 mb and 250 mb during May to October (Figure 1(b)) when U_{w+j} was less than U_w, by an amount which increased with increasing $|j|$ to become about 10 kt. This characteristic was not repeated to a marked extent during November to April (Figure 1(c)). However, during this season there was a general tendency for $U_{w+k}>U_{w+l}$, where $k>l$, in the lower and middle troposphere, while at 150 mb $U_{w+k}<U_{w+l}$ in no uncertain fashion (Figure 1(c)). The major features of the complete period 1960 to 1964 (Figure 1(a)) were also present in 1967. However, the raised values in the region of 800 mb to 500 mb after wet days (Figure 1(a)) were virtually missing in 1966.

Changing the rainfall criterion to 4 mm made little difference to the results.

There appeared to be no systematic features in $U_{w+j}-U_w$ at Nairobi or at Port Victoria. Wind data for Port Victoria were virtually confined to 1964.

In 1964 the mean meridional winds at 900, 850 and 800 mb over Port Victoria were about 3 kt more northerly on wet days (using either criterion) than on the relevant surrounding dry days up to $j=\pm3$. The opposite effect held, with a magnitude of nearly 2 kt, at 700 mb over Nairobi using the 4-mm criterion. These were the only systematic features in $V_{w+j}-V_w$ that attained the 5 per cent significance level over any of the three stations.

Discussion and conclusions. The mechanism causing the decrease in 200-mb and 250-mb easterlies near wet days over Gan during May to October cannot have been geopotential height increases resulting from latent-heat release, because such a mechanism would have caused an effect of similar magnitude during November to April. The most likely cause of the decreased easterlies is advection of air by mean upwards motion associated with the rainfall. This advection will have reduced the easterly components because at these levels the mean easterlies decrease downwards (Figure 1(b)). This mechanism could also have given the very much weaker effects of the same type at 200 mb and 250 mb in November to April (Figure 1(c); see also Table I), when the mean vertical shear of zonal wind was weaker but in



(a) All months (b) May to October (c) November to April

FIGURE 1—MEAN ZONAL WINDS U_{w+j}, j DAYS AFTER WET DAYS AT GAN FOR 1960–64 IN RELATION TO THE MEAN ZONAL WINDS U FOR THIS PERIOD

● indicates $U_w - U_{w+j}$ was found to be significantly different from zero at the 5 per cent level under the assumption that all the relevant data were independent and compatible with a Gaussian distribution.

Wet days are days with 1 mm or more of rain.

TABLE I—MEAN ZONAL WINDS ON WET AND DRY DAYS AT GAN

Level	January			April			July			October		
mb	Wet	Dry	Difference	Wet	Dry	Difference	Wet	Dry	Difference	Wet	Dry	Difference
						knots						
150	−18	−16	−2	−6	−6	0	−49	−56	7*	−35	−33	−2
200	−15	−18	3	−6	−9	3	−31	−42	11*	−23	−27	4
250	−13	−16	3	−6	−8	2	−18	−31	13*	−13	−18	5*
300	−11	−12	1	−5	−7	2	−10	−21	11*	−7	−12	5*
400	−6	−8	2	−4	−5	1	−2	−5	3	−2	−4	2
500	0	−4	4*	−3	−4	1	5	6	−1	3	2	1
600	4	1	3*	−1	−2	1	8	12	−4*	6	4	2
700	7	7	0	2	3	−1	9	13	−4*	10	8	2
800	8	8	0	4	4	0	6	11	−5*	13	11	2
850	7	7	0	5	4	1	4	6	−2	14	11	3*
900	5	3	2	5	3	2	2	1	1	13	9	4*
1010 (surface)	1	1	0	3	1	2*	−1	−2	1	7	4	3

Wet ⩾ 1 mm rainfall; dry < 1 mm rainfall.

Positive differences indicate that the zonal wind was more westerly on wet days than on dry days. An asterisk indicates that wet- and dry-day means were found to be different at the 5 per cent level of significance.

the same sense. Over Port Victoria the mechanism may well have been obscured by complex orographic effects (see also Wright and Ebdon[2]). Over Nairobi mean vertical shears of zonal wind are weak and orographic effects are complex and strong.

There is no obvious reason for the lower and mid-tropospheric increasing westerlies over Gan in November to April shown in Figure 1(c). The significant meridional wind changes found over Port Victoria and Nairobi could have been of orographic origin.

A very recent treatment of a closely related subject has been given by Holton and Colton.[3]

Acknowledgement. The author is much indebted to Mr D. W. Dent who commenced this work.

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REVIEW

Atmosphere–ocean interaction, by E. B. Kraus. 260 mm × 140 mm, pp. viii + 275, *illus.*, Clarendon Press: Oxford University Press, Ely House, 37 Dover Street, London, W1, 1972. Price: £7·50.

Air–sea interaction includes processes with scales ranging from, for example, the transport of heat and moisture from the sea surface to the air in immediate contact, to feedback processes that maintain anomalous sea surface temperatures and weather patterns over very large areas of a hemisphere for considerable lengths of time. Its importance as a link in maintaining the general circulation has long been recognized and in recent years it has been thought worth while to carry out elaborate experiments to try to provide some understanding of the processes such as those which enable the energy released over the tropical oceans on the microscale to be transferred to scales of hundreds or thousands of kilometres. A variety of phenomena such as wave-generation, seasonal thermocline development, storm surges and hurricane development, to mention but a few, all come within the scope of air–sea interaction. Increasing awareness of the importance of this field has stimulated a very rapid increase in the number of workers investigating these and similar topics in recent years. Somewhat surprisingly there has been a notable lack of corresponding text-books giving a wide-ranging and up-to-date description of the subject; the publication of this volume is therefore very welcome.

The book begins with a rather condensed introduction to the fluid-mechanical concepts required for appreciation of some of the material which follows. The second chapter discusses properties of sea water, spray, and sea ice, moist air and the interfacial layer, and this is followed by a section dealing with some relevant topics of solar and terrestrial radiation such as emission and reflection from the sea surface, and penetration of radiation into the sea.

The material of Chapter 4 will be less familiar to most meteorologists; here the properties of surface waves are described and theories of their generation by the surface wind are discussed.

The next two chapters describe turbulent transfer near the interface, and the role of turbulent transports on a somewhat larger scale in controlling the structure of the boundary layers above and below the interface.

The volume concludes with a description of a number of three-dimensional interactions of widely differing character; it includes *inter alia* effects of sea surface temperature on the dynamics of the tropical atmosphere and the response of oceans to storms.

A few minor criticisms of the book can be made, for example the author's decision not to incorporate a review of the role of air–sea interaction in climatic change, and in the fifth chapter, an inadequate discussion of the recent evidence for breakdown of the Jacob's (bulk-aerodynamic) formulation for turbulent transfer of sensible heat from the oceans in regions with high specific humidity. Perhaps more important is the overall impression that the author has attempted to write about more topics than can be conveniently summarized in the space of about 250 pages; a substantially larger volume would have allowed a rather less breathless treatment of some of the subject-matter. These few points will not prevent the book rightly becoming essential reading for all students of air–sea interaction; they will notice a number of misprints and may wonder whether the price of the volume would not have justified the use of a more satisfactory paper than the traditional buff colour of the Oxford University Press.

N. THOMPSON

OFFICIAL PUBLICATIONS

The following publications have recently been issued :

Geophysical Memoirs

No. 117. Northern hemisphere monthly mean 500-millibar and 1000–500-millibar thickness charts and some derived statistics (1951–66). By B. J. Moffitt and R. A. S. Ratcliffe, M.A.

This publication describes the climatology of the 500-mb level and the 1000–500-mb thickness over much of the northern hemisphere using data from many sources for the period 1951 to 1966. Problems associated with the quality control of these data are discussed and an empirical method of deducing 1000–500-mb thickness given only 500-mb height and surface pressure is explained.

Charts include means for each month, currently used in support of long-range forecasting, and their variability in January, April, July and October together with monthly extreme maxima and minima of 1000–500-mb thickness. Extreme values of 500-mb height are also included in tabular form.

Brief mention is made of the annual and spatial variation in the frequency distribution of the data.

Scientific Paper

No. 33. Hydromagnetic waves on a beta-plane: a numerical study of the dispersion relationship. By R. Hide, Sc.D., F.R.S. and M. V. Jones, B.Sc.

Effects due to general rotation of waves in a bounded electrically-conducting fluid pervaded by a magnetic field are of considerable interest in theoretical geophysics and astrophysics. This publication illustrates how, although the general intractability of the governing mathematical equations is the principal obstacle to progress in the study of these effects, in one particular case, namely waves in a thin spherical shell of fluid pervaded by a toroidal magnetic field, the results of a recent exact analysis by Stewartson and Rickard can be used to show that the approximate but explicit dispersion relationship proposed previously by Hide on the basis of a simple physical model is probably valid over a wide range of conditions. Detailed properties of these waves are revealed by a numerical analysis of the dispersion relationship. The analysis is greatly simplified by measuring length and time in suitable units, thus reducing the number of free parameters from three to only one — the orientation of the magnetic field.

ROYAL SOCIETY AWARDS TO THE DIRECTOR-GENERAL

The Royal Society has awarded its Rumford Medal to Dr B. J. Mason, F.R.S., the Director-General of the Meteorological Office, for 'his distinguished contributions to meteorology, especially the physics of clouds'.

The medal and prize were founded by a gift from Count Rumford, F.R.S., in 1796, 'the income to be given as a premium every second year to the author of the most important discovery in any part of Europe: especially in Heat and Light.' The silver-gilt medal is accompanied by a prize of £200.

This award follows closely on Dr Mason being elected in 1971 to give the Bakerian Lecture, founded in 1775, this being accompanied by a Mr and Mrs John Jaffé Prize of £200.

OBITUARY

It is with regret that we have to record the death of Mr N. R. Broadbear, Assistant Scientific Officer, Exeter Airport, on 8 September 1972.

THE METEOROLOGICAL MAGAZINE

VOL. 102 NO. 1206 JANUARY 1973

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

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RAINFALL FORECASTING FOR RIVER AUTHORITIES*

By H. T. D. HOLGATE

Summary. Synoptic criteria are derived as a basis for forecasting rainfall amounts in various river catchments in the hilly districts of north-west England and north Wales, with particular reference to amounts likely to cause flooding. The results of the forecasts are compared with subsequent rain-gauge measurements.

Introduction. River authorities in the United Kingdom have varying requirements for forecasts of the amount of rain expected to fall in a specified period of time. The most common one is that they wish to be warned in advance of rainfall likely to cause flooding. To attempt this the forecaster needs to know the minimum rainfall conditions which are likely to cause flooding if all other factors are favourable. The assessment of other factors such as antecedent precipitation, soil moisture deficit, and the like, is left to the river authority hydrologist. Some river authorities also require forecasts or warnings of smaller amounts of rain for the purpose of regulating river flow by releases from storage lakes and reservoirs. The forecaster needs to have ready access to rain-gauge readings taken in the river catchments, preferably whilst the rainfall is still in progress, or soon after the event, so that he can quickly check the validity of the assumptions on which his forecast was based.

Warnings of major falls have been issued for the Langdale valley in the heart of the English Lake District, for the upper end of the Eden valley which lies between the Lake District hills and the northern Pennines, and for the Gwynedd area of north Wales, which includes the catchments of the Conway, Mawddach, Wnion and Dovey (Figure 1). A study has also been made of flood occasions in catchments of the Lancashire River Authority other than the Langdale valley. A criterion that can be said to be common to all these catchments is that before there is much risk of flooding, more than 35 mm, or about 1½ inches, of rain has to fall within a limited time. The time of the fall is more difficult to specify, but for a total fall of, say, only 36 mm the time should not be longer than 12 hours. In the short steep catchments of the Langdale valley it has been found that the 36 mm has to fall in not more than 6 hours. The 6-mm-per-hour rate appears to be critical for similar catchments in other hilly districts, such as those of north Wales. On the other

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* Presented at the Royal Meteorological Society discussion meeting on 16 February 1972.

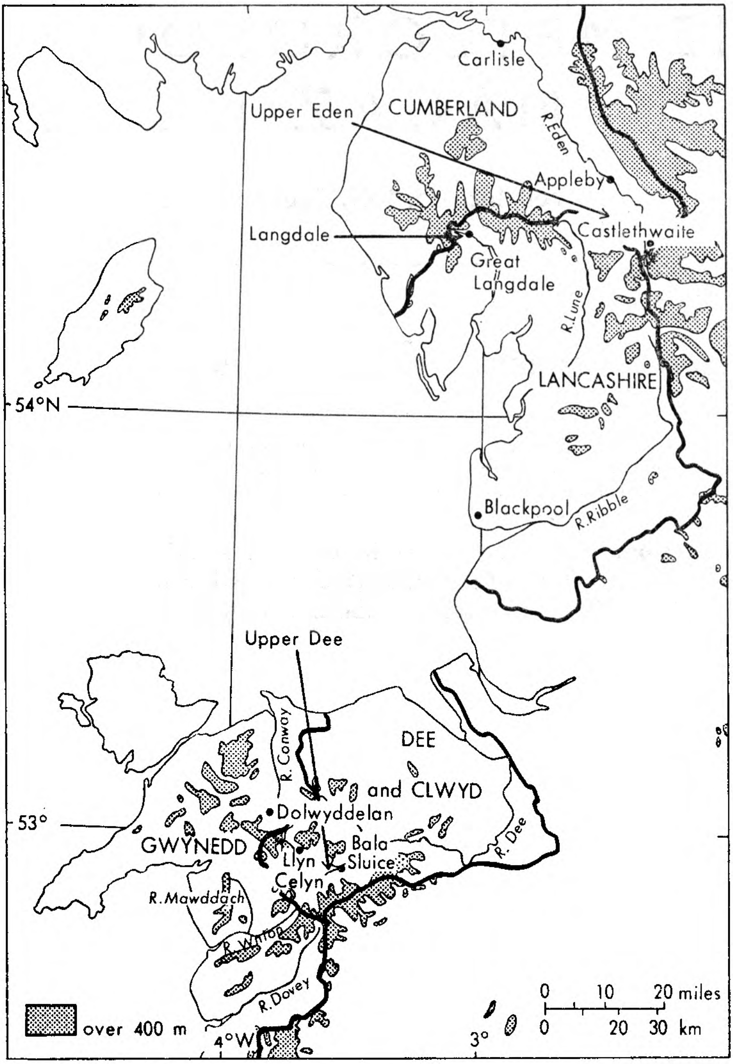

FIGURE 1—FORECAST DISTRICTS, RIVER AUTHORITY AREAS AND RAIN-GAUGE SITES

hand, in the less steep catchments of the broader river valleys, such as those which open out on to the Lancashire plain, there is some evidence that rain falling at rates of only 3 to 4 mm an hour may give rise to flooding if it is sufficiently prolonged for more than 35 mm to accumulate.

Warnings of smaller amounts of rain have been issued to the Lancashire River Authority in connection with a programme of river gauging in the Lake District. Experimental forecasts of rainfall amount, specified in three ranges, have been prepared for the upper part of the Dee catchment in north Wales.

Orographic rainfall. The problem of forecasting rainfall amount in these catchments is concerned with assessing the effect of neighbouring high ground on the general rainfall pattern. Moist airstreams approaching the Langdale valley, for example, from a westerly or south-westerly direction first encounter high ground rising to a general level of about 600 metres with peaks rising to between 750 and 1000 m. A similar comment may be made about the Conway valley in north Wales, lying on the east side of Snowdonia. If the effect of the high ground is assessed on the basis of rainfall readings taken at intervals of 24 hours, there may be a tendency to assume that the so-called 'orographic contribution' is spread over a long period of time at an even rate of 1 or 2 mm per hour. A study of hourly rainfall values, taken either from autographic records or from readings of interrogable gauges, shows that this is seldom the case, but rather that the added rainfall is concentrated into shorter periods when rates of 6 mm an hour are quite common. When the hourly amounts are looked at in relation to synoptic charts, it is seen that the higher rates of rainfall are frequently associated with the approach of warm and cold fronts, particularly cold fronts.

The synoptic situation of 6 January 1971, Figure 2, has been chosen to illustrate the variability of the orographic contribution of the Lake District hills, on an occasion when one might have expected a long period of steady orographic rain superimposed on fairly small amounts of frontal rain. Between 18 GMT on 6 January and 06 GMT on 7 January the low-level wind flow, as reported by the Aughton radar ascents, at levels between 900 mb and 700 mb, approximated closely to 230 degrees 50 knots (1 kt $\approx$ 0·5 m/s). The warm air mass was almost saturated up to the 760-mb level with a lapse rate close to the 11 °C saturated adiabatic. Conveniently, both warm and cold fronts passed through the three reporting stations, Great Langdale (54° 26′N, 03° 03′W, 170 m above MSL), Carlisle on low ground some 65 km to the north, and

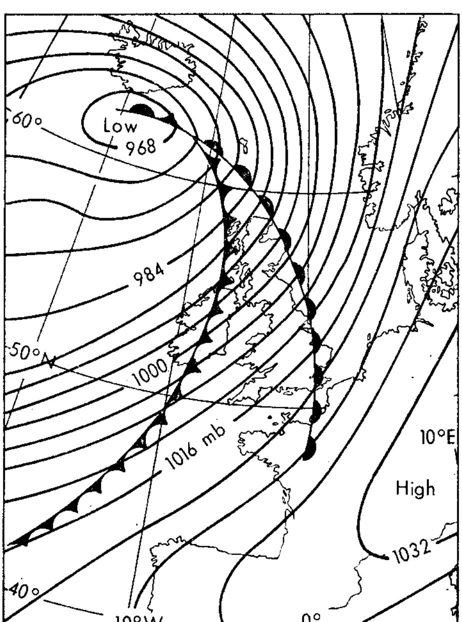

FIGURE 2—SURFACE CHART AT 00 GMT ON 7 JANUARY 1971

Blackpool some 80 km south of the hills, at roughly the same times (the only significant difference being that the warm front reached Blackpool about an hour earlier than it reached the other two stations). At Great Langdale the warm front passed at 1925 GMT on 6 January, and the cold front at 0545 GMT on 7 January 1971.

Figure 3 shows the rates of rainfall obtained from autographic recordings of tilting-siphon rain-gauges at each of the three stations, the area under each graph representing the amount falling in a particular period of time. Table I estimates the additional rainfall at Great Langdale in excess of a

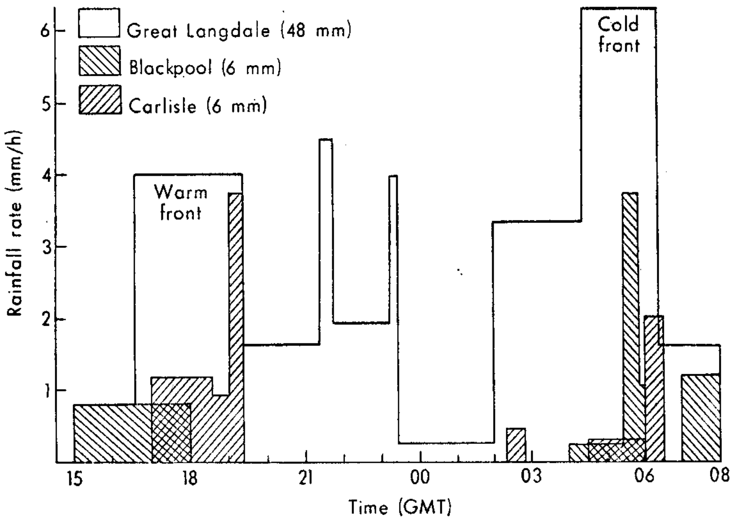

FIGURE 3—DISTRIBUTION OF RAINFALL ON 6 AND 7 JANUARY 1971

mean of the amounts falling at Carlisle and Blackpool, over periods of time which correspond to the steps on the Great Langdale histogram of Figure 3. The most significant periods of orographic rainfall are the three in heavier type (ignoring the two short bursts in the warm sector). Their importance

TABLE I—OROGRAPHIC RAINFALL AT GREAT LANGDALE ON 6/7 JANUARY 1971

Zone	Times GMT	Period *hours*	Excess *mm*	Rate of excess *mm/hour*
Ahead of warm front	1500–1635	1·6	0·6	0·4
Warm frontal zone	**1635–1925**	**2·8**	**10·0**	**3·6**
Warm sector	1925–2125	2·0	3·1	1·6
Warm sector	2125–2150	0·4	1·8	4·5
Warm sector	2150–2320	1·5	2·9	1·3
Warm sector	2320–2330	0·2	0·8	4·0
Warm sector	2330–0200	2·5	0·6	0·2
Ahead of cold front	**0200–0420**	**2·3**	**7·8**	**3·4**
Cold frontal zone	**0420–0620**	**2·0**	**12·2**	**6·1**
Behind cold front	0620–0800	1·7	1·8	1·1
Whole period	1500–0800	17·0	41·6	2·4

lies in the requirement for a forecast of the period, as well as the amount, of the peak fall. On this occasion the peaks were so well separated as to constitute no risk of flooding. For floods to occur the peak figure of the cold frontal zone needs to be maintained over a longer period. Often the peaks on the two frontal zones amalgamate so that the warm frontal rainfall cannot be identified in the long period of heavy rain that occurs ahead of the cold front. Some of the peak rates that have been noted are given underneath Figures 4 and 9.

Occluded fronts seldom show such marked increases in rainfall as any of the warm and cold front examples above. This points to the importance of the release of water droplets by the lifting of warm moist air in the lowest layers of the atmosphere (where the water content is usually greatest). The mechanism which often gives rise to very high rates of rainfall on the approach of a cold front and, less frequently, on the approach of a warm front is not fully understood. Two factors may be worth a mention. Raindrops, falling from a higher level in the frontal zone, will scour out the smaller cloud droplets released by forced uplift over the mountain escarpment. This effect appears to increase the frontal rainfall on both the windward and leeward sides of the mountains. However, the maximum rainfall, and presumably the maximum intensity, usually occurs over a limited distance immediately to the lee of the first mountain barrier. This is a region where the air, in rising up to and past this barrier, achieves its maximum vertical component of velocity, and hence its minimum horizontal component. Here raindrops falling through a rising column of air are given the maximum opportunity for collision with smaller droplets. If, because of the vertical motion, there is some reduction in the horizontal flow, then, in a given time, these raindrops fall into a relatively smaller ground area. The lapse rate of the saturated air is usually neutral, so there is no reason why air which has acquired a vertical motion should not continue to ascend some distance beyond the first mountain barrier.

A calculation before the event of the amount of rain likely to fall in a limited time in a particular area, not only involves assumptions about the efficiency and magnitude of these processes, but also requires forecasts of the rainfall pattern upwind of the mountains, and forecasts of humidity, temperature and wind at different levels in the air masses crossing the mountains. The forecaster does not attempt such a calculation. Instead he attempts to identify and forecast a limited number of synoptic conditions which are normally found to be associated with the specified rainfall.

Langdale valley. This was the first area for which an attempt was made to relate heavy rainfall to synoptic conditions. The reasons are largely historical, but the day-to-day investigation has been greatly assisted by the excellent recordings of the Great Langdale rain-gauge, which have been made available soon after the event, by the rainfall observer, Mr P. G. Satow. Rainfall values which have been obtained from time to time from other gauges in the Lake District suggest that the Great Langdale gauge is fairly representative of rainfall events in central Lakeland. The results obtained for this area have laid the foundation for attempts to forecast rainfall amount in other areas where a requirement has arisen.

Mr Satow first sorted through his autographic records for the 10-year period 1954–63, and extracted 35 occasions of particularly heavy rainfall. When the periods during which the heavy rain occurred were looked at in relation to *Daily Weather Reports*,* it was found that on 30 of these occasions

* London, Meteorological Office. *Daily Weather Report.*

the rainfall was clearly associated with the passage of a warm front, or a cold front, or both. On two other occasions the rainfall appeared to be associated with thundery developments. Table II lists the 10 most outstanding occasions of prolonged heavy falls, each of which satisfies the criterion of a fall of more than 50 mm at a mean rate of at least 8 mm an hour.

TABLE II—OUTSTANDING OCCASIONS OF PROLONGED HEAVY RAINFALL AT GREAT LANGDALE 1954–63

	From		To				
Year	Date	Time GMT	Date	Time GMT	Duration *hours*	Rainfall *mm*	Mean rate *mm/hour*
1954	15 Jun	0920	15 Jun	1910	9·8	98	10·0
1954	2 Dec	0045	2 Dec	0815	7·5	73	9·7
1958	25 Jan	0155	25 Jan	1055	9·0	84	9·3
1958	12 Oct	2210	13 Oct	0500	6·8	64	9·4
1960	26 Feb	1640	26 Feb	2255	6·3	51	8·1
1961	3 Aug	1540	3 Aug	2110	5·5	73	13·3
1962	15 Jan	1420	16 Jan	0030	10·2	85	8·4
1962	12 Feb	0010	12 Feb	0655	6·7	73	10·8
1962	10 Aug	2300	11 Aug	0800	9·0	113	12·6
1963	25 Sept	2100	26 Sept	0500	8·0	80	10·0

Figure 4 shows the Great Langdale recording on the night of 10 to 11 August 1962 when serious flooding occurred, as it almost certainly did on all the other occasions, except on 25 January 1958 when the precipitation was in the form of snow. Floods which sweep down the valley floor constitute a serious threat to grazing stock on adjacent farm lands, particularly if the phenomenon occurs in the hours of darkness. It may be interesting to note that on 6 of these 10 occasions the heavy fall occurred during the night hours, and another 3 were in the late evening.

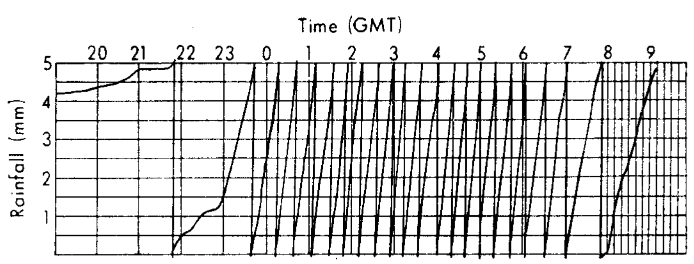

FIGURE 4—DIAGRAMMATIC REPRESENTATION OF HYETOGRAM AT GREAT LANGDALE, 10–11 AUGUST 1962

Commencing at 23 GMT, 10 August, 9 hours rain fell at the rate of 13 mm/h.

All 10 occasions were found to be associated with the same synoptic weather type, namely the easterly passage across the Lake District of the warm sector of a depression enclosing moist air of subtropical origin. Figure 5 illustrates diagrammatically the development of such a depression over the Atlantic between 12 GMT on 6 April and 12 GMT on 9 April 1965. On 9 April 1965 the first of the warnings of heavy rainfall for the Langdale area was issued, and in fact 37 mm fell in the 6-hour period commencing at 18 GMT. Figure 6 shows the vertical distribution of temperature and humidity in the warm air as sampled by the radiosonde released from ocean weather station J, 52°30′N 20°W, at 00 GMT on 9 April.

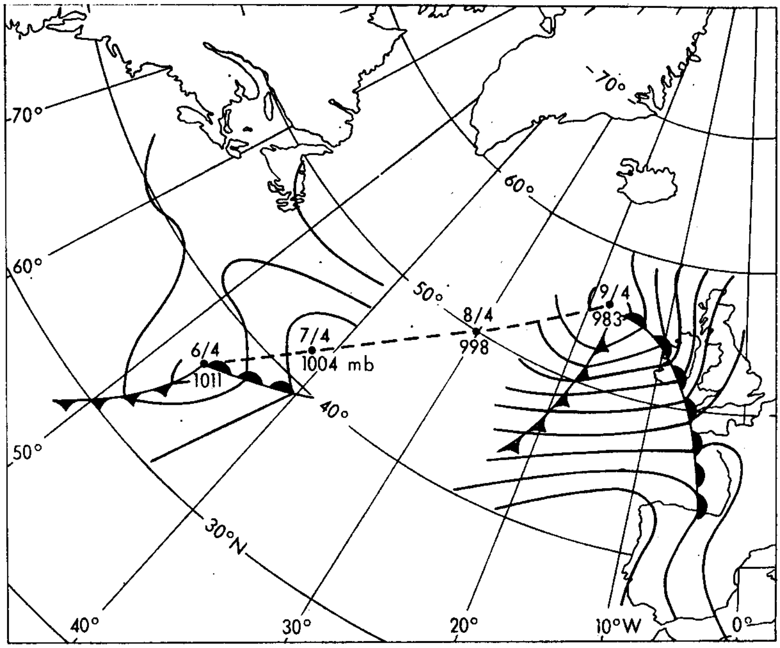

FIGURE 5—TRACK AND DEVELOPMENT OF DEPRESSION 6–9 APRIL 1965
Positions and depths shown at 12 GMT. Isobars are at 4-mb intervals.

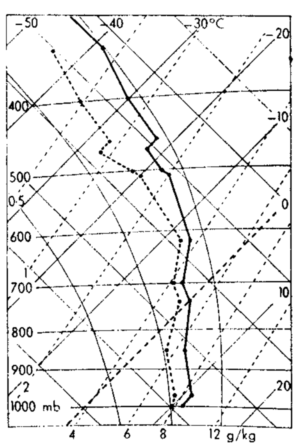

FIGURE 6—UPPER-AIR SOUNDING FOR OCEAN WEATHER STATION 'J' AT 00 GMT ON 9 APRIL 1965

.———. Temperature .– – – – –. Dew-point

Figure 7 illustrates somewhat similar Atlantic developments during the period from 12 GMT, 29 October to 12 GMT, 31 October 1965. In the event, however, the heavy rainfall was confined to a 4-hour period from 1315 to

1715 GMT on 31 October when only 29 mm fell, considerably less than the minimum requirement for a prolonged heavy rainfall warning. The Valentia (south-west Ireland) ascent (Figure 8) for 12 GMT on 31 October provided the first clue to the difference from the occasion of 9 April 1965. This was the first sampling of the temperature and humidity of the more southerly of the two warm air masses in its passage across the Atlantic. Until this sounding was available, the very dry air above the 800-mb level had remained unsuspected.

For prolonged very heavy rainfall in the Langdale valley two alternative sets of criteria have been developed. If 36 mm or more is to fall at a rate of at least 6 mm per hour, one or other set is normally satisfied. The first requires the following three conditions to be satisfied :

(a) A depression moves eastwards, or northwards, across an arbitrary line joining the southern tip of Iceland to Cornwall before it starts to fill.

(b) The warm sector of the depression is occluding, but is not fully occluded as it approaches the Lake District.

(c) Relative humidity in the warm air is high from the surface up to the 650-mb level.

The first condition is perhaps the easiest to forecast. The second is much more subjective because of the difficulties of identifying the position of the 'triple point' on the surface chart. It is most important, however, that the surface warm air has not entirely occluded by the time the fronts reach the Cumberland coast, or prolonged heavy rainfall will not occur. The third

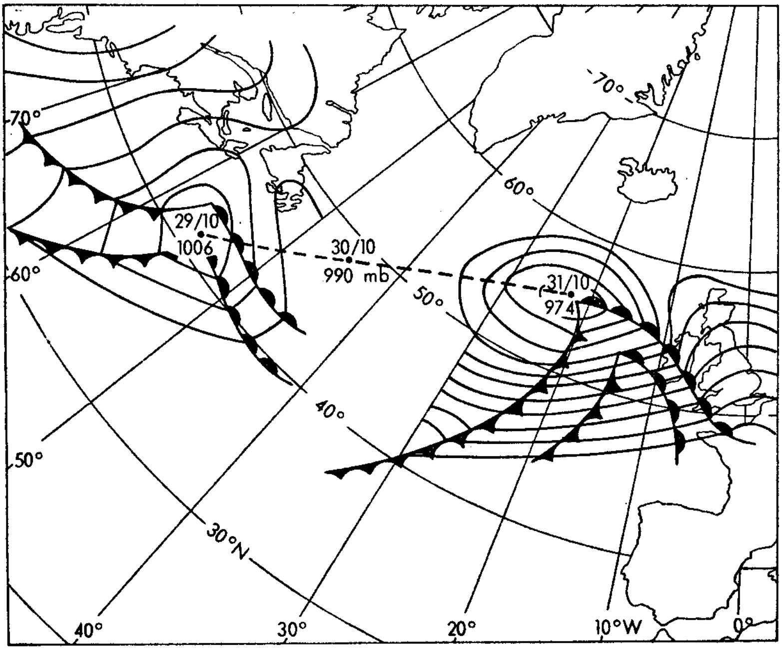

FIGURE 7—TRACK AND DEVELOPMENT OF DEPRESSION 29–31 OCTOBER 1965
Positions and depths shown at 12 GMT. Isobars are at 4-mb intervals.

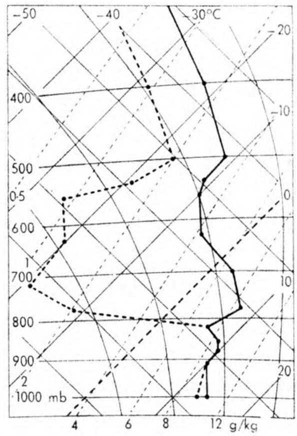

FIGURE 8—UPPER-AIR SOUNDING FOR VALENTIA AT 12 GMT ON 31 OCTOBER 1965
.———. Temperature .– – – –. Dew-point

condition is the most difficult to forecast. The warm air may cross the Atlantic without being sampled by a radiosonde, the distribution of humidity in the vertical often exhibits a latitudinal variation within the warm sector and, perhaps most important, large-scale developments, which so often take place near the British Isles, may result in a rapid increase in the depth of the saturated layer. The forecast that relative humidity is expected to approach saturation throughout much of the layer from the surface to 650 mb may be very subjective.

Many other parameters have been looked at from time to time in an attempt to obtain a more precise definition of the conditions which produce the heaviest falls. Amongst these are wind components normal to the mountain range, surface temperature, surface dew-point, rate of pressure fall, the dew-point depression at the 700-mb level, and the relationship with upper-level jet streams. The 700-mb wet-bulb potential temperature looked promising, but experience suggests that only a minimum value is required, above which there is no direct correlation with the rainfall. Some of these variables are already implicit in the three specified conditions.

The alternative set of criteria is :

(a) An active cold front often with small waves becomes slow moving as it approaches the Lake District.

(b) Relative humidity in the warm air ahead of the cold front is high from the surface up to the 700-mb level.

(c) The geostrophic wind speed ahead of the front is 35 knots or more from a south-westerly direction, the arc from 190 to 250 degrees true being the most favourable.

Neither set of criteria covers the thunderstorm occasion, when large falls may occur in a short period of time. In this area the association of intense thundery activity with flooding appears to be infrequent, though floods which followed prolonged thundery activity during the evening of 13 August 1966 were noteworthy in both the Langdale and Borrowdale valleys.

The Lancashire River Authority engineers intimated at one stage that, in addition to warnings of prolonged very heavy rainfall, they would also be glad to receive warnings of less intense falls. The minimum condition specified was 4 hours of heavy rain, defined in accordance with the standard definition of rain falling at more than 4 mm per hour. This condition is satisfied by many cold fronts, and by warm fronts — but not necessarily by occluded fronts — which approach the Lake District from a general westerly, south-westerly, or southerly direction, provided that certain criteria for humidity and low-level wind flow are achieved. These may be summarized :

(a) Relative humidity of the air ahead of the cold or warm front is high throughout the layer from the surface up to the 700-mb level (there should be no relatively dry layer).

(b) Geostrophic wind direction lies in the arc 150 to 270 degrees.

(c) Geostrophic wind speed is normally 35 knots or more, but the minimum rainfall conditions may be achieved with a lower speed of, say, 25 knots if this is accompanied by pressure falls of about 4 mb per 3 hours.

Gwynedd River Authority area. In a 2-year period commencing November 1966 during which warnings of prolonged very heavy rainfall were issued to the Authority, it was found that the synoptic criteria developed for the more intense falls in the Lake District applied equally well here. This is not surprising in that the mountainous area of north Wales is one of three in the British Isles which have similar contours and a similar exposure to moist south-westerlies (the third being the North-west Highlands of Scotland). The rainfall limits specified for the issue of warnings were similar to the Langdale figures of 36 mm or more at a rate of at least 6 mm per hour, but in addition it was suggested by the Authority that a fall of 50 mm in a 24-hour period might be enough to produce flooding on its own, regardless of the detailed rates of fall. In the event all the 9 major occasions that occurred in the 2-year period appeared to satisfy both specifications.

Figure 9 shows the surface chart for 06 GMT on 27 February 1967, an occasion when the first set of criteria for prolonged very heavy rainfall, as listed under the Langdale valley heading (page 40), was satisfied. This occasion was selected as one on which the rainfall produced by the warm and cold fronts of a single depression fell in the standard rainfall day. Rainfall values for the 24-hour period commencing 09 GMT on 27 February 1967 were obtained for about 500 climatological stations extending from the Scottish border to central Wales. Figure 10 shows isohyets drawn from the plotted values. Values over 75 mm were reported by 3 stations in the Lake District, and one station in Snowdonia reported over 100 mm. This situation is also of interest in producing the highest rate of prolonged frontal rainfall that has been noted. An interrogable tipping-bucket rain-gauge at Dolwyddelan, 366 m above MSL, in the Upper Conway, collected 76 mm of rain in the $4\frac{1}{4}$ hours commencing 1215 GMT on 27 February, a mean rate over this period of 18 mm per hour. At the same time other gauges in the Gwynedd area were obtaining rates of 10 to 11 mm per hour over periods of between 5 and 7 hours.

Figure 11, the surface chart for 18 GMT on 1 October 1967, illustrates an occasion when the second set of criteria for prolonged heavy rainfall was

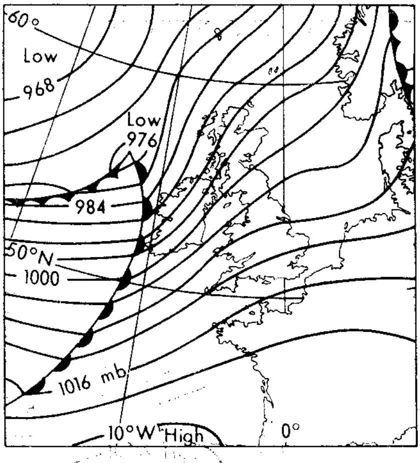

FIGURE 9—SURFACE CHART AT 06 GMT ON 27 FEBRUARY 1967
4 hours rain at 18 mm/h in Upper Conway, 5 hours rain at 10 mm/h in Langdale.

satisfied in respect of the Gwynedd area. The slow-moving cold front with waves, shown just west of the area, produced a reading of 99 mm in the Dolwyddelan gauge in the 13-hour period commencing at 12 GMT on 1 October. Flooding was reported from the Conway valley next morning. This cold frontal zone also produced one of the largest falls, 35 mm in 10 hours, noted in the Upper Dee area.

Upper Eden area. Rainfall warnings for the upper end of the Eden valley have been issued to the Cumberland River Authority since March 1969. The Authority requires advance warning of the likelihood of flooding in Carlisle and Appleby. The minimum rainfall conditions likely to cause this were not known, but the Authority agreed that it should be alerted on occasions when 38 mm or more is expected in any period of 24 hours or less. The synoptic conditions likely to produce 38 mm of rain in this very sheltered area are still not fully tested, because in the 3 years since March 1969 this figure has only been achieved on three occasions, and no flooding has occurred. They may be summarized in two sets, the first requiring three conditions to be satisfied :

(a) An active cold front, often with waves, becomes slow moving as it approaches the area.
(b) Relative humidity in the warm air ahead of the cold front is high from the surface up to the 700-mb level.
(c) The geostrophic wind speed ahead of the front is 45 knots or more from a general south-westerly direction, 210 to 250 degrees probably being the most favourable.

Figure 12, the surface chart for 18 GMT on 12 February 1971, illustrates an occasion when these criteria were achieved. A tipping-bucket gauge at Castlethwaite (244 m above MSL) recorded just 38 mm in the 9-hour period commencing 13 GMT on 12 February. This was the only occasion in 1971 on which the specified minimum amount was reported at any of three gauges

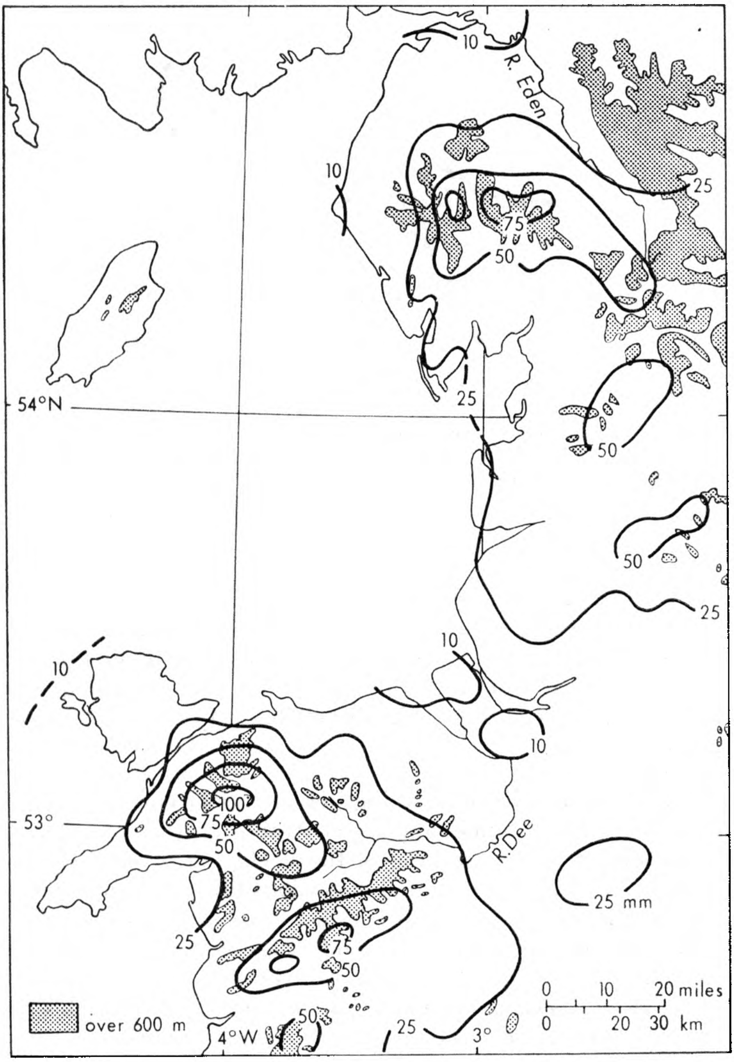

FIGURE 10—RAINFALL DAY 27 FEBRUARY 1967

Correction : Stippling denotes height over 400 m, not 600 m as shown.

in the catchment area. The criteria listed above are almost identical with the second set for major falls in the Langdale valley.

An attempt was made to modify the first set of criteria for the Langdale valley by adding a fourth condition :

(d) Geostrophic wind speed is 50 knots or more.

The assumption was that very strong winds would carry appreciable rain as far beyond the first mountain barriers as the Eden valley. Although this does occur, the amount appears to fall short of the 38-mm figure.

Instead the second set of criteria relate to the condition of almost continuous showers, produced by uplift over the hills of a strong south-westerly unstable

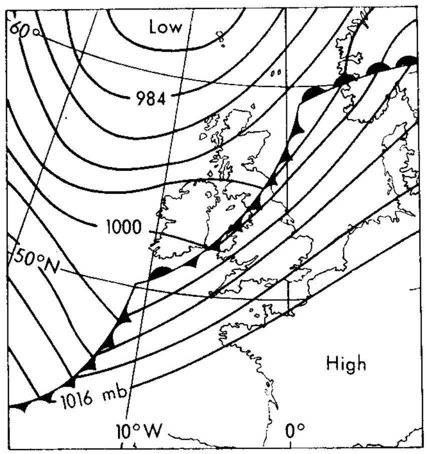

FIGURE 11—SURFACE CHART AT 18 GMT ON 1 OCTOBER 1967
13 hours rain at 7 mm/h in Upper Conway, 10 hours rain at 3·5 mm/h in Upper Dee.

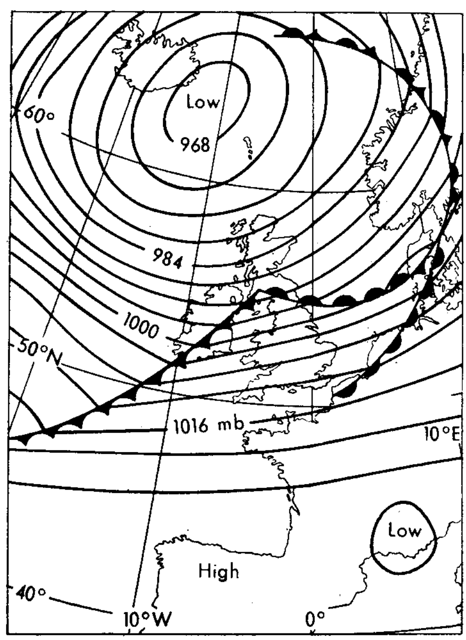

FIGURE 12—SURFACE CHART AT 18 GMT ON 12 FEBRUARY 1971
9 hours rain at 4 mm/h in Upper Eden.

airstream, and carry over into parts of the Eden catchment. The conditions may be summarized :

(a) An unstable south-westerly airstream, with instability extending to the 600-mb level, is maintained over the area for 9 hours or more.
(b) The gradient wind speed is 45 knots or more from a direction between 210 and 250 degrees.

These conditions were satisfied on 9 September 1970 (not illustrated) when the Castlethwaite gauge collected 67 mm in a 37-hour period commencing at 09 GMT on 9 September, and indicated rates of fall of 4 mm per hour for short periods.

Lancashire River Authority area. A flood warning scheme being developed by this Authority requires warnings of heavy rainfall covering all catchments in their area. A preliminary study has been made of the incidence of flooding over the area as a whole during the period 1964 to 1970 inclusive. On each occasion of appreciable flooding, evidence has been found from the autographic record of one rain-gauge or another of a fall of 35 mm or more. On the majority of occasions this fall occurred in a period of between 8 and 12 hours. The 28 occasions when floods were reported may be classified in relation to the prevailing synoptic weather type :

Occluding warm sector of a developing depression	7
Slow-moving cold fronts	7
Unstable west to south-west airstreams	5
Thunderstorms	5
Open-wave depression developing to north of area	1
Quasi-stationary frontal zone	1
Deepening depression over area	1
Trough in a warm sector	1

This analysis is encouraging in that the first three types are those already identified for other areas. The thunderstorm problem remains, since, on the basis of this very limited evidence, on average not more than one thunderstorm occasion, out of the many that occur each year, causes significant flooding in any part of the Authority's area. When the occasion does arise, the results may be quite spectacular, such as on 8 August 1967 when the village of Wray, near Lancaster, was partly swept away by flood waters.

Upper Dee area. This area lies to the east of the main mountain ranges of north Wales, and does not normally experience the more intense rainfalls of Gwynedd. The Water Resources Board are mounting a large-scale experiment to control the flow of the River Dee by using the regulating reservoirs of Bala Lake and Llyn Celyn. A high-powered radar has been set up to measure areal rainfall as it occurs, and it is expected that there will be a requirement for forecasts of the amount of rain expected to fall in a specified period. Over a period of several years, experimental forecasts of rainfall amount covering periods up to 24 hours ahead, have been written out in the three ranges 5 to 15 mm, 15 to 30 mm, and more than 30 mm, and subsequently compared with actual rain-gauge readings. A number of empirical forecasting rules have been developed in an attempt to identify the synoptic features associated with different rainfall amounts. The ones summarized below specify differing criteria for forecasts of amounts of 15 to 30 mm. Their similarity with criteria found in other areas will be noted.

(a) A developing wave, on either a cold front or a warm front, is expected to pass near to the area in the form of an open sector of moist air. The wave tip usually moves with an easterly component between latitudes 52°N and 54°N.

(b) An active cold front, often with waves, is expected to become slow moving across the area.
(c) An occluding warm sector of a developing depression is expected to cross the area. Relative humidity in the warm air mass should be high up to the 700-mb level.
(d) A moist south-westerly airstream of 45 knots or more and unstable to the 600-mb is expected to be maintained for some time. Rainfall accumulates at a rate of about 2·5 mm per hour on average.
(e) Thunderstorms, or thundery rain, are expected in association with a slow-moving trough or with weak pressure gradients.
(f) An active warm front is expected to approach the area.

Autographic records of gauges at Bala Sluice (164 m above MSL) and at Llyn Celyn (271 m above MSL) are subsequently analysed for the time of the forecast. If the mean of these two values falls within the range forecast the forecast is regarded as correct. The results of forecasting amounts of 15 mm or more are given in the next paragraph. It has seldom been possible to forecast amounts of more than 30 mm, as distinct from the 15- to 30-mm range. Similarly there are difficulties in forecasting the smaller amounts in the 5- to 15-mm range, these forecasts being correct only on about half the occasions.

Results. Table III lists the number of occasions on which the specified rainfall conditions were achieved, the number of these that were correctly forecast, and the total number of forecasts issued.

TABLE III—NUMBER OF OCCASIONS OF SPECIFIED RAINFALL AND THE NUMBER CORRECTLY FORECAST

Area	Period	Specified rainfall	Observed	Forecast correctly	Total forecast
Langdale	1 year 1965–66	24 mm at 4 mm/hour	11	8	18
Langdale	2 years 1966–68	36 mm at 6 mm/hour	13	5	13
Langdale	4 years 1968–72	16 mm at 4 mm/hour	50	38	77
Gwynedd	2 years 1967–68	36 mm at 6 mm/hour or 50 mm in 24 hours	9	7	16
Upper Eden	3 years 1970–72	38 mm in 24 hours	4	3	14
Upper Dee	2+ years 1970–72	15 mm	57	47	78

The results indicate that if a number of significant occasions are not to be missed, a good many more warnings must be issued than will be justified by the event. The first two entries for Langdale in Table III illustrate this. After receipt of the first year's warnings the recipient said he was being warned too often when floods did not occur. The result of attempting to be more selective in the two years that followed was that warnings were not issued on eight occasions. On the other hand, warnings for the Upper Eden are regarded as quite successful despite the relatively large number of alerts, which, with experience, is now decreasing.

Concluding remarks. The procedure of empirical forecasting of rainfall amount involves a number of meteorological variables which in themselves are often difficult to forecast. The decision whether or not to issue a warning is often very subjective, and the overall accuracy is quite sensitive to the requirements of the recipients. River authorities use the warnings as a first alert and then arrange to monitor rain-gauge and river-level recordings as the rain progresses. On some occasions the river levels may be so low that no immediate action is necessary. Sometimes the forecaster is able to modify his original warning in the light of later information on the synoptic charts and of actual rain-gauge readings from the catchment areas.

Acknowledgement. I am indebted to Mr P. G. Satow for supplying the Great Langdale rainfall recordings, and to the Lancashire River Authority for permission to publish Figure 4.

551.5(09):06

A SHORT HISTORY OF THE FORMER HOMES OF THE METEOROLOGICAL OFFICE

By L. JACOBS

At the end of a new phase of building at Bracknell with the Operational Instrumentation Branch buildings at an expanded experimental ground (Beaufort Park, originally 30 acres and now 90), the Richardson Wing,[1] and the College at Shinfield Park,[2] it is fitting to put on record the history of the former homes of the Meteorological Office.

A general history of the Meteorological Office was included in the special issue[3] of the *Meteorological Magazine* to commemorate the centenary of the Office in 1955. Few details are given here, however, of the exact locations of the Office and the dates of occupation. The annual reports of the Office from the first one, dated 23 May 1855 and issued in January 1856, have been studied and several of the sites mentioned have been visited and recent official photographs have been taken.

The Office was first established as part of the Board of Trade in January 1855 with Admiral FitzRoy as Director and only three other staff members. Strangely enough although the address Parliament Street, London SW, is given in all the early reports there is only one mention of the building being Number 2. The minutes of the Meteorological Committee are quite specific in quoting Number 2 as the address, so it appears that Shaw[4] is wrong in quoting the address as Number 1. The only description of the location of the Office that can be traced is in 'The clerk of weather' by Wynter,[5] who states :

> 'If the lounger is on his way to the Abbey, as he gets towards the end of Whitehall, he sees before him, on his left hand, looking down King Street,

PLATE I—A MODERN PHOTOGRAPH OF THE PREMISES AT 63 VICTORIA STREET

See page 49

PLATE II—THE BUILDING IN EXHIBITION ROAD

See page 50

PLATE III—THE BELL-PUSH STILL IN SITU IN DECEMBER 1971

See page 50

PLATE IV—VICTORY HOUSE, KINGSWAY

See page 50

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PLATE V—ADASTRAL HOUSE, KINGSWAY

See page 50

an over-hanging bow window; here is the den or cave of the magician who takes under his care the four winds, and foretells rain or snow with certainty.'

King Street is not on a London street map of 1912 but is on such a map of 1851; this latter map shows that the southern end of Whitehall had in the centre of the present road another row of buildings starting from about the present site of the Cenotaph and extending to the southern end of Whitehall. Looking from the Cenotaph to the southern end of Whitehall, King Street ran on the right-hand side of this central row of buildings, while Parliament Street was on the left of this row of buildings; Number 2 was almost exactly where the Cenotaph is now. It is puzzling that Wynter speaks of seeing the Office 'on his left, looking down King Street' as this would imply that the Office faced on to King Street; perhaps it did and extended right through from Parliament Street to King Street.

No mention has been traced of the details of the rooms occupied by the Office at Number 2 Parliament Street; it is, however, possible that some of the unexamined FitzRoy papers held in the Meteorological Office archives may mention them. It is interesting, however, to find that in the first annual report, mentioned above, it is stated that 'at present the rooms allotted to the Meteorological Office are so filled that additional persons would be detrimental. Space is wanted for packing and storing instruments, as well as for keeping records accessively; but, with more accommodation and additional assistance our fast accumulating materials may be overtaken, and their results promptly published'.

Clearly the Office outgrew whatever accommodation was allotted to it by the Board of Trade in Parliament Street. Shaw[4] indicates that the Office indeed had to move out: 'In 1869 the Department was dispossessed of its quarters in 1 [see remarks above regarding this being an error for 2] Parliament Street, belonging to the Board of Trade and hired for itself the residential flat then known as 116 Victoria Street'. While there was no mention in the minutes of the Meteorological Committee of this 1869 move it is recorded that the meeting of 24 May 1869 took place at 2 Parliament Street while the next meeting on 7 June 1869 was at 116 Victoria Street. On 12 December 1888 the minutes give the meeting address as 116 Victoria Street while the next meeting, that on 9 January 1889, is at 63 Victoria Street; this, at first sight, indicates a change of location in Victoria Street but Shaw[4] firmly states 'from 1869 to the present time [1910] the Office has occupied the premises at 116 which was renumbered 63 Victoria Street'. Descriptions of this Office at 63 Victoria Street are given, amongst others, by Lempfert.[6]

A modern photograph of the site and the building is given in Plate I which shows the narrow balcony on the second floor of Number 63 referred to[7] in the following extract: 'various weather reports stand out in bold lettering from an upper balcony, signifying that this office has telegraphic connection with various important positions on our coast'. This balcony is clearly the one referred to by Bench.[8] Although in 1902 an article[7] stated that the Office had 'capacious chambers in Victoria Street', Sir Herbert Maxwell's Committee, the first to investigate the Office, pronounced in 1903 'the premises at 63 Victoria Street unsuitable for the work that had to be done in them . . .' (Shaw[4]). This led to discussion in 1906 on the future location of the Office

(Report of the Meteorological Committee for the year ending 31 March 1906, Appendix I); it was eventually agreed to design a new building in Exhibition Road, South Kensington, specially for the Meteorological Office on the upper floors and with a district Post Office on the ground floor. The transfer of the Office staff to the new premises was completed on 15 November 1910 and the Meteorological Committee invited a large party to an 'at Home' in the new building on 1 December. Details of the accommodation are given in the Sixth Annual Report of the Meteorological Committee for the year ending 31 March 1911, and the frontispiece is a photograph of the new Office viewed from the north-east. Plate II shows the building, still standing in December 1971, and, it appears, with the original four trees still in front of it. Plate III, also taken in December 1971, shows that the push button of the bell of the Meteorological Office still exists outside the main door; the Office vacated this accommodation in November 1939.

Owing to the general expansion of the Office it was necessary to find additional accommodation in 1919; it was agreed (Fifteenth Annual Report for the year ending 31 March 1920) that space would be provided for the Directorate, the Forecast Branch and the Marine Division on the third to fifth floors of the Air Ministry, Adastral House, Kingsway (Plate V), and the move took place in stages from 1 July to 18 November 1919. The remainder of the Office stayed at South Kensington until November 1939 when it moved with the Marine Division to Wycliffe College, Stonehouse, Gloucestershire. The Adastral House contingent moved to nearby Victory House in Kingsway (Plate IV) in April 1938, then occupying the top three floors and the famous 'Air Ministry roof'. There was an overflow of staff from Victory House to the nearby Public Trustee Office in November 1957; meanwhile in 1945 the marine, climatological and instruments branches and the library had moved from Stonehouse to Harrow. The forecasting section left its position under the 'Air Ministry roof' at the end of August 1939 and went to a temporary home in Birmingham; in February 1940 it moved to its permanent war-time home at Dunstable.

The first section of the Office to move to the new Headquarters at Bracknell was the Directorate from Victory House in February 1961 and the main move from Harrow, Dunstable and the Public Trustee Office took place in the autumn of that year.

This present version is condensed from a fuller account.[9]

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551.543:551.577.36:551.589.5(420+429)

CYCLONIC-TYPE RAINFALL AND ATMOSPHERIC MEAN-SEA-LEVEL PRESSURE OVER ENGLAND AND WALES

By E. N. LAWRENCE

Summary. For days of cyclonic type of atmospheric circulation over the British Isles region' the long-term monthly and annual averages of the daily rainfall amount over England and Wales (combined) for 5-mb ranges of MSL pressure and the corresponding frequencies of these ranges were calculated for the period 1950–69 (20 years).

The results show that the annual average rainfall amount increases approximately linearly with decreasing pressure from 1020 to 980 mb. The amplitude of the annual variation has a flat minimum from 1005 to 1020 mb and similarly, the ratio of this amplitude to the average has a minimum at around 1010 mb. There is a small systematic change with pressure in the date of the annual maximum average daily rainfall amount, from early November to October, as pressure increases from 985 to 1010 mb (baroclinic lows); when pressure is about 1015 to 1020 mb (thermal lows), maximum average daily rainfall amount tends to occur in summer (July–August).

The average annual frequency of cyclonic-type days is at a maximum with pressures around 1005 mb; in winter, maximum frequencies occur at 995–999 mb, and in summer at 1005–1009 mb; the amplitude of the annual variation of frequency is at a maximum with pressures of 1005–1010 mb. The ratio of the annual amplitude to the annual total frequency for a 5-mb range of pressure has a minimum at 995–999 mb. For pressures below 995 mb, the annual maximum frequency occurs in winter (November–December or January) while for pressures greater than 995 mb, the maximum frequency occurs in summer (July–August); there is a sharp discontinuity around 995 mb.

The results are discussed in relation to sea temperature and land–sea orientation.

Introduction. The register of daily synoptic types for the British Isles region[1] has two 'wet' types with comparatively large frequencies, namely the 'straight' westerly type and the cyclonic type. For the purpose of improving estimates of individual monthly values of areal rainfall over England and Wales from synoptic-type rainfall averages,[2] averages for 'straight' westerly-type days were obtained for 5-mb ranges of MSL pressure.[3] In the present work, similar rainfall averages are obtained for cyclonic-type days.

Method. To ascertain objectively the daily pressure over England and Wales on cyclonic-type days during the period of 20 years from 1950 to 1969, the pressure (to the nearest millibar) was read from the midday chart of the *Daily Weather Report** for the central point of 53°N 02°W.

For these days, the direct estimates of daily areal rainfall amounts over England and Wales[2] were processed to obtain for each calendar month the average daily rainfall amount for 5-mb ranges of pressure (e.g. 990–994, 995–999, 1000–1004 mb, etc.) and the corresponding average frequencies of these ranges (days per month).

To eliminate irregularities arising from small samples, rainfall and frequency averages for a particular month and 5-mb ranges of pressure were calculated as explained in a previous paper.[3] The resulting rainfall averages were slightly adjusted, proportionally, so that the annual rainfall for the cyclonic type is that previously estimated.[2]

The values thus obtained include some 'theoretical' categories, that is, for pressure ranges beyond the extremes actually observed in any month or in either of the two adjacent months. These 'theoretical' categories were eliminated by grouping the three pressure categories at each extreme of pressure, for each month separately. If the total of the three frequencies was less than 0·015 (0·3 over the 20 years), it was grouped with the adjacent

* London, Meteorological Office, *Daily Weather Report*.

frequency and so on. Categories eliminated by this restriction are indicated by a dash in Table I, which shows the final rainfall and frequency averages.

TABLE I—AVERAGES OF RAINFALL OVER ENGLAND AND WALES FOR GIVEN RANGES OF MSL PRESSURE AND FREQUENCIES OF THESE RANGES, IN THE PERIOD 1950–69, FOR CYCLONIC-TYPE CIRCULATION

		Pressure range (mb)													
		955–959	960–964	965–969	970–974	975–979	980–984	985–989	990–994	995–999	1000–1004	1005–1009	1010–1014	1015–1019	1020–1024
Jan.	*R*	9·6	7·7	6·2	5·3	5·2	5·4	5·4	5·0	4·6	4·5	4·2	3·9	3·9	4·5
	F	0·02	0·04	0·07	0·13	0·21	0·27	0·34	0·43	0·50	0·47	0·37	0·24	0·13	0·08
	RF	0·19	0·31	0·43	0·69	1·09	1·46	1·84	2·15	2·30	2·11	1·55	0·94	0·51	0·36
Feb.	*R*	9·1	5·5	4·6	4·7	4·9	4·9	4·9	5·0	4·8	4·5	4·2	3·9	3·7	3·4
	F	0·02	0·03	0·05	0·08	0·13	0·21	0·35	0·49	0·56	0·48	0·32	0·18	0·09	0·05
	RF	0·18	0·17	0·23	0·38	0·64	1·03	1·71	2·45	2·69	2·16	1·34	0·70	0·33	0·17
Mar.	*R*	—	6·1	3·3	4·3	5·2	4·9	4·6	4·7	4·7	4·4	4·0	3·7	3·4	2·6
	F	—	0·03	0·03	0·04	0·09	0·18	0·32	0·50	0·60	0·55	0·38	0·21	0·10	0·04
	RF	—	0·18	0·10	0·17	0·47	0·88	1·47	2·35	2·82	2·42	1·52	0·78	0·34	0·10
Apr.	*R*			—	4·2	6·4	5·7	4·9	4·8	4·7	4·5	4·2	3·8	3·3	2·8
	F			—	0·02	0·05	0·11	0·21	0·37	0·58	0·70	0·62	0·40	0·17	0·06
	RF			—	0·08	0·32	0·63	1·03	1·78	2·73	3·15	2·60	1·52	0·56	0·17
May	*R*						7·2	5·8	5·2	4·9	4·6	4·3	3·8	3·4	2·7
	F						0·07	0·12	0·31	0·64	0·97	1·05	0·78	0·38	0·14
	RF						0·50	0·70	1·61	3·14	4·46	4·51	2·96	1·29	0·38
June	*R*						7·4	6·3	5·5	5·1	4·8	4·4	4·2	4·0	3·9
	F						0·03	0·08	0·27	0·60	0·97	1·14	0·96	0·54	0·22
	RF						0·22	0·50	1·49	3·06	4·66	5·02	4·03	2·16	0·86
July	*R*						7·3	6·5	5·9	5·4	5·0	4·8	4·7	4·8	4·9
	F						0·06	0·13	0·33	0·68	1·07	1·28	1·11	0·66	0·27
	RF						0·44	0·85	1·95	3·67	5·35	6·14	5·22	3·17	1·32
Aug.	*R*						7·7	6·9	6·2	5·7	5·3	5·0	4·8	4·8	
	F						0·10	0·19	0·40	0·75	1·16	1·37	1·16	0·90	
	RF						0·77	1·31	2·48	4·27	6·15	6·85	5·57	4·32	
Sept.	*R*			—	—	6·3	7·1	6·9	6·6	6·2	5·7	5·2	4·8	4·5	
	F			—	—	0·04	0·10	0·23	0·41	0·64	0·87	0·96	0·78	0·56	
	RF			—	—	0·25	0·71	1·59	2·71	3·97	4·96	4·99	3·74	2·52	
Oct.	*R*			4·9	6·5	7·6	7·7	7·6	7·4	6·9	6·3	5·7	5·1	4·6	
	F			0·03	0·03	0·08	0·21	0·40	0·55	0·63	0·64	0·57	0·40	0·24	
	RF			0·15	0·19	0·61	1·62	3·04	4·07	4·35	4·03	3·25	2·04	1·10	
Nov.	*R*		8·8	7·2	6·5	6·9	7·5	7·7	7·4	6·7	6·0	5·4	5·0	4·7	4·1
	F		0·03	0·04	0·09	0·19	0·34	0·51	0·61	0·61	0·54	0·41	0·24	0·10	0·04
	RF		0·26	0·29	0·59	1·31	2·55	3·93	4·51	4·09	3·24	2·21	1·20	0·47	0·16
Dec.	*R*		9·7	7·5	6·0	6·0	6·5	6·7	6·2	5·4	4·8	4·3	3·9	3·9	4·4
	F		0·06	0·07	0·13	0·24	0·34	0·42	0·48	0·50	0·47	0·37	0·23	0·12	0·07
	RF		0·58	0·53	0·78	1·44	2·21	2·81	2·98	2·70	2·26	1·59	0·90	0·47	0·31
Year	*R*	9·25	7·89	5·97	5·54	5·95	6·45	6·30	5·93	5·46	5·06	4·70	4·42	4·32	3·95
	F	0·04	0·19	0·29	0·52	1·03	2·02	3·30	5·15	7·29	8·89	8·84	6·69	3·99	0·97
	RF	0·4	1·5	1·7	2·9	6·1	13·0	20·8	30·5	39·8	45·0	41·6	29·6	17·2	3·8

R = monthly or annual rainfall averages in mm/day
F = average frequencies of the pressure ranges in days/month or days/year
RF = product of *R* and *F* in mm.

Annual variation. The monthly values of the average daily rainfall amount for 5-mb ranges of pressure (*R* mm per day) and the averages of frequency of the 5-mb ranges (*F* days per month) were harmonically analysed, as previously described.[3] Theoretical values and other values obtained before the grouping of some categories were used throughout, in order to provide complete (annual) sets of 12 calendar-month values for the analysis of the more extreme ranges of pressure. Resulting harmonic coefficients (a_n, b_n) are given in Table II.

Figures 1–6 show rainfall and frequency patterns in simplified, general form, that is, excluding 'noise'. The theoretical and other pre-grouped values were used for these figures, which are not intended to replace the averages of Table I.

Figure 1 shows the annual variation of average daily cyclonic-type *rainfall amount* over England and Wales, together with the first harmonic curves for five alternate 5-mb ranges of pressure. There were relatively few occasions

TABLE II—HARMONIC COEFFICIENTS OF (a) THE ANNUAL VARIATION OF CYCLONIC-TYPE RAINFALL AMOUNT AND (b) FREQUENCY OF CYCLONIC TYPE FOR DIFFERENT RANGES OF MSL PRESSURE, OVER ENGLAND AND WALES, 1950–69

Pressure range *mb*	a_0	a_1	b_1	a_2	b_2	a_3	b_3	a_4	b_4	a_5	b_5
(a) Rainfall amount, *R*											
					millimetres/day						
975–979	+6·747	−1·413	−0·527	−0·216	−0·394	+0·093	−0·056	−0·027	+0·215	+0·052	−0·125
980–984	+6·530	−0·907	−0·919	−0·153	−0·517	−0·020	+0·005	−0·047	+0·146	+0·056	−0·077
985–989	+6·193	−0·438	−1·236	−0·132	−0·463	−0·110	+0·052	−0·072	+0·113	−0·009	−0·048
990–994	+5·822	−0·214	−1·201	−0·302	−0·268	−0·190	+0·120	−0·068	+0·104	−0·041	−0·002
995–999	+5·423	−0·183	−0·975	−0·394	−0·114	−0·180	+0·165	−0·017	+0·093	−0·018	+0·025
1000–1004	+5·026	−0·198	−0·768	−0·339	−0·044	−0·106	+0·155	+0·052	+0·090	+0·019	+0·020
1005–1009	+4·649	−0·231	−0·647	−0·230	+0·003	−0·083	+0·132	+0·092	+0·117	+0·044	+0·022
1010–1014	+4·313	−0·288	−0·600	−0·090	+0·063	−0·141	+0·116	+0·077	+0·139	+0·044	+0·033
1015–1019	+4·075	−0·309	−0·660	+0·151	+0·062	−0·183	+0·062	+0·069	+0·095	+0·035	+0·030
1020–1024	+3·938	−0·268	−0·838	+0·519	−0·016	−0·092	−0·050	+0·178	+0·005	+0·037	+0·028
(b) Frequency, *F*											
					days/month						
975–979	+0·089	+0·100	−0·032	+0·022	−0·028	−0·006	−0·016	−0·001	−0·002	+0·002	−0·002
980–984	+0·162	+0·135	−0·063	−0·002	−0·029	−0·026	−0·013	−0·004	+0·006	+0·003	−0·002
985–989	+0·274	+0·147	−0·088	−0·036	−0·007	−0·046	+0·002	−0·007	+0·017	+0·005	−0·004
990–994	+0·429	+0·093	−0·070	−0·043	+0·021	−0·047	+0·009	−0·009	+0·024	+0·007	−0·008
995–999	+0·608	−0·077	−0·018	−0·011	+0·030	−0·020	−0·009	−0·011	+0·030	+0·008	−0·015
1000–1004	+0·741	−0·331	+0·009	+0·046	+0·016	+0·025	−0·041	−0·019	+0·040	+0·009	−0·021
1005–1009	+0·736	−0·516	−0·005	+0·109	+0·008	+0·053	−0·055	−0·027	+0·041	+0·009	−0·022
1010–1014	+0·558	−0·485	−0·024	+0·137	+0·017	+0·040	−0·041	−0·023	+0·025	+0·007	−0·016
1015–1019	+0·295	−0·281	−0·019	+0·105	+0·016	+0·012	−0·020	−0·010	+0·008	+0·004	−0·008
1020–1024	+0·098	−0·090	−0·004	+0·048	+0·004	+0·000	−0·008	−0·001	+0·000	+0·001	−0·002

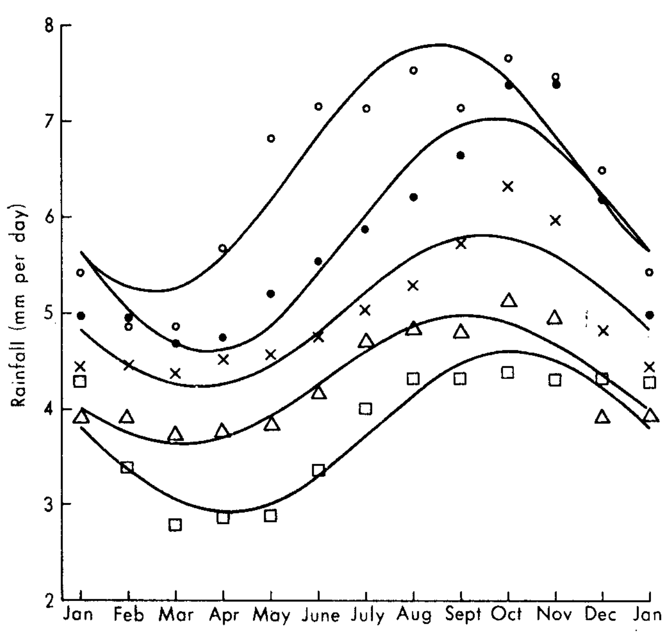

FIGURE 1—ANNUAL VARIATION OF THE AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

○——○ 980–984 mb ×——× 1000–1004 mb □——□ 1020–1024 mb
●——● 990–994 mb △——△ 1010–1014 mb

of cyclonic-type days with pressures of 1020–1024 mb and so the graph and averages for this pressure range in Figure 1 are based on data which exclude that for 28 July 1969, a day of exceptionally heavy rainfall (1·54 in) and a pressure index of 1015 mb. The pressure pattern for this day was very complex: the main low was centred to the south-west of the British Isles and a 'flat' thundery 'trough' extended over much of England and Wales; the pattern might justifiably be described as 'unclassifiable'.[1,2]

Figure 2 shows the amplitude, $\sqrt{(a_1^2 + b_1^2)}$, of the annual variation of the average daily rainfall amount, and Figure 3 gives the date of the maximum average daily rainfall amount (based on the first three harmonics) for 5-mb ranges of pressure. Figures 4 to 6 (corresponding to Figures 1 to 3) show results for the *frequencies* of the 5-mb ranges of pressure.

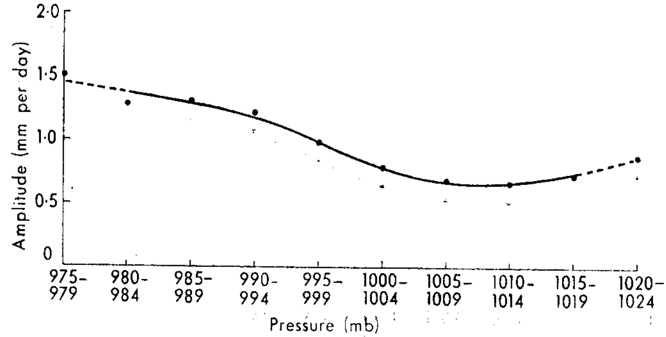

FIGURE 2—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

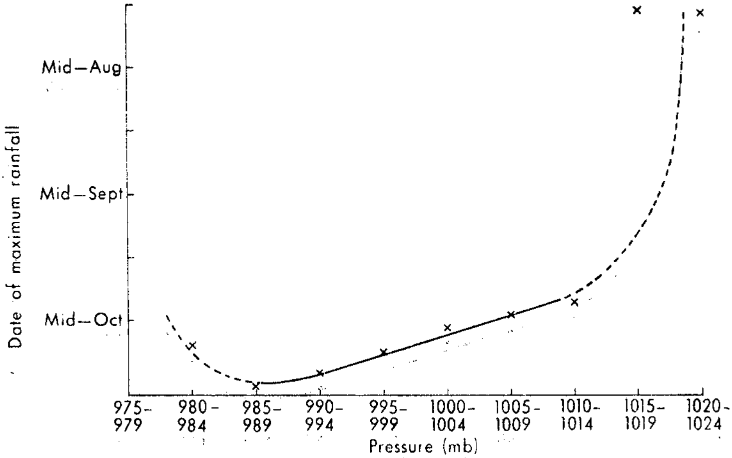

FIGURE 3—DATE OF THE ANNUAL MAXIMUM AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON THREE HARMONICS, DURING THE PERIOD 1950–69

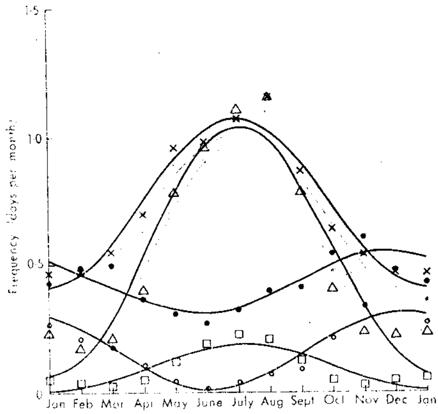

FIGURE 4—ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

○——○ 980–984 mb ×——× 1000–1004 mb □——□ 1020–1024 mb
●——● 990–994 mb △——△ 1010–1014 mb

Data are insufficient to calculate results for the pressure level of 975–979 mb in Figure 3; in the graphs of Figures 2, 3, 5 and 6, the extremities, to the points for pressure levels of 975–979 mb and 1020–1024 mb, are generally less certain and are indicated by pecked lines. Also, in Figures 3 and 6, the steep gradients (shown also by pecked lines) are not intended to denote exact values in the pressure ranges concerned.

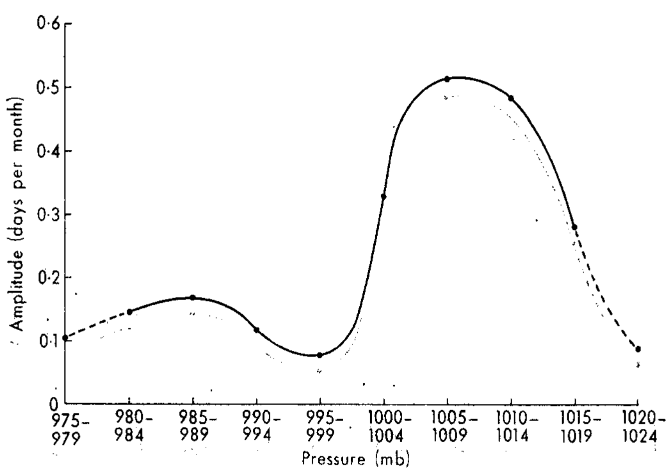

FIGURE 5—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

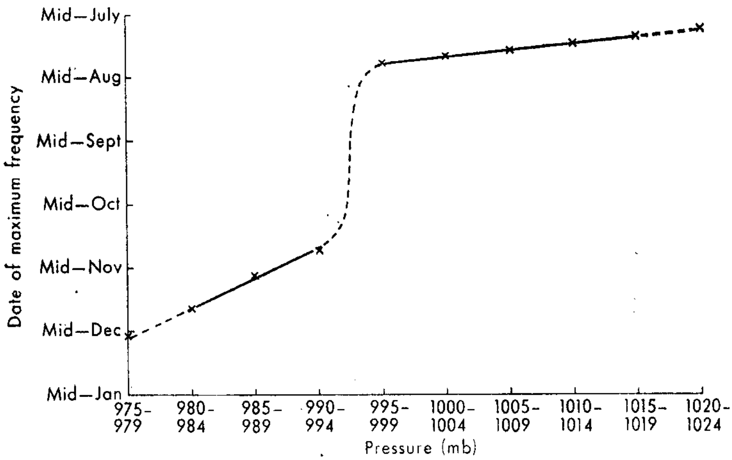

FIGURE 6—DATE OF THE ANNUAL MAXIMUM AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON THREE HARMONICS, DURING THE PERIOD 1950–69

Discussion. Results (Table I) show that the annual average rainfall amount for cyclonic-type days increases approximately linearly with decreasing pressure from 1020 to 980 mb. There is a tendency for the daily rainfall amount to level off with further decrease of pressure; this may be caused by the association of very low pressures with deep depressions at or near their maximum depth, with a large part of England and Wales well away from active fronts and with drier and colder air aloft, associated with the 'cold pool' stage of cyclonic development (cf. westerlies[3]). In some months the rainfall amount levels off (rate of decrease being less than the linear rate) as pressure rises above 1010 mb; this could possibly be due to thundery (thermal) lows in summer and to cols in winter.

The amplitude of the annual variation of rainfall amount (Table I and Figures 1 and 2) has a flat minimum from 1005 to 1020 mb, and similarly, the ratio of this (single) amplitude to the average increases from a minimum value of approximately 0·16 at around 1010 mb to a maximum value of about 0·23 with pressures below 990 mb.

There is a small systematic change with pressure in the date of the annual maximum average daily rainfall amount (Table I and Figure 3), from early November to October, as pressure increases from 985 to 1010 mb (baroclinic lows); when pressure is about 1015 to 1020 mb (thermal lows), maximum average daily rainfall amount tends to occur in summer (July–August).

The annual average frequency of cyclonic-type days (Table I) is at a maximum with pressures around 1005 mb; in winter, maximum frequencies occur at 995–999 mb, and in summer at 1005–1009 mb; the amplitude of the annual variation of frequency (Table I and Figures 4 and 5) is at a maximum with pressures of 1005–1010 mb. The ratio of the annual (single) amplitude to the annual total frequency for a 5-mb range of pressure increases from a minimum of about 0·01 to 0·02 at 995–999 mb to about 0·07 or more at 980–984 mb and at $\geqslant$ 1010 mb.

For pressures below 995 mb, the annual maximum frequency occurs in winter (November–December or January) while for pressures greater than 995 mb, the maximum frequency occurs in summer (July–August). There is a surprisingly sharp discontinuity around 995 mb (Table I and Figure 6), a result which suggests the need for further research into other characteristics of cyclones which vary with atmospheric pressure.

The autumn maximum of average daily rainfall amount (985–1010 mb, Table I and Figure 3) suggests that for baroclinic disturbances, the rainfall mechanism is closely related to sea surface temperatures in the north-west of the North Atlantic.[3,4] The summer rainfall maximum with higher pressures (thermal lows) indicates the importance of thermal convection overland. The tendency to a slightly earlier annual maximum with very low pressures (980–984 mb, Table I) may be associated with increased convection in 'flat' central low-pressure areas.

Concluding remarks. The cyclonic-type circulation over the British Isles region, like the 'straight' westerly type, has a frequency and an average daily rainfall amount which change systematically with surface pressure.

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ASSESSMENT OF CONVECTIVE DEVELOPMENT IN THE SINGAPORE AREA

By J. KONIECZNY

Summary. Convective development, or lack of it, is shown to be highly dependent on the moisture content between the 1000- and 500-mb levels and on various upper-wind parameters. Development is also related to the positive energy available, represented by the area between the environment curve and the convective path curve expected at maximum temperature.

Introduction. With an abundance of energy and moisture in the Singapore area, every day is likely to be a potential 'development' day for large-scale convection. An assessment of the amount of development, or lack of it, becomes of primary importance. The main object of this investigation was to find some rules, so that with reasonable confidence, convective development could be forecast as nil or only slight.

To find some guiding criteria in day-to-day forecasting, a number of elements were considered and evaluated. The most important factors were found to be :

(a) The positive energy available for convection.
(b) The humidity of the environment as represented by the dew-point depression.
(c) The vertical wind profile.

Data used. Only convective development over land was considered, i.e. that occurring between 0730 and 1930 local time (00 – 12 GMT). Occasions with the shear line (intertropical convergence zone[1]) in the vicinity of Singapore Island or with a sumatra-type[1] convergence zone were not considered. Assessment of convective development over the area was made from the Changi radar plots, based on the following criteria :

(A) Nil/slight — complete absence of echoes, or only isolated small echoes.
(B) Heavy — general widespread echoes or numerous large echoes.
(C) Moderate — any pattern which could not be classified as (A) or (B). These occasions were rejected.

Development (C) is fairly closely connected with development (B) on many occasions, so, if at some stage radar plots indicated the presence of development (B), these days were included in the investigation even though the development was mainly (C).

As apparently straightforward convection can turn out to be involved with lines of convergence, in practice cases are often not clear-cut, and this made objective classification of the data difficult.

Temperature and wind data were obtained from the 00 GMT (0730 local time) Payar Lebar Airport upper-air soundings. Only one ascent is available during a 24-hour period.

The period February 1965 to February 1967 was investigated. Some 258 occasions of development (A) or (B) were found and resulted in criteria which, used independently for a period of time, gave a useful indication of actual convective development in day-to-day forecasting (Table I).

TABLE I—NUMBER OF CASES OF EACH DEVELOPMENT TYPE DURING THE SOUTH-WESTERLY AND NORTH-EASTERLY MONSOON PERIODS

Development type	South-westerly monsoon	North-easterly monsoon	Total
A	66	55	121
B	71	66	137
Total	137	121	258

The selected cases were subdivided into those occurring in the north-east monsoon (approximately November to March) and those in the south-west monsoon (approximately April to October) because it was found that the 1000–700-mb layer was important in both monsoon periods but the 700–500-mb layer was relatively unimportant in the south-westerly period. This is probably because in the north-east monsoon the north or north-easterly current is deep and therefore the middle-level water content is important and would favour convection in the afternoon at maximum heating. During the south-westerly monsoon, however, the airflow is more complex, having at times only a fairly shallow south-westerly or north-westerly flow, with the height of the change-over to the main upper north-easterlies fluctuating through the middle troposphere (8000–20 000 ft*).

Analysis of Payar Lebar upper-air ascent. A measure of the moisture content of the 1000–500-mb layer was obtained by taking the sum of the temperature differences (in degrees Celsius) between the environment temperature and the dew-point at the 900, 800, 700, 600, and 500-mb levels (see Figure 1).

* 10 000 ft≈3 km.

A measure of the positive energy available was obtained by similar summation of temperature differences, at the same levels, between the environment temperatures and the temperatures of the theoretical convective path curve for the forecast day maximum temperature.

The following wind parameters were extracted for the two layers :

(a) Mean wind speed — an average of the arithmetical sum of wind speeds at 1000, 3000, 5000, 7000 and 10 000 ft for the layer 1000–700 mb and at 10 000, 12 000, 14 000 and 19 000 ft for the layer 700–500 mb.

(b) Maximum wind speed — highest reported speed in each of the layers.

(c) Vertical wind shear — measure of difference between the highest and lowest wind speed in the layer for each of the layers, irrespective of the heights at which the extremes occurred.

Results.

Moisture and energy parameters. Values were extracted as shown by the example in Figure 1 and then plotted on a scatter diagram, Figure 2; different symbols were used for development types (A) and (B). The zone where the two types of development occurred together was marked off by the two separation lines PJ and PN. There are insufficient data to be able to decide precisely where these lines should be or what slopes they should have. If the environment were very moist a development type (B) would be likely regardless of any other condition. This argument would lead to PN being horizontal; the data indicate that it has a slight positive slope. The line PJ is better defined by the data and is consistent with the idea that less heating will be required to produce development type (B) in a very moist environment than in a drier one.

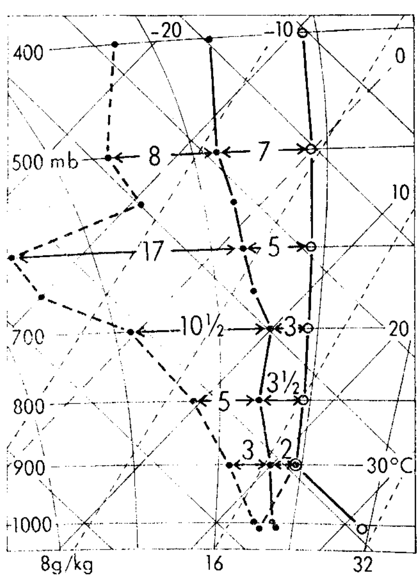

FIGURE 1—DIFFERENCES IN TEMPERATURE AT STANDARD LEVELS

.——. Dry bulb .- - - -. Dew-point o——o Convective parcel

The zone between PN and PJ was then subdivided into four equal sectors II, III, IV and V and the frequency of each type of development in each sector is presented in Table II; the two other sectors containing either (A) or (B) were numbered I and VI.

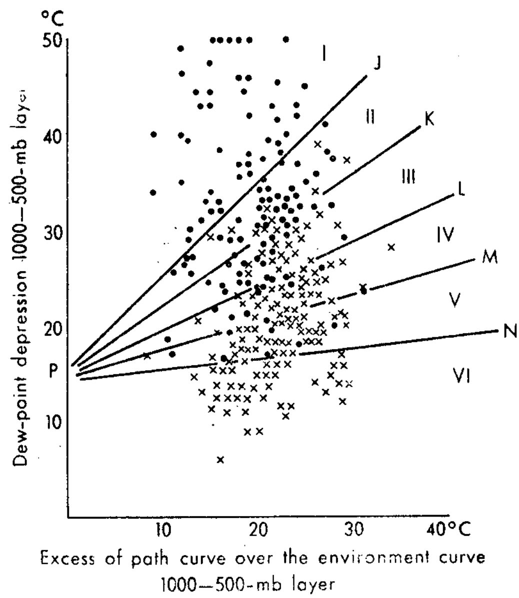

FIGURE 2—DEW-POINT DEPRESSION PLOTTED AGAINST EXCESS OF MAXIMUM TEMPERATURE PATH CURVE OVER THE ENVIRONMENT CURVE

● Nil/slight — type (A) × Heavy — type (B)

Since the surface heating is almost constant throughout the year (the average maximum temperature ranges between 28°C and 32°C[2]) the changes in the moisture content are the most likely cause for the different developments which occur. This has also been suggested by Johnson and Mörth.[3] The changes in the temperature of the environment are likely to be the other contributing factor. These changes are far greater than found for Gan by Dent and Preedy[4] and are more comparable to those found by Goldie, Moore and Austin[5] for south-east Asia.

As the south-westerly monsoon is a shallow airstream, the moisture and energy parameters were examined in the 1000–700-mb layer to see if the frequency distribution in Table II could be improved, but this gave only a marginal improvement.

TABLE II—FREQUENCY OF EACH DEVELOPMENT TYPE IN EACH REGION OF FIGURE 2

Development type	Region I	II	III	IV	V	VI	Total
			number of cases				
A	47	35	22	10	7	0	121
B	0	9	17	33	39	39	137
			percentage				
A	100	80	56	23	15	0	
B	0	20	44	77	85	100	

Wind parameters. The average values of the mean speed, maximum speed and wind shear in the 1000–700-mb and 700–500-mb layers, Table III, indicate that the wind speeds and shear are generally stronger in the lower

TABLE III—AVERAGE VALUES FOR THE WIND PARAMETERS IN THE TWO LAYERS

Development type	Layer	Average maximum *kt*	Average mean *kt*	Average vertical shear *kt*
A	1000–700 mb	16·8	12·1	16·1
B	1000–700 mb	13·3	8·1	12·2
A	700–500 mb	13·8	10·0	14·3
B	700–500 mb	13·1	9·8	12·4

layer when there is little or no development (type (A)). This aspect is examined in greater detail in Table IV, and in Table V the wind shear in each layer is given separately for each monsoon. During the preparation of Table III it was also noticed that a wind speed exceeding about 18–20 kt (1 kt$\approx$0·5 m/s) at any level in the 1000–700-mb layer favoured development type (A). Table IV shows that the difference in the mean wind between the lower and the upper layer is clearly the best indicator of development (giving a Heidke's[6] skill score of 0·66). Table V shows that the wind shear in the lower layer gives some indication of a preference for (A) or (B) development in both monsoons, but in the 700–500-mb layer the shear gives a useful indication in the north-easterly monsoon only.

TABLE IV—FREQUENCY OF EACH DEVELOPMENT TYPE WITH THE RELATIVE DISTRIBUTION BETWEEN THE TWO LAYERS OF VARIOUS WIND PARAMETERS

Development type	Mean wind $P_L \geqslant P_U$*	Mean wind $P_L < P_U$	Maximum wind $P_L \geqslant P_U$	Maximum wind $P_L < P_U$	Vertical shear $P_L \geqslant P_U$	Vertical shear $P_L < P_U$
A	106	15	102	19	88	33
B	29	108	50	87	41	96
			percentage			
A	79	12	67	18	68	26
B	21	88	33	82	32	74

*$P_L \geqslant P_U$ means wind parameter in lower layer $\geqslant$ wind parameter in upper layer.
Lower layer = 1000–700 mb, upper layer = 700–500 mb.

TABLE V—FREQUENCY DISTRIBUTION OF EACH DEVELOPMENT TYPE AND WIND SHEAR IN THE TWO DIFFERENT LAYERS FOR EACH MONSOON

Development type	Layer	South-westerly monsoon (137 cases) Wind shear $\leqslant$15 kt	South-westerly monsoon (137 cases) Wind shear >15 kt	North-easterly monsoon (121 cases) Wind shear $\leqslant$15 kt	North-easterly monsoon (121 cases) Wind shear >15 kt
A	1000–700 mb	22	44	24	31
B	1000–700 mb	52	19	50	16
A	700–500 mb	36	30	34	21
B	700–500 mb	43	28	53	13

Forecasting method. Results suggest that the moisture and energy parameters and the mean wind of the lower layer relative to the upper layer are the best indicators. The next step in the analysis would have been to take the occasions in the regions of Figure 2 where both development types can occur and examine how the mean-wind parameter would resolve them. However, at this stage the original data were no longer available and therefore this aspect was studied by assuming that the mean-wind parameter is independent of the moisture and energy parameters and multiplying the frequencies of

TABLE VI—PRODUCTS OF THE FREQUENCIES IN TABLES II AND IV (MEAN WIND)

Development type	Wind parameter	Region I	II	III	IV	V	VI
A	$P_L \geqslant P_U$*	4982	3710	2332	1060	742	0
B	$P_L \geqslant P_U$	0	261	493	957	1131	1131
A	$P_L < P_U$	705	525	330	150	105	0
B	$P_L < P_U$	0	972	1836	3564	4212	4212

* See note below Table IV

TABLE VII—PERCENTAGE RATIO OF TYPE A TO TYPE B FOR ASSOCIATED VALUES OF THE MEAN WIND PARAMETER AND THE MOISTURE AND ENERGY PARAMETER IN FIGURE 2

Development type	Wind parameter	Region I	II	III	IV	V	VI
				per cent			
A	$P_L \geqslant P_U$*	100	93	83	52	40	0
B	$P_L \geqslant P_U$	0	7	17	48	60	100
A	$P_L < P_U$	100	35	15	4	2	0
B	$P_L < P_U$	0	65	85	96	98	100

* See note below Table IV

development types (A) and (B) for each sector given in Table II by the frequencies for mean wind given in Table IV; from these combined contingency ratios, given in Table VI, percentage ratios of types (A) and (B) were calculated and are given in Table VII. Thus a forecaster only needs to calculate the three parameters and then decide from Figure 2 to which sector the temperature and energy parameters belong; the relative likelihood of types (A) and (B) is then given in Table VII against the mean-wind parameter.

Other parameters. No evidence was found that the changes in the tropopause height or changes in the transition height of the wind flow to the upper north-easterlies had any influence on type of development. Only the sea-breeze, forming convergence lines, was a significant factor and can change the development pattern from (A) to (B).

Further comments. As a result of the availability of moisture and energy over the area, development type (C) is present on nearly half of the days of the year and is more usual than either (A) or (B). Types (A) and (B) are both extremes of development and are therefore more important, the former as being a complete or almost complete absence of radar echoes while the latter constitutes the main hazard.

As development (C) falls between the two extremes, the position of the plot in Figure 2 of the obtained values of the moisture and energy parameters, especially if the wind criteria are also considered, will indicate the tendency towards one or other of the extremes.

Large changes in the environment occur from day to day, especially in moisture content, without a detectable change in air mass. These changes, which are too large to be considered as fluctuations in the air mass itself, can be attributed to the convergence/divergence flow pattern, though they are extremely difficult to forecast. Changes in the wind field are indicated in the local routine pilot-balloon data.

Conclusion. Although the synoptic situation with its convergence/divergence pattern is the main basis for forecasting likely convective development in the tropics, and in spite of the difficulties of objective classification of the cases mentioned earlier, it is considered that the criteria derived from dew-point depression/convective path curve as obtained in Figure 1, in conjunction with wind profile parameters, serve as a useful guide to convective development. An earlier version of this method was used for a considerable period at Singapore/Tengah and gave a fairly good assessment of actual observed convective development during day-time hours. Unfortunately, with only one upper-air ascent during a 24-hour period, changes in the environment, apart from purely synoptic ones, are hard to assess. The local pilot-balloon ascent can be used as a pointer to changes in the wind field. For development type (A), wind values in the 1000–700-mb layer are more applicable than values for the higher layer.

Acknowledgement. The author wishes to thank Mr J. J. Parry and Mr P. F. Abbott for their helpful suggestions and co-operation.

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NOTES AND NEWS

Retirement of Mr T. N. S. Harrower

Mr T. N. S. Harrower, Assistant Director of the Meteorological Office Branch responsible for meteorological services to the Royal Air Force and Army, retired on 31 December 1972 after 36 years service. He read mathematics and physics, amongst other subjects, at Glasgow University and, after taking his degree, was posted to Croydon to be one of the first Technical Officers in the Office to be given formal training in forecasting. Immediately after this training Mr Harrower was posted to Foynes to forecast for early transatlantic flights.

Tom served, as a Flight Lieutenant in the Royal Air Force, for most of the war years in the Middle East and was very lucky to escape with his life in the evacuation from Crete. On his return to the United Kingdom in 1944 he spent the next six years at Pitreavie where he was promoted to Principal Scientific Officer. After about seven years at London/Heathrow Airport and a similar time in branches dealing with aviation and general services he was promoted to Senior Principal Scientific Officer and took charge of the Forecasting Techniques Branch. As Assistant Director in charge of forecasting techniques he can claim that the work of his branch was largely responsible for putting the 3-level model into operational practice on KDF 9 to produce, for the first time in the Meteorological Office, numerical forecasts on a routine basis.

In 1966 Tom was posted to take charge of the Defence Services Branch where he remained until he retired. As Assistant Director (Defence Services) he controlled about one-third of the whole of the staff of the Meteorological Office. In the last few years there have been large changes in the organization of the Royal Air Force, including the withdrawal of British Forces from the Far East and the Persian Gulf and these changes have given rise to a heavy load of work in the Branch.

Tom has wide interests in scientific fields other than meteorology. He could easily have been a medical consultant or ornithologist and his ability to see, faster than most, the wood from the trees, would have ensured that he was successful in these disciplines. In addition he possesses a tenacity of purpose and his forthright way of stating his case will be missed in the Office, where undoubtedly he has been one of the characters for the last 36 years.

We all wish Mr and Mrs Harrower many years of happiness and good health in their native land to which they have returned.

V. R. C.

Conference on the observation and measurement of atmospheric pollution

The World Meteorological Organization and the World Health Organization are sponsoring a Technical Conference on the Observation and Measurement of Atmospheric Pollution in Helsinki, Finland, from 30 July to 4 August 1973. An international exhibition of meteorological and pollution-measuring instruments, sponsored by the host country will be held from 2 to 9 August 1973. The call for papers has been issued with a deadline of 1 March 1973 for submission of abstracts. Persons wishing to participate in the Technical Conference are invited to obtain further information about it from M. J. Blackwell, Meteorological Office, Met O 16, Beaufort Park, Easthampstead, Wokingham, Berks. Persons wishing to participate in the instrument exhibition are invited to obtain further information from the METEOREX 73 Exhibition Committee, P.O. Box 503, Helsinki 10, Finland.

OBITUARY

It is with regret that we have to record the death of Mr W. G. Fowler, Assistant Scientific Officer, St Mawgan, on 3 October 1972.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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WARMING OF THE LOWER TROPOSPHERE BY THE SEA

By R. M. BLACKALL

Summary. From simple assumptions an equation is derived for calculating the effect of a warm sea passage on the surface temperature of cold air. It makes allowance for the duration of passage and for the depth of warming. An equation is also derived which relates the change in surface humidity mixing ratio to the change of surface temperature. A graphical method of using the calculated surface temperature and dew-point to estimate the temperature and dew-point throughout the convective layer is explained.

Introduction. 'It is well known in a general way that the North Sea in winter has a very marked effect upon the cold dry winds from the continent, but at present no theory is available which will enable a quantitative estimate to be given of the effect which is produced upon an air current which has had a sea track of a given length.

In this note a simple rule is given which it is hoped will be of service to forecasters who are faced with these difficulties. The rule applies only when the air is colder than the sea.'

Thus starts the paper by Frost[1] which gives the well-known equations

$$T = T_0 + 0{\cdot}6(T_s - T_0)\,, \qquad \ldots (1)$$

$$X = X_0 + 0{\cdot}6(X_s - X_0)\,, \qquad \ldots (2)$$

where T and X are the final temperature and humidity mixing ratio of air initially at T_0 and X_0 after crossing water at temperature T_s (the saturated humidity mixing ratio at T_s being X_s).

These equations are unsatisfactory because they imply that the duration of warming and depth of convection are irrelevant to the final answer. The factor 0·6 was intended to apply only to North Sea crossings of about 300 nautical miles,* and the theory on which the equations are based ignores the presence of any anticyclonic inversion. Neither gives any indication of conditions other than at the surface and the second equation leads, in some circumstances, to values of X greater than the saturated humidity mixing ratio at T. The purpose of this paper is to present a simple and practical method (using the tephigram) of deriving values of T and X throughout the convective layer which takes into account both the duration of warming and the depth of convection. It has been assumed that the rate of heat transfer from the sea to the air is proportional to the temperature difference between them when the sea is the warmer.

* 1 n.mile ≈ 2 km.

Variation of temperature. In addition to T, T_o and T_s as defined above (and measured at screen level) the following notation is used :

T_d = dew-point
t = time
Q = quantity of heat
h = depth of convection (in units of length)
d = depth of convection (in millibars)
c_p = the specific heat of air at constant pressure
ρ = the density of the air
g = the acceleration due to gravity.

The initial assumption is that over unit area the combined effect of the transfer of heat by convection, conduction and radiation is given by

$$\frac{dQ}{dt} = k(T_s - T)\,, \qquad \ldots (3)$$

where k is a constant. If the lapse is unchanged, the rate of change of the mean temperature, T_m, of the layer being heated, dT_m/dt, and the rate of change of the surface temperature, dT/dt, will be equal so that

$$\frac{dT_m}{dt} = \frac{1}{hc_p} \cdot \frac{dQ}{dt} = \frac{dT}{dt}\,. \qquad \ldots (4)$$

Combination of equations (3) and (4) gives

$$\frac{dT}{dt} = \frac{k}{hc_p\rho}(T_s - T)\,. \qquad \ldots (5)$$

Since it is inconvenient to have to deal with ρ over the depth of convection h, it is eliminated by recourse to the hydrostatic equation $h\rho = d/g$ so that equation (5) becomes

$$\frac{dT}{dt} = \frac{kg}{dc_p}(T_s - T)\,.$$

Integration between T_o and T, the initial and final temperature over a period t, and rearrangement of the terms gives

$$\frac{T_s - T}{T_s - T_o} = \exp\left(-\frac{kgt}{dc_p}\right). \qquad \ldots (6)$$

A paper by Craddock[2] deals with the closely related problem of changes in the 1000–700-mb thickness on a warm sea passage. From pairs of soundings he was able to find a value for k of 162 kJ/m^2 h degC. By substitution of 1·01 kJ/kg degC for the value of c_p for dry air and 9·81 m/s^2 for the value of g the exponential becomes $\exp(-15{\cdot}8\ t/d)$. A trial using this value gave encouraging results but always a little too warm. Errors were minimized when the exponential function was $\exp(-12\ t/d)$, implying that k should be 120 kJ/m^2 h degC.

Thus the final solution is

$$T = T_s - (T_s - T_o)\exp(-12\ t/d). \qquad \ldots (7)$$

Table I gives values of $\exp(-12\ t/d)$ for varying t and d. Equation (7) has two important properties: when $t = 0$ then $T = T_o$, when $t = \infty$ then $T = T_s$.

TABLE I—VALUES OF $\exp(-12\,t/d)$

d (mb)	Duration of crossing, t (hours) 1	2	3	4	5	6	7	8	9	12	15	18	21	24	Most probable lapse (degC
700	0·98	0·97	0·95	0·93	0·92	0·90	0·89	0·87	0·86	0·81	0·77	0·73	0·70	0·66	
600	0·98	0·96	0·94	0·92	0·90	0·89	0·87	0·85	0·84	0·79	0·74	0·70	0·66	0·62	
500	0·98	0·95	0·93	0·91	0·89	0·86	0·84	0·82	0·81	0·75	0·70	0·65	0·60	0·56	40
450	0·98	0·95	0·92	0·89	0·88	0·85	0·83	0·81	0·79	0·73	0·67	0·62	0·57	0·53	35
400	0·97	0·94	0·91	0·89	0·86	0·84	0·81	0·79	0·76	0·70	0·64	0·58	0·53	0·49	31
350	0·97	0·93	0·90	0·87	0·84	0·81	0·79	0·76	0·73	0·64	0·60	0·54	0·49	0·44	26
300	0·96	0·92	0·89	0·85	0·82	0·79	0·76	0·73	0·70	0·62	0·55	0·49	0·43	0·38	22
250	0·95	0·91	0·86	0·83	0·79	0·75	0·71	0·68	0·65	0·57	0·49	0·42	0·36	0·32	17
200	0·94	0·89	0·84	0·79	0·74	0·70	0·66	0·62	0·58	0·49	0·41	0·34	0·28	0·24	14
180	0·94	0·88	0·82	0·77	0·72	0·67	0·63	0·59	0·55	0·45	0·37	0·30	0·25	0·20	13
160	0·93	0·86	0·80	0·74	0·69	0·64	0·59	0·55	0·51	0·41	0·33	0·26	0·21	0·17	12
140	0·92	0·84	0·77	0·71	0·65	0·60	0·55	0·50	0·46	0·36	0·28	0·21	0·17	0·13	10
120	0·90	0·82	0·74	0·67	0·61	0·55	0·50	0·45	0·41	0·30	0·22	0·17	0·12	0·09	9
100	0·89	0·79	0·70	0·62	0·55	0·49	0·43	0·38	0·34	0·24	0·17	0·12	0·08	0·06	8
80	0·86	0·74	0·64	0·55	0·47	0·41	0·35	0·30	0·26	0·17	0·11	0·07	0·04	0·03	6
60	0·82	0·67	0·55	0·45	0·37	0·30	0·25	0·20	0·17	0·09	0·05	0·03	0·01	—	5
50	0·79	0·62	0·49	0·38	0·30	0·24	0·19	0·15	0·12	0·06	0·03	0·01	—	—	4
40	0·74	0·55	0·41	0·30	0·22	0·17	0·12	0·09	0·07	0·03	0·01	—	—	—	4
30	0·67	0·45	0·30	0·20	0·14	0·09	0·06	0·04	0·03	0·01	—	—	—	—	3

Eddy diffusion studies suggest that equation (3) should read

$$\frac{dQ}{dt} = k'\,V(T_s - T)\,,$$

where V is some wind speed. Because difficulties arise when $V = 0$ a compromise was tried that

$$\frac{dQ}{dt} = (k + k'\,V)\,(T_s - T).$$

This makes equation (7)

$$T = T_s - (T_s - T_o)\,[\exp(-12\,t/d)]\,[\exp(-k'Vgt/dc_p)] \qquad \ldots (8)$$

The influence of the extra term $\exp(-k'Vgt/dc_p)$ was studied by calculation of its apparent value on 24 occasions from equation (8), substituting for T the observed air temperature after the sea crossing. When these values were plotted against the associated values of Vt/d it was found that the extra exponential term, although it scattered about a mean value close to 1 when Vt/d was small, tended to scatter about values a little greater than 1 as Vt/d increased. However the errors arising from the assumption that the value of the extra exponential term was 1 for all values of Vt/d appeared to be small in relation to the general scatter. This suggests that on the synoptic scale equation (7) is a reasonable practical approximation for the range of wind speeds and associated times of sea crossing explored (15 to 50 kt and 30 min to 15 h) (1 kt $\approx$ 0·5 m/s).

As the air moves out over the sea convection very rapidly causes mixing, setting up a lapse rate represented on a tephigram by a line whose slope lies between the dry and saturated adiabatic lapse rates. The slope is described in Figure 1, which shows the variation of lapse rate with the depth of convection; the data were derived from 45 ascents, from ships or from coastal stations with winds from the sea, and are summarized at the side of Table I (see above). It is assumed that mixing occurs up to that level at which a dry adiabatic from the sea surface temperature and pressure meets the environment curve. This mixing alone can produce large changes in surface temperature and the full expected change has been observed on a short English Channel crossing taking only 40 min.

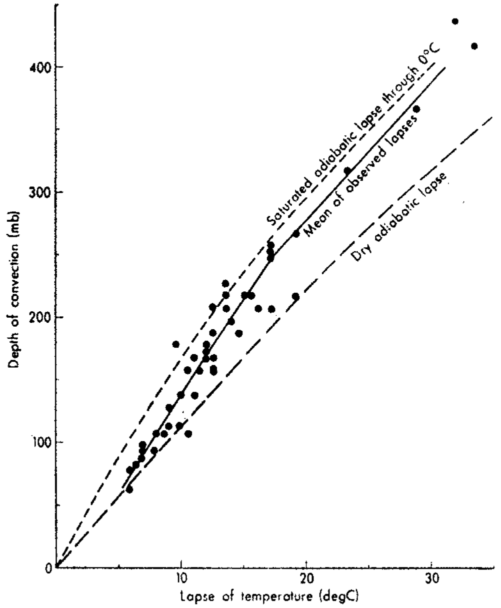

FIGURE 1—VARIATION OF OBSERVED LAPSE RATE OF TEMPERATURE WITH DEPTH OF CONVECTION OVER THE SEA

The plotted points represent data from 45 radiosonde ascents.

Practical forecasting of temperature. The following steps are necessary for the prediction of the final air temperature after a warm sea crossing and are illustrated in Figures 2 and 3.

(a) On the sounding in the air upwind of the sea crossing, draw in the sea level isobar and, if necessary, extend the ascent downwards to meet this isobar at coastal temperatures.

(b) Draw the dry adiabatic through the sea temperature T_s (see (g)). The pressure at which this line meets the environment curve is subtracted from the surface pressure to give the depth of convection d in millibars.

(c) Establish the expected lapse rate: if the air already has a lapse rate implying convection throughout the layer d (see Figure 2) the environment curve should not be changed as any change is unlikely to lead to more-accurate results. If a lapse rate needs to be forecast construct a modified environment curve as follows: draw a line through the layer d, with a lapse appropriate to d (see Figure 1 or side of Table I) such that the environment curve encloses equal areas (A and B in Figure 3) on each side of the line. Where this line meets the surface isobar is T_0. This step represents complete mixing without addition of heat.

(d) Determine the time, t, that the air will spend over the sea from the available wind information for the layer d and the fetch. Note that because of mixing the wind velocity in the convection layer is more or less uniform and great care is required if actual winds are to be used from upwind stations when the soundings from these stations indicate

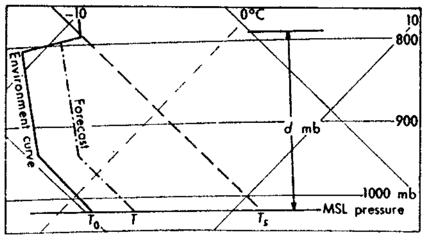

FIGURE 2—STEPS IN THE PREPARATION OF A FORECAST OF TEMPERATURE WHEN THE ENVIRONMENT CURVE NEEDS NO MODIFICATION AND STEP (c) MAY BE OMITTED

See also Figure 5.

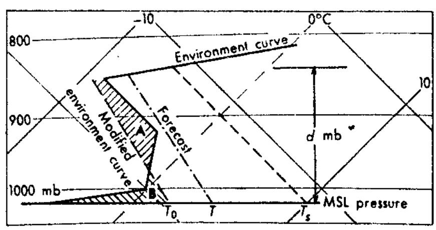

FIGURE 3—STEPS IN THE PREPARATION OF A FORECAST OF TEMPERATURE WHEN A MODIFICATION OF THE ENVIRONMENT CURVE IS NECESSARY

See also Figure 6.

stability over land but instability over the sea. Gradient winds from surface and 850-mb analyses and prognoses should be sufficiently accurate in most cases.

(e) From Table I for the appropriate values of t hours and d millibars find the value of $\exp(-12\,t/d)$ and thence T from equation (7).

(f) From temperature T on the surface isobar, draw a line parallel to the environment curve produced in step (c); this is the predicted environment curve for when the air finishes its crossing.

(g) If the sea temperature is far from uniform a mean value will often give good answers; however, if the changes in T_s will mean changes in d such that $\exp(-12\,t/d)$ alters significantly then it will be necessary to proceed by steps — as will also be necessary when the passage is expected to take more than 24 hours.

The procedure described above does not allow for the presence of fronts and other dynamical means of heating and cooling.

Variation of humidity. In the paper by Craddock cited earlier[2] it was found that over the sea the flux of water vapour, m, was a linear function of the air–sea temperature difference (at the rather low temperatures of the investigation) so that

$$\frac{\mathrm{d}m}{\mathrm{d}t} = A(T_s - T) \qquad \ldots (9)$$

where A was 1·2 mg/cm^2 h °F, i.e. 21·6 g/m^2 h K.

Integrating $$\int_0^m \mathrm{d}m = A\int_0^t (T_s - T)\mathrm{d}t \text{, and}$$

substituting from equation (7)

$$m = A\int_0^t \Big[(T_s - T_o)\ \exp(-\ 12t/d)\Big]\mathrm{d}t \,,$$

$$m = \frac{Ad}{12}(T_s - T_o)\Big[1 - \exp(-\ 12t/d)\Big] \,.$$

Substituting from equation (7) again gives

$$m = \frac{Ad}{12}(T - T_o) \,,$$

where m is the mass of water in grams evaporated into the layer of air of depth d millibars over an area of one square metre in t hours. This vapour is mixed with M kg of dry air in the same volume where

$$M = h\rho = d/g \times 100, \quad (1 \text{ mb} = 100 \text{ N/m}^2).$$

If the change in the mean humidity mixing ratio for the layer, $\Delta X'$, is measured in grams per kilogram, then

$$\Delta X' = \frac{Ag}{1200}(T - T_o) = 0{\cdot}18(T - T_o) \,. \qquad \ldots (10)$$

Now it is clear from an inspection of tephigrams that the humidity mixing ratio normally decreases rapidly with height and that through a layer affected by convection the dew-point depression is roughly constant: to add $\Delta X'$ throughout the layer of depth, d, would lead to changes in dew-point lapse at variance with observation. At the low temperatures with which this paper is concerned, near 0°C, nearly all the moisture will be in the lowest layers, so that to add $\Delta X'$ to the surface humidity mixing ratio and then allow the dew-point depression to remain constant with height should not be far from the truth.

Practical forecasting of dew-point. The procedure for forecasting dew-point is similar to that described for temperature in sections (a) and (b) and is illustrated in Figure 4. Rearrange the dew-point curve on the ascent

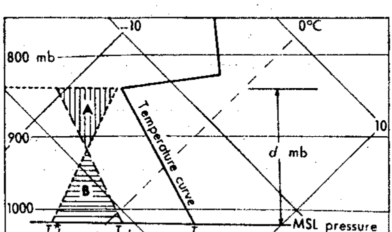

FIGURE 4—STEPS IN THE PREPARATION OF A FORECAST OF DEW-POINT

T_d* - - - - - - - Initial dew-point curve.
T_d— — — — — Modified dew-point curve.

so that it is parallel to the dry-bulb curve through the layer of depth, *d*, but without any change in the total water content (as a first approximation the original dew-point curve should enclose equal areas on each side of this new line). Note the surface humidity mixing ratio and add to this $0{\cdot}18(T - T_o)$ g/kg; from this new surface humidity mixing ratio draw a line parallel to the forecast temperature curve and this will give a good indication of conditions aloft. Surface dew-points forecast this way were used to compile Tables II and III.

TABLE II—COMPARISON OF ERRORS IN FORECASTING TEMPERATURE AND DEW-POINT ON 24 OCCASIONS

	Method of forecasting temperature		Method of forecasting dew-point	
Range of errors*	Frost's	Present	Frost's	Present
− 6·6 to − 7·5				1
− 5·6 to − 6·5				
− 4·6 to − 5·5				
− 3·6 to − 4·5				2
− 2·6 to − 3·5	1			
− 1·6 to − 2·5	1	2		3
− 0·6 to − 1·5	3	1		4
− 0·5 to + 0·5	3	11	1	6
+ 0·6 to + 1·5	5	7	1	5
+ 1·6 to + 2·5	6	3	2	3
+ 2·6 to + 3·5	2		2	
+ 3·6 to + 4·5			4	
+ 4·6 to + 5·5	2		5	
+ 5·6 to + 6·5	1		5	
+ 6·6 to + 7·5			2	
+ 7·6 to + 8·5			2	

* The error is expressed as (calculated value − observed value).

TABLE III—COMPARISON OF ERRORS OBTAINED WHEN USING FROST'S METHOD AND THE PRESENT METHOD DERIVED FROM THE SAME 24 OCCASIONS AS IN TABLE II

	Frost's method for		Present method for	
	T	T_d	T	T_d
Mean error	2·0	4·6	1·0	1·5
Root-mean-square error	2·75	5·4	1·25	2·4

In practice, since with dew-points in the range 0°C to − 15°C the change of saturation humidity mixing ratio with temperature is near to 0·18 g/kg K, the application of the above technique will often result in an approximately constant dew-point depression during the warming and this can be very useful when surface charts are analysed on which cold air is being warmed over water, as it decreases the temptation to insert extra fronts.

Results. The data used were collected in the winters of 1968–69 and 1969–70 when the track of cold air across the North Sea or eastern North Atlantic could be shown to begin at a place with a radiosonde ascent and finish at a station from which a synoptic report was available. There were 24 occasions when this occurred and the data were readily available; the duration of crossing varied from 40 min to 15 h and the depth of convection from 35 mb to 500 mb. Table II compares the errors obtained on these occasions by the use of both the present method and Frost's method (equations (1) and (2) on page 65). An attempt to gather another independent set of data from earlier winters was largely frustrated by uncertainties of trajectory and timing which required a quite disproportionate amount of effort to resolve.

The new method usually gives better results; if the layer being warmed is deep — as for an Arctic northerly — the results are greatly superior. A count of the errors in temperature showed that Frost's method (equation (1)) gave better results on 8 occasions but the new method gave better results on 13 occasions (there was no difference on the other 3 occasions). A similar count of the errors in dew-point showed that Frost's method (equation (2)) gave better results on only 2 occasions but the new method gave better results on 21 occasions (on 1 occasion there was no difference). The results obtained for the dew-point are particularly good although there are well-known difficulties in getting an accurate dew-point in sub-freezing wet-bulb conditions. Table III, which summarizes the mean errors and the root-mean-square error obtained by the two methods, also shows the superiority of the present method.

Experience shows that in the construction of a modified temperature profile, the conditions in the bottom layers, say within 20 mb of the surface, have very little effect on T because the mixing spreads them through a considerable depth. In other words the diurnal temperature cycle on the continental coast will not normally be apparent after the air has made a sea passage lasting more than about 30 min unless the heating is going to be confined to a shallow layer only.

Figures 5 and 6 are examples of what can happen. In Figure 5 the Arctic maritime air is warmed as it moves from ship 'M' to Lerwick, but there is a problem in deciding a representative temperature and dew-point structure,

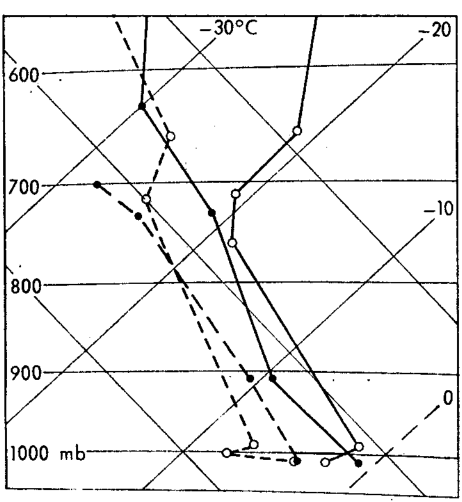

FIGURE 5—EFFECT ON THE SURFACE TEMPERATURE OF COLD AIR OF A WARM SEA PASSAGE FROM OWS 'M' TO LERWICK

●—● OWS 'M', 12 GMT, 10 January 1968; ○—○ Lerwick, 00 GMT, 11 January 1968.
Pecked lines denote dew-point.
Distance 370 n. mile, speed 40–50 kt.

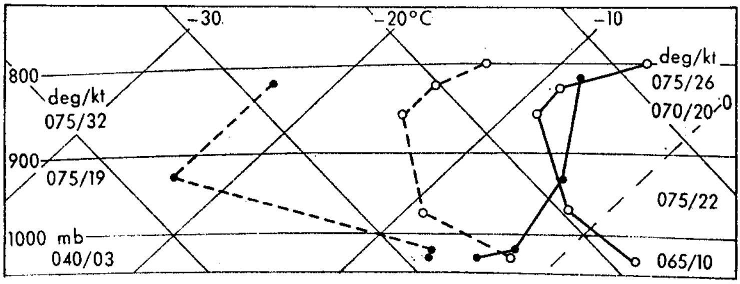

FIGURE 6—EFFECT ON THE SURFACE TEMPERATURE OF COLD AIR OF A SHORT WARM SEA PASSAGE FROM DE BILT TO SHOEBURYNESS, 26 FEBRUARY 1968

●—● De Bilt, 00 GMT; ○—○ Shoeburyness, 12 GMT.
Pecked lines denote dew-point. De Bilt winds on left, Shoeburyness on right.
Distance 90 n. mile.

since either ascent may have been affected by the presence of cumulonimbus, and a short passage over a snow-covered surface has created an inversion in the lowest 20 mb at Lerwick. Figure 6 shows the profound effect of a short sea crossing on air that was cold, stable and dry; particularly worthy of note is that mixing has caused a fall in temperature at 850 mb which was not compensated for by subsequent heating.

Finally it is worth repeating the warning that when fronts, troughs and other means of dynamical heating and cooling affect the passage, or are very close to it, then these cannot be ignored and some allowances should be made even if they cannot be calculated exactly.

Acknowledgements. The author would like to thank all his colleagues who helped collect the raw data for this paper and who offered advice, and especially Mr R. J. Ogden, Mr S. E. Virgo, O.B.E., and Mr N. Thompson for their constructive criticisms.

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551.524.36:551.589.1

RECENT TEMPERATURE CHANGES DUE TO CHANGES IN THE FREQUENCY AND AVERAGE TEMPERATURE OF WEATHER TYPES OVER THE BRITISH ISLES

By A. H. PERRY and R. G. BARRY
University College, Swansea, and University of Colorado, Boulder

Summary. Mean daily maximum and minimum temperatures for the mid-season months of 1925–35 and 1957–67 have been determined for the 'weather type' categories of Lamb at four stations in the British Isles. Evaluation of the changes between the periods due to changes in type frequency and within-type changes of temperature level shows that, apart from January, the latter have a more significant effect on the total change. Problems of explaining these changes are discussed.

Introduction. The temperature fluctuation over the last 30–40 years in the British Isles has been attributed primarily to the decrease in frequency of westerly circulation[1] and the corresponding increase in meridional air-flow types. It has been suggested,[2] however, that temperature changes at Eskdalemuir between 1925–35 and 1957–67 represent the combined effect of changes in the temperature of individual types and changes in type frequency. Only in January, apparently, is the latter effect dominant. This analysis is now extended to three other stations.

Method. The expressions used to determine the contribution of within-type changes of temperature and of changes in airflow-type frequency to the change in monthly mean temperature between two periods are derived as follows :

The average monthly mean temperature during the first time period

$$\overline{T} = \sum_{i=1}^{k} \frac{f_i T_i}{n},$$

where f_i = frequency of type i during the first time period,

T_i = mean temperature of type i during the first time period,

n = total number of days in the first time period,

$\sum_{i=1}^{k}$ = summation over all k types.

Let $f_i + \Delta f_i$ = frequency of type i during the second time period,

$T_i + \Delta T_i$ = mean temperature of type i during the second time period,

$\overline{T} + \Delta \overline{T}$ = average monthly mean temperature during the second time period.

Then

$$\Delta \overline{T} = \sum_{i=1}^{k} \left\{ \frac{(f_i + \Delta f_i)\ (T_i + \Delta T_i)}{n} - \frac{f_i T_i}{n} \right\}$$

$$= \sum_{i=1}^{k} \left\{ \frac{\Delta f_i\ (T_i + \Delta T_i)}{n} + \frac{f_i \Delta T_i}{n} \right\}. \qquad \ldots (1)$$

The second term on the right hand side in (1), which is independent of any change in frequency, is a component due to within-type changes of temperature. The first term on the right hand side in (1) represents the effect on $\Delta\overline{T}$ of a change in type frequency when a change occurs in the temperature of type i in the second period.

In the previous study[3] the component attributed to changes in type frequency was determined from

$$\sum_{i=1}^{k} \frac{\Delta f_i}{n} \left[(T_i + \Delta T_i) - \overline{T} \right]. \qquad \ldots (2)$$

The additional term in (2), $(\frac{\Delta f_i}{n} \overline{T})$, is zero when summed over $i = 1$ to k

and whenever $\Delta f_i = 0$. This expression avoided ambiguity when examining types with a negative Celsius temperature.

In the present analysis the contributions of terms $\Delta f_i\ (T_i + \Delta T_i)/n$ and $f_i \Delta T_i/n$ have been evaluated for mean daily maximum and minimum temperatures for January, April, July and October between 1925–35 and 1957–67 at Buxton, Gorleston and Valentia, and recalculated at Eskdalemuir using the revised catalogue of 'weather types'.[4] Gorleston and Valentia were selected because of their homogeneous record at extreme longitudinal locations in the British Isles, while the results for Buxton should provide some check on those obtained for Eskdalemuir where site changes may have influenced the findings.[5]

Some inaccuracy is present in the data through conversion of units from degrees Fahrenheit in the records of the first period and consequent rounding errors. The computations, which were performed on a desk-top computer, are therefore summarized in Tables III to VI for changes of 0·10 degC or more in the components for individual types. This serves to focus attention on the major changes and is realistic in the light of the significance levels for the observed values of $\Delta \overline{T}$ (Tables III–VI).

Results. Table I gives the type frequency and mean temperatures of the types at the four stations in 1957–67. The change in type frequencies for 1957–67 minus those for 1925–35 and the corresponding changes in the mean daily maximum and minimum temperature for each type at the four stations are shown in Table II. The contributions of the two components of equation (1) to $\Delta \overline{T}$ are tabulated in Tables III–VI.

The results in Tables III–VI reinforce the earlier suggestion[2] that changes in type frequency have contributed significantly to the average temperature change between the two periods only in January. In the other three months the greater part of the total change is due to a component of within-type changes of temperature ($f_i \Delta T_i/n$).

The main features of the tables can be summarized briefly. In January, maximum and minimum temperatures decreased from 1925–35 to 1957–67 at all four stations. Except for minima at Eskdalemuir and Buxton most of this change resulted from the decrease in frequency of W type (Tables I and III). The increased frequencies of N and E types and their generally lower temperatures in 1957–67 (Table II) make only limited contributions to the overall temperature changes (Table III), although further calculations (not included) indicate that $\Sigma \Delta f_i \Delta T_i/n$ accounts for approximately one third of the $\Sigma \Delta f_i\ (T_i + \Delta T_i)/n$ term, primarily due to changes with N and E types. Comparison of the results for Valentia and Eskdalemuir in Table III shows that the use of the expression $\Delta f_i\ (T_i + \Delta T_i)/n$ causes some ambiguity, since minimum temperatures at Eskdalemuir are below 0°C for N, NE and E types. To avoid this problem the component $\Delta f_i\ (T_i + \Delta T_i)/n$ may be computed in kelvins. If this is done in the case of Buxton and Eskdalemuir minima in January, for example, the distinction between W and SW types on the one hand, and N and E types, on the other, is made evident. However, in using kelvins to compare between types, or two stations with the same type, temperature level is subordinated to the change of type frequency so that the results essentially reflect the Δf_i in Table II.

TABLE I—TYPE FREQUENCY $(f_i + \Delta f_i)$ AND MEAN DAILY MAXIMUM AND MINIMUM TEMPERATURE OF TYPES $(T_i + \Delta T_i)$ AT BUXTON, ESKDALEMUIR, GORLESTON AND VALENTIA, 1957–67

		Buxton		Eskdalemuir		Gorleston		Valentia	
		$T_i + \Delta T_i$							
Type	$(f_i+\Delta f_i)$	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January				degrees Celsius					
NW	16	4·7	0·9	4·4	−0·2	5·4	2·1	8·6	6·3
N	37	1·8	−2·9	2·0	−2·6	3·5	−0·6	6·9	0·8
NE	10	−0·6	−4·5	1·9	−5·0	2·1	−1·2	4·5	0·8
E	37	0·1	−3·3	1·0	−2·3	2·5	0·0	5·6	2·1
SE	9	−0·2	−0 9	1·9	−2·7	3·4	1·4	8·8	6·1
S	32	5·2	0·9	5·3	0·6	6·7	3·4	10·8	7·6
SW	14	6·7	1·6	6·4	3·2	7·0	2·9	10·9	7·4
W	54	6·8	2·0	5·3	0·8	8·0	3·5	10·4	6·2
AW	9	5·8	0·1	6·2	1·7	5·3	1·2	10·6	6·1
CW	20	6·5	2·0	5·0	1·6	8·4	4·0	9·8	5·8
A	60	2·8	−2·8	3·3	−3·4	4·0	0·2	8·4	3·1
C	31	4·2	0·6	3·0	−0·7	6·5	2·8	9·0	4·6
U	12	3·6	−0·4	3·1	−2·0	5·5	3·1	9·1	3·7
Mean		3·8	−0·7	3·8	−1·1	5·4	1·7	8·8	4·1
April				degrees Celsius					
NW	21	8·7	3·6	10·1	2·8	11·6	5·5	11·4	7·7
N	33	8·2	2·8	9·8	1·3	9·4	4·3	12·2	5·4
NE	15	7·3	1·8	8·8	1·4	7·3	4·6	12·1	5·3
E	41	6·5	1·2	7·4	0·8	7·2	4·1	11·8	5·5
SE	6	10·2	2·2	10·0	2·0	9·7	6·3	13·2	8·7
S	27	12·1	5·0	10·7	4·1	11·4	6·5	13·2	7·7
SW	10	12·4	6·2	11·7	5·8	12·4	6·8	13·2	8·6
W	50	10·2	3·4	9·9	2·9	12·5	5·3	11·9	7·6
AW	13	11·3	4·6	12·0	3·3	13·1	4·9	13·1	6·8
CW	4	8·2	2·6	8·7	2·2	12·5	4·8	11·2	6·8
A	60	11·1	2·8	13·3	0·7	9·6	5·2	13·9	5·8
C	34	8·9	3·6	8·5	3·0	11·4	6·5	11·7	6·4
U	16	9·0	2·4	9·8	0·8	9·2	4·5	12·0	6·1
Mean		9·7	3·1	10·3	2·1	10·4	5·3	12·4	6·5
July				degrees Celsius					
NW	37	14·7	9·0	15·9	8·1	17·9	11·1	16·6	12·0
N	46	14·7	9·1	16·7	7·2	17·0	11·2	17·3	11·5
NE	5	14·2	9·4	16·6	9·2	16·4	13·4	19·8	11·6
E	13	17·2	11·3	17·6	9·3	16·9	13·5	18·5	11·8
SE	2	21·7	8·6	22·0	8·5	18·0	15·0	19·5	13·0
S	12	19·2	10·4	17·0	8·3	18·5	13·3	17·4	13·2
SW	7	20·6	12·6	18·0	11·8	21·0	14·3	18·3	13·3
W	59	17·0	10·7	15·9	8·9	20·6	13·2	16·8	12·7
AW	42	18·7	10·5	17·4	9·1	20·6	13·0	17·8	12·0
CW	8	16·1	10·2	15·0	9·5	19·4	11·4	15·6	11·6
A	52	18·4	9·1	18·5	6·9	18·0	12·5	18·4	10·9
C	63	16·6	10·4	16·3	9·5	19·5	13·1	16·9	12·0
U	13	18·8	10·9	17·8	6·6	19·5	14·1	17·5	11·2
Mean		16·9	10·1	17·0	8·5	19·0	12·7	17·4	12·0
October				degrees Celsius					
NW	19	9·5	4·7	10·6	4·0	12·0	6·7	13·1	8·9
N	22	8·1	2·9	9·3	2·1	10·9	6·2	12·2	6·4
NE	3	8·5	5·2	9·6	5·0	11·7	7·7	13·0	6·3
E	18	12·0	7·7	11·7	7·6	14·3	10·5	16·2	9·0
SE	19	13·0	6·1	14·1	4·7	14·5	12·1	16 9	12·0
S	28	13·9	6·4	14·1	6·7	15·7	10·9	15·9	10·8
SW	14	13·0	5·9	11·7	6·1	15·1	8·8	14·4	10·1
W	69	11·9	6·9	11·0	5·2	14·7	8·7	13·9	9·8
AW	20	12·0	4·6	11·6	4·7	14 2	6·3	14·2	9·3
CW	14	12·2	7·2	11·3	6·5	14·9	9·8	13·8	9·8
A	59	11·6	5·3	11·9	4·4	13·9	9·0	14·9	8·5
C	47	10·9	6·2	10·9	5·0	14·3	9·9	13·1	7·6
U	9	11·8	6·2	11·5	3·4	14·4	9·0	14·1	7·6
Mean		11·6	5·9	11·7	5·1	14·1	9·0	14·3	9·4

NW = anticyclonic north-westerly, north-westerly, and cyclonic north-westerly; similarly for the other types except W.

W = westerly type; AW = anticyclonic westerly; CW = cyclonic westerly; A = anticyclonic; C = cyclonic U = unclassifiable days.

In April (Table IV) the changes $\Delta\overline{T}$ are small and mainly non-significant except for increases in minimum temperature at Eskdalemuir and in maximum temperature at Valentia. The within-type component of temperature change

TABLE II—CHANGE IN TYPE FREQUENCY (Δf_i) AND IN MEAN DAILY MAXIMUM AND MINIMUM TEMPERATURE OF TYPES (ΔT_i) AT BUXTON, ESKDALEMUIR, GORLESTON AND VALENTIA, BETWEEN 1925–35 AND 1957–67

		ΔT_i							
		Buxton		Eskdalemuir		Gorleston		Valentia	
Type	Δf_i	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January				*degrees Celsius*					
NW	4	−0·2	0·3	−1·6	−1·2	−0·8	−0·4	−1·2	0·0
N	19	−1·9	−2·5	−1·0	0·3	−1·4	−1·2	−1·1	−3·1
NE	7	−2·8	−3·4	−0·8	−1·5	−4·5	−2·7	−1·7	−2·0
E	29	−1·9	−1·4	−0·8	−1·3	−0·3	−0·1	−1·1	1·0
SE	4	−5·1	−3·1	−1·7	−0·8	−1·5	−0·8	−2·4	−1·6
S	3	−0·1	1·1	−0·5	0·2	0·4	0·2	0·2	0·2
SW	−15	0·6	0·0	−0·3	1·5	−1·0	−1·6	0·6	1·2
W	−68	0·4	0·0	−1·0	−0·4	0·1	−0·1	0·4	−0·3
AW	1	0·9	−1·2	0·3	2·1	−0·2	−0·5	0·4	−0·3
CW	2	0·7	0·8	0·2	1·7	0·4	1·6	1·1	1·1
A	8	−0·1	−1·4	−0·1	−0·1	−1·2	−1·1	0·7	−0·6
C	4	0·1	0·8	−0·2	−0·1	0·3	0·9	0·9	0·7
U	2	−0·5	−0·5	1·0	2·7	0·6	1·5	0·8	1·6
April				*degrees Celsius*					
NW	−7	0·6	1·3	1·0	2·5	0·8	1·6	0·5	0·6
N	−11	0·7	1·6	1·1	1·5	0·6	1·6	1·1	0·5
NE	1	1·3	1·0	1·0	1·3	−0·3	0·4	1·7	1·1
E	5	−2·0	−1·2	−1·0	−0·7	−1·5	−1·3	0·4	0·2
SE	−1	−0·5	−1·1	−0·6	−0·5	0·4	0·6	0·6	1·3
S	3	0·9	0·3	−1·5	−0·1	0·2	−0·9	0·5	−1·2
SW	1	0·8	3·2	2·3	3·1	−0·2	−0·3	0·6	1·2
W	2	−0·2	−0·5	0·1	1·3	0·1	0·2	0·7	0·5
AW	0	0·1	0·3	1·5	−1·1	−1·4	−2·0	0·5	−1·9
CW	−4	−1·9	−1·0	0·5	1·1	0·8	0·4	1·1	0·5
A	25	1·7	1·0	2·3	1·7	−0·7	0·9	1·6	0·6
C	−16	0·3	0·6	−0·1	1·9	0·7	0·7	0·6	0·9
U	2	−1·8	−0·2	−0·7	0·1	−2·1	−0·8	−0·5	0·3
July				*degrees Celsius*					
NW	7	−1·9	−1·5	−1·0	−0·5	−1·5	−0·1	−0·2	−0·7
N	24	−1·0	−0·2	0·2	−0·9	−0·2	0·7	0·6	−0·2
NE	−2	−8·5	−3·0	−0·4	0·5	−3·4	−0·5	0·9	0·6
E	−5	−3·3	0·1	−2·6	−0·7	−2·4	−1·2	−1·3	−1·3
SE	−4	−2·6	−2·6	−2·5	−2·5	0·3	−0·2	−3·7	−1·6
S	−6	−0·8	−1·9	−2·3	−2·6	−2·1	−1·0	−1·1	−0·1
SW	−9	0·9	0·7	0·5	0·5	−1·3	−0·8	0·9	−0·4
W	−15	−0·3	0·0	−0·6	−0·6	−0·4	−0·2	−0·1	−0·5
AW	4	0·4	−0·2	0·9	−0·8	−1·0	−0·8	0·7	−0·8
CW	8	−1·0	−0·8	−1·7	−0·3	−0·9	−1·2	−0·6	−1·0
A	1	−1·8	−1·5	−2·7	−1·1	−0·9	0·2	−1·3	−0·6
C	11	−0·8	−0·8	−0·3	−0·3	−0·4	0·0	0·3	−0·3
U	2	−1·0	0·3	−0·1	−3·2	−0·3	0·1	0·3	−1·3
October				*degrees Celsius*					
NW	−4	−0·2	0·0	0·8	1·4	0·1	2·0	0·8	−0·5
N	−6	−0·6	0·3	1·5	1·6	0·2	2·5	0·6	−0·5
NE	−3	−2·1	0·1	−0·8	3·3	−1·4	−1·6	−0·7	−3·0
E	2	1·1	2·5	1·2	4·2	1·2	0·7	2·6	0·2
SE	16	4·2	2·9	4·0	3·1	1·6	2·1	0·2	0·5
S	13	1·6	−1·0	1·9	−0·9	0·9	0·0	1·0	−0·6
SW	1	−0·1	−2·8	−0·5	−2·0	−1·6	−2·0	−0·3	−1·3
W	−35	0·3	0·8	−0·1	0·8	0·0	0·0	0·2	−0·4
AW	11	−3·1	−4·0	−3·3	−2·4	−1·6	−3·9	−1·4	−2·1
CW	−9	1·1	1·3	1·4	3·4	0·0	1·5	1·0	0·7
A	5	0·5	2·1	0·6	2·8	0·0	2·2	−0·2	0·7
C	12	0·4	0·9	1·3	1·8	0·5	2·6	0·4	−1·0
U	−3	2·9	2·9	3·8	4·9	2·6	4·2	1·5	−0·2

See note below Table I.

accounts for almost all of these increases. The positive contribution at all four stations of the $\Delta f_i\,(T_i + \Delta T_i)/n$ term with Anticyclonic type is cancelled out by negative contributions from Cyclonic, Northerly and North-westerly types (see Δf_i in Table II).

TABLE III—CONTRIBUTION OF COMPONENTS OF CHANGE OF TYPE FREQUENCY AND OF CHANGE OF TEMPERATURE WITHIN TYPE TO THE CHANGES IN MEAN DAILY MAXIMA AND MINIMA AT BUXTON, ESKDALEMUIR, GORLESTON, AND VALENTIA BETWEEN 1925–35 AND 1957–67 IN JANUARY (CHANGES <0·1 degC OMITTED)

	Buxton				Eskdalemuir			
	Maximum		Minimum		Maximum		Minimum	
Type	a*	b	a	b	a	b	a	b
				degrees Celsius				
NW								
N	0·10	−0·10	−0·16	−0·13	0·11		−0·15	
NE							−0·10	
E			−0·28				−0·20	
SE								
S								
SW	−0·29				−0·28		−0·14	0·13
W	−1·35	0·14	−0·40		−1·06	−0·36	−0·16	−0·14
AW								
CW								
A				−0·21				
C								
U								
Total for all types	−1·2	0·0	−1·1	−0·3	−0·8	−0·6	−0·8	0·1
$\Delta\overline{T}$	−1·2		−1·3		−1·3		−0·8	
Significance level (%)	10		8		6		n.s.	

	Gorleston				Valentia			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
				degrees Celsius				
NW					0·10			
N	0·19				0·38			−0·16
NE								
E	0·21				0·48		0·18	
SE					0·10			
S					0·10			
SW	−0·31		−0·13	−0·14	−0·48		−0·33	0·10
W	−1·60		−0·70		−2·07	0·14	−1·24	−0·11
AW								
CW								
A	0·10	−0·18		−0·17	0·20	0·11		
C					0·11			
U								
Total for all types	−1·0	−0·4	−0·6	−0·3	−0·8	0·3	−1·0	−0·1
$\Delta\overline{T}$	−1·3		−1·0		−0·5		−1·2	
Significance level (%)	8		n.s.		n.s.		3	

See note below Table I.

*a denotes contribution of $\Delta f_i(T_i + \Delta T_i)/n$ to the changes in mean daily maxima and minima at each station.

b denotes contribution of $f_i \Delta T_i/n$ to the changes in mean daily maxima and minima at each station.

In July, the contribution of the temperature decrease with Anticyclonic type (Table II) to $\Delta\overline{T}$ is apparent in the $f_i \Delta T_i/n$ term at Buxton and Eskdalemuir (Table V). This decrease is strengthened by similar temperature changes with other types whereas the $\Delta f_i\ (T_i + \Delta T_i)/n$ contributions again largely cancel out, as in April.

In October, a total temperature increase $\Delta\overline{T}$ occurred at Eskdalemuir and less clearly at Buxton while it was limited to the minimum temperature at Gorleston and the maximum at Valentia (Table VI). Anticyclonic and Westerly types made large contributions to the within-type change of minima

TABLE IV—CONTRIBUTION OF COMPONENTS OF CHANGE OF TYPE FREQUENCY AND OF CHANGE OF TEMPERATURE WITHIN TYPE TO THE CHANGES IN MEAN DAILY MAXIMA AND MINIMA AT BUXTON, ESKDALEMUIR, GORLESTON, AND VALENTIA BETWEEN 1925–35 AND 1957–67 IN APRIL (CHANGES <0·1 degC OMITTED)

	Buxton				Eskdalemuir			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
				degrees Celsius				
NW	−0·18			0·11	−0·21			0·21
N	−0·26	0·10		0·21	−0·33	0·15		0·20
NE								
E	0·10	−0·22		−0·13	0·11	−0·11		
SE								
S	0·11					−0·11		
SW								
W								0·19
AW								
CW	−0·10				−0·11			
A	0·81	0·18	0·21	0·11	1·01	0·24		0·18
C	−0·42		−0·17		0·41		−0·14	0·29
U								
Total for all types	0·2	0·2	0·0	0·4	0·3	0·4	−0·1	1·1
$\Delta\overline{T}$	0·4		0·4		0·8		0·9	
Significance level (%)	n.s.		n.s.		8		6	

	Gorleston				Valentia			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
				degrees Celsius				
NW	−0·25		−0·11		−0·24		−0·17	0·14
N	−0·31		−0·14	0·21	−0·41	0·15	−0·18	
NE								
E	0·11	−0·16		−0·14	0·18			
SE								
S	0·10				0·12			
SW								
W						0·10		
AW								
CW	−0·15				−0·14			
A	0·73		0·39	0·10	1·05	0·17	0·44	
C	−0·55	0·11	−0·32	0·11	−0·57		−0·31	0·14
U								
Total for all types	−0·1	−0·1	−0·0	0·3	0·2	0·8	−0·0	0·5
$\Delta\overline{T}$	−0·2		0·3		1·0		0·3	
Significance level (%)	n.s.		n.s.		1		n.s.	

See notes below Tables I and III.

at Buxton and Eskdalemuir. The contribution to $\Delta\overline{T}$ of the decrease in frequency of Westerly type (Table II) in the expression $\Delta f_i\ (T_i + \Delta T_i)/n$ was generally more than offset by the increased frequencies of S, SE and C types.

Discussion. There are several possible reasons for within-type temperature changes. If, for example, there were differences between two periods in the mean airflow trajectories of days recognized as a single type, then a within-type temperature change could result. The Lamb catalogue has recently been revised[4] in order to minimize inconsistencies in type identification and we assume, therefore, that for moderate-sized samples of a given type there will be no bias from this source in the calculated type temperatures for the two periods. It is possible, however, that changes in the spell length of

TABLE V—CONTRIBUTION OF COMPONENTS OF CHANGE OF TYPE FREQUENCY AND OF CHANGE OF TEMPERATURE WITHIN TYPE TO THE CHANGES IN MEAN DAILY MAXIMA AND MINIMA AT BUXTON, ESKDALEMUIR, GORLESTON, AND VALENTIA BETWEEN 1925–35 AND 1957–67 IN JULY (CHANGES <0·1 degC OMITTED)

	Buxton				Eskdalemuir			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
NW	0·30	−0·17	0·18	−0·13	0·33		0·17	
N	1·03		0·64		1·17		0·51	
NE		−0·17			−0·10			
E	−0·25	−0·17	−0·16		−0·26	−0·14	−0·14	
SE	−0·25		−0·10		−0·33		−0·10	
S	−0·34		−0·18	−0·10	−0·30	−0·12	−0·15	−0·14
SW	−0·54		−0·33		−0·48		−0·31	
W	−0·75		−0·47		−0·70	−0·14	−0·39	−0·13
AW	0·22		0·12		0·20		0·11	
CW	−0·38		−0·24		−0·35		−0·22	
A		−0·27		−0·22		−0·40		−0·16
C	0·54	−0·12	0·34	−0·12	0·53		0·31	
U	0·11				0·10			−0·10
Total for all types	−0·3	−1·1	−0·2	−0·6	−0·1	−1·0	−0·2	−0·8
$\Delta\overline{T}$	−1·4		−0·7		−0·9		−0·9	
Significance level (%)	6		5		n.s.		3	

	Gorleston				Valentia			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
NW	0·37	−0·13	0·23		0·34		0·25	
N	1·24		0·79		1·22		0·81	
NE	−0·10				−0·12			
E	−0·25	−0·13	−0·20		−0·27		−0·17	
SE	−0·21		−0·18		−0·23		−0·15	
S	−0·33	−0·11	−0·23		−0·31		−0·23	
SW	−0·55		−0·38		−0·48		−0·35	−0·11
W	−0·90		−0·58		−0·74		−0·56	
AW	0·24		0·15		0·21		0·14	
CW	−0·46		−0·27		−0·37		−0·27	
A		−0·13				−0·19		
C	0·63		0·42		0·54		0·39	
U	0·11				0·10			
Total for all types	−0·2	−0·9	−0·3	−0·2	−0·1	−0·3	−0·1	−0·6
$\Delta\overline{T}$	−1·0		−0·4		−0·3		−0·8	
Significance level (%)	5		n.s.		n.s.		5	

See notes below Tables I and III.

certain types[5] may be of some significance in this respect. This aspect of the problem merits further study. Differences in the wind speed on days of a specified type in the two periods may be another contributory factor to within-type temperature change. However, to evaluate this, one would require type averages of wind speed at each station and along the airflow trajectory, which poses the problems of data unavailability and involved synoptic analysis of uncertain reliability. Lawrence[6] has drawn attention to the possible effects of pollution at Eskdalemuir, but this factor can be ruled out in the case of Valentia, at least, where with the exception of October the overall and within-type temperature changes are similar to those at the other three stations.

Changes in sea surface temperature in the eastern North Atlantic between the two periods are another likely source of within-type temperature change

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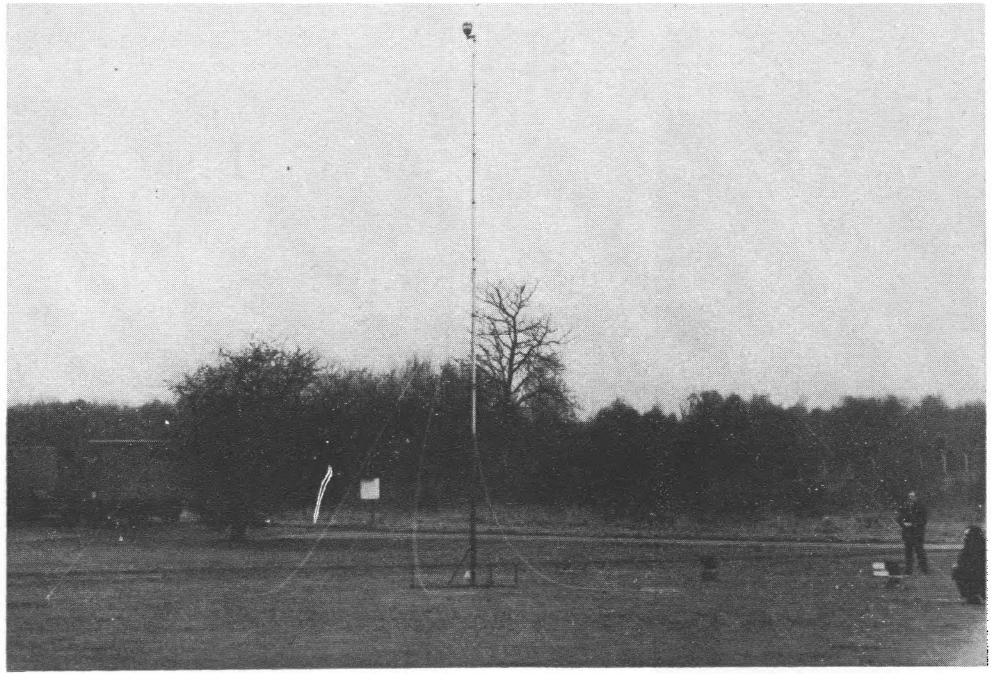
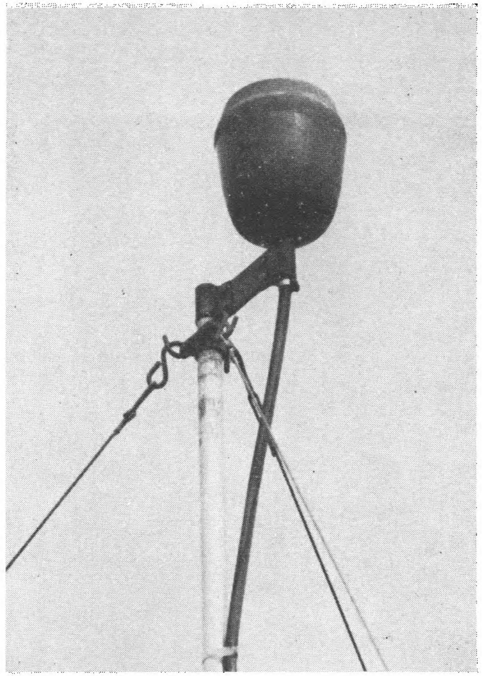
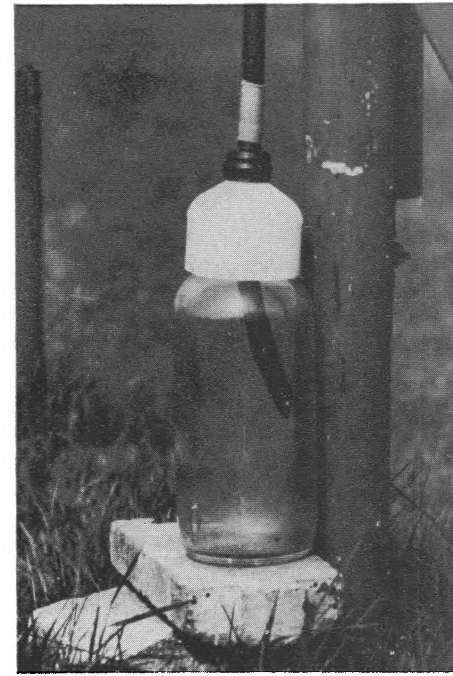


PLATE I—MAST-TOP RAIN-GAUGE AT BEAUFORT PARK, EASTHAMPSTEAD

See page 83.



(a) Collecting funnel



(b) Collecting bottle

PLATE II—MAST-TOP RAIN-GAUGE AT BEAUFORT PARK, EASTHAMPSTEAD

See page 83.

PLATE III—MAJOR K. G. GROVES WITH MR P. R. ROWNTREE, WINNER OF THE MEMORIAL PRIZE FOR METEOROLOGY

See page 93.

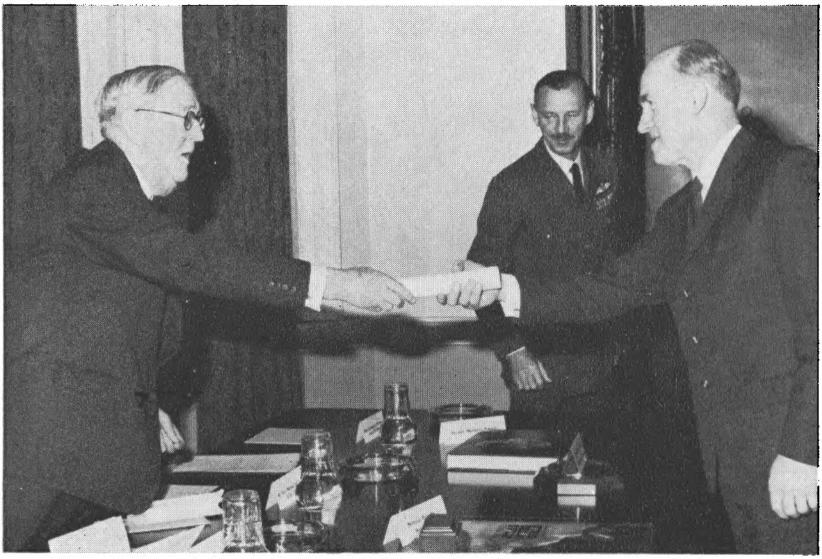


PLATE IV—MAJOR K. G. GROVES WITH MR J. I. P. JONES, WINNER OF THE SECOND MEMORIAL AWARD

See page 93.

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PLATE V—MAJOR AND MRS K. G. GROVES WITH MASTER ELECTRONICS OPERATOR M. B. DANE, M.B.E., WINNER OF THE AIRCRAFT SAFETY PRIZE

See page 92.

TABLE VI—CONTRIBUTION OF COMPONENTS OF CHANGE OF TYPE FREQUENCY AND OF CHANGE OF TEMPERATURE WITHIN TYPE TO THE CHANGES IN MEAN DAILY MAXIMA AND MINIMA AT BUXTON, ESKDALEMUIR, GORLESTON, AND VALENTIA BETWEEN 1925–35 AND 1957–67 IN OCTOBER (CHANGES <0·1 degC OMITTED)

	Buxton				Eskdalemuir			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
NW	−0·11				−0·12			
N	−0·14				−0·16	0·12		0·13
NE								
E				0·12				
SE	0·61		0·29		0·66		0·22	
S	0·53		0·24		0·54		0·26	
SW				−0·11				
W	−1·22		−0·71	0·25	−1·13		−0·53	0·24
AW	0·39		0·15	−0·11	0·37		0·15	
CW	−0·32		−0·19		−0·30		−0·17	0·23
A	0·17			0·33	0·17			0·44
C	0·38		0·22		0·38	0·13	0·18	0·18
U	−0·10			0·10	−0·10	0·13		0·17
Total for all types	0·2	0·4	−0·1	0·8	0·4	0·6	0·1	1·5
$\Delta\overline{T}$	0·7		0·8		1·1		1·7	
Significance level (%)	n.s.		9		2		1	

	Gorleston				Valentia			
	Maximum		Minimum		Maximum		Minimum	
Type	a	b	a	b	a	b	a	b
NW	−0·16			0·14	−0·15		−0·10	
N	−0·19		−0·11	0·21	−0·21		−0·11	
NE	−0·10				−0·11			
E					0·10	0·12		
SE	0·68		0·57		0·79		0·56	
S	0·60		0·41		0·61		0·41	
SW								
W	−1·51		−0·89		−1·42		−1·00	−0·12
AW	0·46		0·20	−0·10	0·46		0·30	
CW	−0·39		−0·26	0·10	−0·36		−0·26	
A	0·20		0·13	0·35	0·22		0·12	0·11
C	0·50		0·35	0·27	0·46		0·27	−0·10
U	−0·13			0·15	−0·12			
Total for all types	0·1	0·1	0·3	1·0	0·3	0·4	0·1	−0·3
$\Delta\overline{T}$	0·2		1·3		0·9		−0·2	
Significance level (%)	n.s.		2		4		n.s.	

See notes below Tables I and III.

through the mechanism of air-mass modification. However, the limited availability of sea surface temperature data makes it doubtful whether adequate resolution can be obtained to examine this question in view of the small temperature changes observed and the fact that feedback processes undoubtedly make the air–sea interaction very complex. For example, temperatures were higher in the second period with NW and N types in April (Table II) although in view of the recent expansion of polar pack-ice this change would not have been expected. The frequencies of particular airflow directions are correlated with sea surface temperature anomalies, as is evident from the associations established by Ratcliffe and Murray[7] between such anomalies in areas of the western North Atlantic and the subsequent month's pressure anomaly pattern over the British Isles. Nevertheless, preliminary examination of Ratcliffe's catalogue of monthly sea surface temperature anomaly patterns[8] indicates no evident relationship with the changes of within-type temperature.

The present authors' findings confirm Goedecke's[9] conclusion that the pattern of temperature change over the British Isles between two periods is complex, highly variable from month to month, and a result of many factors, both atmospheric and terrestrial. In order to isolate the causes of the within-type changes considerable detailed analysis will be required. Goedecke's study, which only recently came to the authors' notice, in fact provides useful information on which to base the selection of other stations for analysis since he maps changes of mean seasonal temperature between 1901–30 and 1921–50. Additional spatial coverage seems necessary in view of the complex response of the four stations to within-type temperature changes shown in Tables II and V. It would be valuable also to extend the analysis to a number of consecutive decadal periods. This would determine to what extent, if any, the changes between 1925–35 and 1957–67 constitute a trend. The temporal and spatial complexity of the changes of type temperatures between these two periods illustrates the problems of interpreting inferred temperature changes in the historical (and earlier) periods in terms of simplified models of the regional atmospheric circulation.

Acknowledgements. The authors wish to thank Professor H. H. Lamb for kindly making available his then unpublished catalogue of weather types.

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551.507.7:551.508.77

THE PERFORMANCE OF A MAST-TOP RAIN-GAUGE IN THE FIELD

By L. S. CLARKSON

Summary. A tulip-shaped rain-gauge funnel mounted on top of a 10-m mast was found to have collected, over two years, 98·4 per cent of the rainfall collected in a standard Mk 2 rain-gauge nearby. Random differences of rainfall rarely exceeded ± 0·75 mm for daily values or ± 2 mm for monthly totals. By applying a small correction to allow for evaporation the random variations of the mast-top gauge were reduced and its overall deficiency in catch was eliminated.

The mast-top rain-gauge. The base and rim-flange of a 150-cm^2 Mk 4 glass-fibre rain-gauge were cut away and the resulting simple tulip-shaped collecting funnel was mounted on top of a slender mast 10 m above the ground (see Plates I and II(a)) at Beaufort Park, Easthampstead, adacent to the array of rain-gauges used in the trials previously reported on.[1]

Rain-water caught by the mast-top funnel was led down ½-inch* polythene tubing into a collecting bottle at the foot of the mast (Plate II(b)). The entry of the tubing into the bottle was carefully shielded to prevent any rain-water that might run down the outside of the tube from entering the bottle. The bottle was sheltered from direct sunshine and its contents were measured daily in a standard rain measure.

The mast was kept vertical — and the rim of the collecting funnel horizontal — by staying with six guy ropes: three attached to the top of the mast and three to a point about half-way up it. These last three had been found necessary in a preliminary experiment; without them the slender mast tended to bow slightly in a strong wind, resulting in the orifice of the collecting funnel tilting into the wind.

After the first rainfall, many small droplets of rain-water could be seen clinging to the interior walls of the polythene tube. However, it was noticed that these were very slow to evaporate, the tube rarely becoming dry before the onset of the next period of rain.

Field trial results and discussion. In the two-year period from 22 May 1970 to 31 May 1972, 169 measurements were made of daily rainfall of amounts $\geqslant 1$ mm which did not fall as snow.

Designating the daily amount in millimetres collected by the mast-top gauge as M, and by the Mk 2 gauge used as a standard in previous rain-gauge trials as S, the overall ratio $\Sigma M/\Sigma S$ was 98·4 per cent, and the regression equation of M on S was

$$M = 1{\cdot}003S - 0{\cdot}13 \pm 0{\cdot}75 \text{ (95 per cent confidence limits).}$$

Table I compares the results of the field trial with results from an adjacent Mk 2 rain-gauge S_2 for the period 25 June 1969 to 30 June 1970.[1]

TABLE I—COMPARISON OF RESULTS OF FIELD TRIAL WITH THOSE OF AN ADJACENT MARK 2 RAIN-GAUGE

Period	n	$\sum M$ *mm*	$\sum S$ *mm*	Ratio *per cent*	Regression ±95 per cent confidence limits
22/5/70–31/5/72	169	1179·5	1198·5	98·4	$M = 1{\cdot}003S - 0{\cdot}13 \pm 0{\cdot}75$
		$\sum S_2$ *mm*	$\sum S$ *mm*		
25/6/69–30/6/70	89	491·8	494·7	99·4	$S_2 = 0{\cdot}997S - 0{\cdot}02 \pm 0{\cdot}29$

n = number of occasions of 24-hour rainfall $\geqslant 1$ mm.

In a comparison of the two regression equations, it is seen that a negligible addition of 0·02 mm to the daily catch in the S_2 gauge will cause it on average to register virtually the same (within 0·3 per cent) as the standard rain-gauge, with random differences not exceeding 0·29 mm on 95 per cent of rain days. For the mast-top gauge, however, the addition to its daily catch required to cause it on average to read the same (within 0·3 per cent) as the standard

* 1 in = 25·4 mm.

gauge is 0·13 mm, six and a half times greater, and the random differences are considerably larger, not exceeding 0·75 mm on 95 per cent of rain days.

Despite the danger of reading a physical significance into a purely statistical relationship, the regression equation does imply that, relative to the standard rain-gauge, the mast-top gauge systematically loses on average 0·13 mm, and randomly differs by $\pm$ 0·75 mm per rain day, the loss being practically independent of the amount of daily rain. Reasons for the systematic relative loss could be that additional turbulence at the mast-top level diverts raindrops out of the funnel, and/or that there is a loss by evaporation of droplets on the interior walls of the polythene tube between rainfall events. The confidence limits of the regression equation indicate that occasionally. i.e. on about 2·5 per cent of rain days, the mast-top gauge can be expected to collect over 0·62 mm *more* than the standard rain-gauge. The only plausible explanation for such an over-collection is that on these rather rare occasions droplets clinging to the inner wall of the polythene tube are shaken down into the collecting bottle by the vibration of the tube in strong winds.

It is likely that effects due to the polythene tube leading from the funnel to the collecting bottle are the main source of the overall deficit and the day-to-day additional variability of the catch in the mast-top gauge relative to that in the standard rain-gauge.

If evaporation from the tube is the main cause of the deficit, then the mast-top gauge deficit should be larger than average for rain days preceded by several dry days, and below average for rain days which followed rain days. In the daily data there were 16 rain days prior to which there had been no precipitation at all during the previous 5 days. For these, $\sum S$ was 120.5 mm. and $\sum M$ was 115·5 mm, giving a deficit per rain day preceded by 5 dry days of 5/16 mm, or 0·313 mm. From the data another 16 rain days were found at around the same dates as the previously considered 16, but for each of which rain had fallen the day before. For these, $\sum S$ was 180·9 mm, and $\sum M$ was 180·3 mm, giving a deficit of only 0·6 mm, or 0·038 mm per rain day. (Over the whole two years, the average deficit per rain day was 19/169 mm, or 0·11 mm.)

The figures quoted above support the contention that the main difference in performance between the mast-top and the surface rain-gauges may be ascribed to evaporation from the polythene tube on occasions when a rain day was not preceded by a day with precipitation.

In Table II the rain days are aggregated into 23 approximately monthly periods. Applying a 'correction' of $+$ 0·11 mm per rain day to the mast-top gauge readings results in $M_1 = S \pm 2{\cdot}0$ mm (95 per cent confidence limits) for monthly totals, while correcting by the addition of 0·23 mm on only those occasions when the previous day was dry gives $M_2 = S \pm 1{\cdot}6$ mm (95 per cent confidence limits). The latter method can be expected to yield the more consistent results if the loss is really due mainly to evaporation, and this is in fact what is found. By either method, monthly totals obtained from the standard and the (corrected) mast-top rain-gauges are seen to differ very rarely by as much as 2 mm.

Conclusions. Some general conclusions which follow from this field trial are :

(a) When no 'corrections' are applied, the mast-top rain-gauge over two

TABLE II—PERFORMANCE OF MAST-TOP RAIN-GAUGE COMPARED WITH THAT OF A STANDARD MARK 2 RAIN-GAUGE NEARBY

Period	$\sum S$	$\sum M$	n	M_1	$S-M_1$	n'	M_2	$S-M_2$
	mm				mm			mm
22/5–23/6/70	25·7	25·0	4	25·4	0·3	3	25·7	0·0
24/6–11/8/70	104·4	102·0	16	103·8	0·6	9	104·1	0·3
12/8–7/10/70	78·9	78·2	13	79·6	−0·7	5	79·3	−0·4
8/10–6/11/70	28·4	28·5	6	29·2	−0·8	3	29·2	−0·8
7/11–2/12/70	129·6	130·1	13	131·5	−1·9	3	130·8	−1·2
3/12/70–16/1/71	17·5	16·9	4	17·3	0·2	2	17·4	0·1
17/1–15/2/71	99·5	98·4	13	99·8	−0·3	2	98·9	0·6
16/2–28/2/71	8·3	7·5	4	7·9	0·4	1	7·7	0·6
1/3–31/3/71	45·8	45·0	3	45·3	0·5	3	45·7	0·1
1/4–30/4/71	57·8	54·8	4	55·2	2·6	4	55·7	2·1
1/5–31/5/71	45·4	45·4	6	46·1	−0·7	4	46·3	0·9
1/6–30/6/71	121·7	122·8	6	123·5	−1·8	2	123·3	−1·6
1/7–31/7/71	12·3	11·3	5	11·9	0·4	3	12·0	0·3
1/8–31/8/71	65·5	64·6	16	66·4	−0·9	3	65·3	0·2
1/9–31/9/71	10·8	10·4	2	10·6	0·2	1	10·6	0·2
1/10–31/10/71	62·2	62·5	5	63·1	−0·9	3	63·2	−1·0
1/11–31/11/71	30·1	29·5	4	29·9	0·2	3	30·4	−0·3
1/12–31/12/71	18·5	18·0	3	18·3	0·2	3	18·7	−0·2
1/1–31/1/72	52·3	5·07	11	51·9	0·4	6	52·1	0·2
1/2–29/2/72	63·4	62·0	9	63·0	0·4	5	63·1	0·3
1/3–31/3/72	47·5	46·4	5	47·0	0·5	4	47·3	0·2
1/4–30/4/72	33·3	32·7	7	33·5	−0·2	5	33·8	−0·5
1/5–31/5/72	39·6	36·7	10	37·8	1·8	7	38·3	1·3
22/5/70–31/5/72	1198·5	1179·5	169	1198·0	0·5	84	1198·9	−0·4
Standard deviations of differences (mm)					1·00			0·81

n = number of rain days, i.e. rainfall $\geqslant 1$ mm.
n' = number of rain days each preceded by a day with not more than a trace of precipitation.

$M_1 = \sum M + 0{\cdot}11\, n.$

$M_2 = \sum M + 0{\cdot}23\, n'.$

years under-read compared with the standard gauge by less than 2 per cent, and for daily rainfalls was relatively no more variable than were the tipping-bucket rain-gauges at Glasgow Airport and Bristol/Filton investigated previously.[1]

(b) After a correction of + 0·23 mm was applied to each daily rainfall of 1 mm or more measured on the mast-top rain-gauge provided the previous day was dry, this gauge over two years collected the same amount of rain as was collected in the standard Mk 2 rain-gauge; monthly totals very rarely differed by as much as 2 mm, and daily totals by as much as 1 mm.

(c) The under-reading and additional variability, if primarily due to the 10-m length of polythene tube, could possibly be obviated by arranging for automatic metering of the rain-water by a suitable mechanism mounted on the mast, just below the collecting funnel.

(d) The mast-top rain-gauge appears potentially suitable for operational use in situations where it is impracticable properly to site and expose a standard rain-gauge at ground level, for example over shallow water, on ground liable to flooding and on rocky terrain.

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551.513:551.547.3

SEASONAL VARIATIONS IN THE 500-mb MONTHLY OSCILLATION OVER THE NORTHERN HEMISPHERE

By M. G. COLGATE and R. J. HEWS

Summary. An analysis of six years of daily 500-mb data filtered for retention of oscillations of about a month over a grid network which covered most of the northern hemisphere revealed some interesting seasonal variations in the location of large monthly oscillations. A comparison between time-series oscillations obtained by use of the monthly filter, and also a filter designed to retain short-period oscillations, illustrates the significant contribution that monthly oscillations make to the 500-mb fluctuations.

Introduction. Several papers have been written describing methods of using filters to detect the presence of oscillations in time series of meteorological data. In particular, a paper by Sawyer[1] described how 500-mb, 1000–500-mb thickness, and surface pressure data over the northern hemisphere were filtered to retain only those oscillations with a period of about a month. Although the results of his paper indicated that these were prominent fluctuations on a monthly time-scale, the yearly time series that were analysed merged together any seasonal variations that might be present. This paper describes a similar analysis on a seasonal time series of 500-mb data only. Besides monthly oscillations, short-period oscillations were also analysed for comparison.

Data and filters. Six years of daily 500-mb data starting from 1949 onwards were analysed for a grid network of 112 points shown in Figure 1. The four seasons were each defined as a three-calendar-month period with spring starting on 1 March.

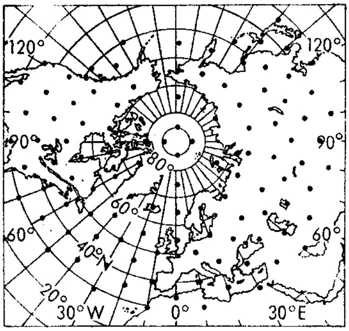

FIGURE 1—112-POINT GRID USED FOR THE TIME-SERIES ANALYSIS

Three filters of order 15 (i.e. 31 terms) were used. They were designed to retain the following fluctuations :

(a) those with a time period of about a month,
(b) those with time periods of 10 days or less, and
(c) those with a time period of about a week.

Graphs of the magnification factor of the amplitude against the period of oscillations for the three filters are shown in Figure 2. The inclusion of a filter to retain all periods of 10 days or less was chosen because this passed all the high frequencies that were not passed by the monthly filter. Thus filters (a) and (b) pass mutually exclusive and complementary wavebands which will provide useful comparison.

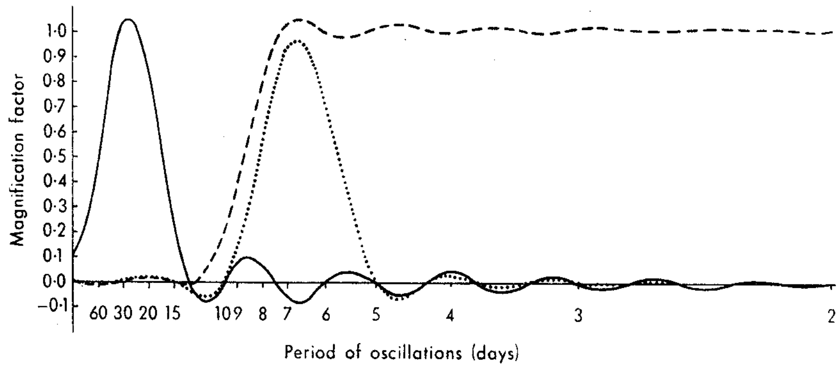

FIGURE 2—GRAPH OF MAGNIFICATION FACTOR AGAINST PERIOD FOR DIFFERENT FILTERS

——— Filter for periods of about a month
– – – Filter for periods of less than 10 days
. . . . . . Filter for periods of about a week

Analysis of hemispheric data. The results reproduced here are those formed by using the monthly filter only. Four seasonal charts of the root mean square (r.m.s.) of the filtered time series for each of the points were drawn for each year. The six charts corresponding to each season were then combined, and the results are shown in Figures 3–6.

During spring Alaska has the highest fluctuation of monthly oscillations. This feature is prominent in all six years. Two other important areas of high monthly fluctuations during spring were over the Atlantic, and over the Gulf of Ob. The centre of high r.m.s. values over the Atlantic tended to wander from this position for three of the years, moving to a position over south Greenland or the west Atlantic. The centres of low fluctuation were generally over and around the North Pole, south of 50°N and over most of North America.

Summer monthly oscillations (Figure 4) are generally of smaller magnitude than those for the other seasons, which is to be expected since fluctuations of unfiltered 500-mb data are lowest during summer. The summer centres of high r.m.s. values over the Atlantic are generally in the same regions as those that occur during spring although the spring high cell over Alaska has moved south-westwards over the Bering Sea, and the Gulf of Ob high centre is less prominent. The high r.m.s. values over north-west Greenland are a special feature of the summer season.

As in the spring and summer, autumn cells of high r.m.s. values are mainly over the north-east Atlantic, Gulf of Ob and Gulf of Alaska. One prominent area which is different during autumn is over the Great Lakes. This region had a high cell during two of the years whilst none was present during any of the other seasons.

Although the winter season possessed the largest monthly oscillations, it was the least consistent for the recurrence from year to year of high r.m.s. values. Moreover the latitudinal extent for the presence of high cells increases during winter with centres in some years occurring as far south as 45°N over

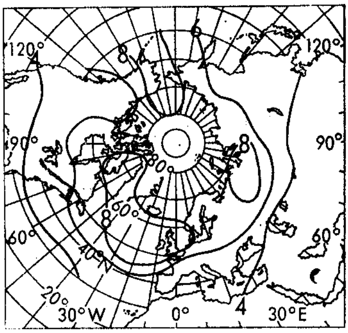

FIGURE 3—SPRING r.m.s. OF DAILY 500-mb HEIGHTS FILTERED TO RETAIN MONTHLY OSCILLATIONS ONLY

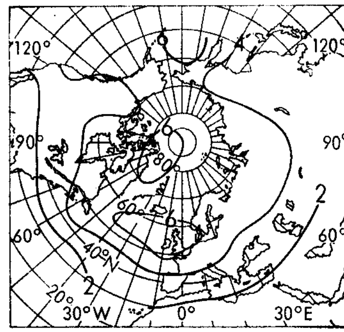

FIGURE 4—SUMMER r.m.s. OF DAILY 500-mb HEIGHTS FILTERED TO RETAIN MONTHLY OSCILLATIONS ONLY

Units are geopotential decametres.

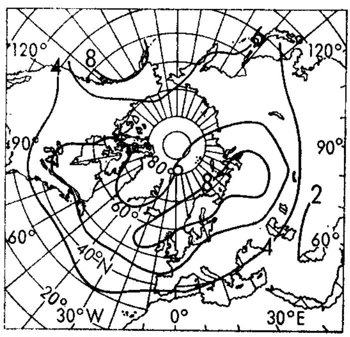

FIGURE 5—AUTUMN r.m.s. OF DAILY 500-mb HEIGHTS FILTERED TO RETAIN MONTHLY OSCILLATIONS ONLY

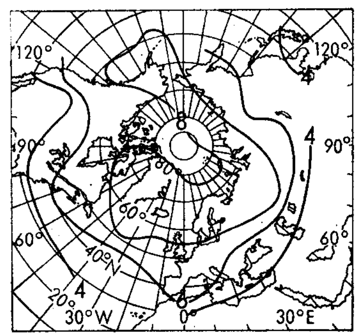

FIGURE 6—WINTER r.m.s. OF DAILY 500-mb HEIGHTS FILTERED TO RETAIN MONTHLY OSCILLATIONS ONLY

Units are geopotential decametres.

southern France, and as far north as 75°N over the Laptev Seas. Nevertheless, the combined winter r.m.s. chart for the six years shows strong similarity to those of the other seasons.

Thus the results for the four seasons can be summarized as indicating that the main areas for high monthly fluctuations lie in middle latitudes with preferred areas over the northern North Atlantic, Gulf of Ob and the Alaskan region.

Analysis of time series at selected points. In order to reduce computational effort, only four points were selected from the grid network for the purpose of illustrating the effect of filtering 500-mb time-series data. The points chosen were: along the Greenwich meridian at 55°N, 65°N 20°E, 65°N 160°W and 45°N 60°W.

Figure 7 displays the effect of filtering a four-month time series starting from 1 May 1952 at 55°N, 0°. It can be clearly seen how the monthly filtered time series reflects all the large-amplitude fluctuations in the original time series. Also shown is the distinctly large amplitude of monthly oscillations

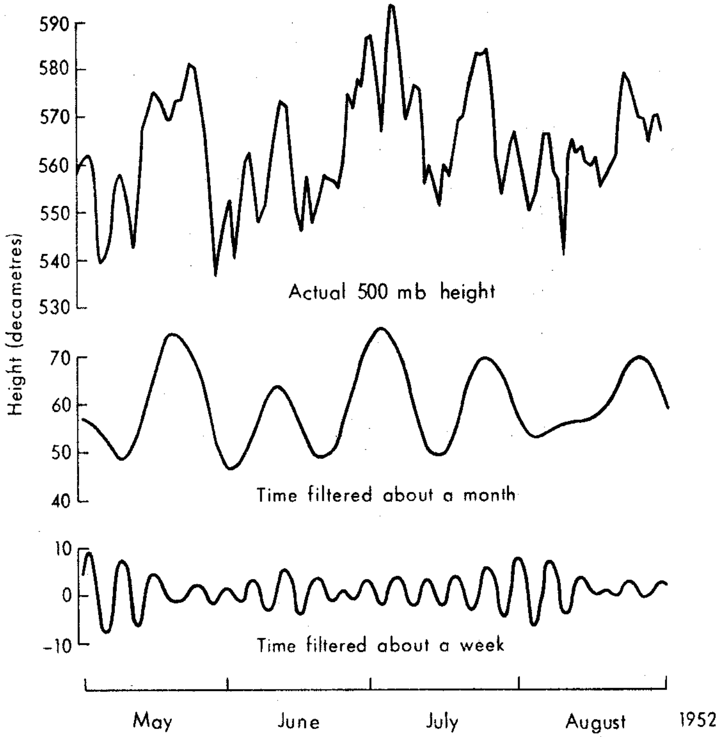

FIGURE 7—TIME-FILTERED AND ORIGINAL 500-mb HEIGHT SERIES OFF NORTH-EAST ENGLAND AT 55°N, 0°

relative to the oscillations of the time series filtered for periods of about a week. These large-amplitude oscillations in the monthly filtered time series are consistent with the commonly observed association between quasi-stationary blocking types and large-magnitude 500-mb anomalies. Similarly the small-amplitude oscillations present in the weekly filtered time series are probably associated with fast-moving, small-amplitude waves in the 500-mb flow.

An objective method for testing the significance of monthly oscillations was carried out as follows. The variance of a filtered time series can be used to estimate the variance of the original time series by dividing the filtered time-series variance by the 'power' of the filter (see Craddock[2,3]). If two such estimates are made from filters passing waves whose periods lie in non-overlapping wavebands then Fisher's variance ratio test ('F' test) can be used to compare the variance of the waves retained within the respective wavebands. By choosing a filter which passes all periods of 10 days or less, it is possible to test the significance of monthly oscillations. Table I shows the 'F' ratio for each of the four points, and for each of the seasons between summer 1949 and winter 1952. The 0·1-per-cent level of significance for the 'F' ratio is 4·10, which is exceeded in all the instances listed in Table I except on two occasions. Clearly, the results are highly significant.

TABLE I—RATIO OF VARIANCE OF THE ESTIMATES OF THE ORIGINAL VARIANCE FROM THE MONTHLY FILTERED SERIES AND THE SERIES FILTERED FOR PERIODS OF TEN DAYS OR LESS (DEGREES OF FREEDOM 7 AND 70)

		55°N 0°	65°N 20°E	65°N 160°W	45°N 60°W
1949	Summer	11·52	17·01	12·28	12·88
	Autumn	12·70	30·03	13·24	4·01
	Winter	8·01	41·27	28·15	4·74
1950	Spring	21·78	22·50	27·25	4·18
	Summer	8·27	8·90	64·86	5·44
	Autumn	5·12	29·68	19·28	6·01
	Winter	11·99	27·30	24·15	7·08
1951	Spring	12·43	24·58	45·47	12·19
	Summer	12·33	15·93	15·77	11·83
	Autumn	12·13	14·94	5·41	5·21
	Winter	9·34	14·94	25·53	6·34
1952	Spring	20·21	10·65	11·04	4·30
	Summer	21·01	28·75	16·60	9·98
	Autumn	10·74	35·94	11·05	7·10
	Winter	20·46	7·68	28·76	2·38

Conclusions. The comparison of monthly oscillation with short-period oscillations has demonstrated the importance of monthly oscillations in 500-mb fields. Most of the high fluctuations lie between 50°N and 65°N. For all seasons the regions with the highest monthly fluctuations can be summarized as being over the northern North Atlantic, Gulf of Ob and the Alaskan region. Nevertheless, there are distinct variations from season to season with regard to the position of high fluctuations over the Alaskan region; being over Alaska/Bering Strait during winter and spring, over the Bering Sea during summer and over the Gulf of Alaska during autumn. Other differences in the seasons can be noted, but generally they are not consistent from year to year.

In middle latitudes the most consistent area for low monthly oscillations was over the Rockies.

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NOTES AND NEWS

Retirement of Mr J. H. Brazell

On 2 January 1973 John Brazell retired from the Meteorological Office in which, for the past two years, he held the post of Assistant Director, Observational Requirements and Practices.

He joined the Office in 1936 and for much of his career was concerned with the provision or organization of forecasts for aviation or the general public. He served in the Central Forecasting Office before the War and at several RAF stations until he was mobilized in the Royal Air Force Volunteer Reserve in 1940 and sent to Iceland. He was in Malta for 18 months in the most active part of the siege until 1943 when he was posted to Habbaniya and later to Cairo. On demobilization in 1946 he became Senior Meteorological Officer at Uxbridge (Air Traffic Control Centre) and in 1950 moved to the newly formed RAF Flying College at Manby. In 1956 he was lent to the East African High Commission to become Director of the East African Meteorological Service for three years. On his return from Nairobi in 1959 he helped to set up the London Weather Centre where he was Senior Meteorological Officer until 1967; it was largely due to his efforts that this office developed into the important and effective Centre that we now know, with its varied service to the Press, television, radio and the general public and its specialized service for oil and gas drilling in the North Sea. In 1967 he was promoted Senior Principal Scientific Officer and took charge of the Climatological Services Branch at Bracknell; later he was Chief Meteorological Officer at London/Heathrow Airport before returning to Headquarters.

John Brazell was an authority on the weather of London. He wrote papers on air pollution, the effects of weather on the building industry and other topics and was the author of *London weather* (HMSO, 1968).

John has now returned to his native valley in south Wales, within easy reach of the sports grounds of Llanelli, Swansea and Cardiff, where he can once again enjoy some of the best rugby-football there is. We wish him many happy years of retirement.

J. K. BANNON

NASA launch satellite carrying Heriot-Watt University experiment

A rocket was launched from NASA's Western Test Range in California on 11 December 1972 which placed into polar orbit the weather satellite NIMBUS-E.

Aboard the satellite is a scientific experiment (developed jointly by Heriot-Watt University, Edinburgh, and the University of Oxford) which has already revolutionized the technique of measuring the temperature of the earth's atmosphere by providing one of the earliest quantitative global surveys — at a fraction of the cost per measurement by conventional methods (radiosonde balloons).

This was achieved by the similar experiment currently orbiting aboard the NIMBUS-4 weather satellite which has been in orbit since April 1970. (From this experiment some 10 million readings have been obtained at a cost of £250 000 — i.e. 2½p per measurement.)

The experiment results from the invention and development by Professor Desmond Smith at Heriot-Watt University and Dr John Houghton at the University of Oxford of an instrument called a Selective Chopper Radiometer which from the orbiting satellite continuously monitors the temperature of the earth's atmosphere at various levels. From the data it produces, scientists at Heriot-Watt University using a computer in their research laboratory at

Riccarton can produce, twice daily, an accurate vertical temperature profile of the earth's atmosphere up to a height of 50 kilometres and provide information, vital to meteorologists, on its water vapour content and cloud cover.

The Selective Chopper Radiometer works by measuring the infra-red radiation emitted by carbon dioxide in the earth's atmosphere. From this information the vertical temperature profile can be built up.

So successful was the NIMBUS-4 experiment that, in the face of stiff competition from no less than 36 major research laboratories in the U.S.A., the British experiment developed (with the financial support of the Science Research Council) by research teams at Heriot-Watt and Oxford Universities was chosen for the NIMBUS-E project.

The Selective Chopper Radiometer on NIMBUS-E is an improved version of the NIMBUS-4 experiment. This new radiometer provides 16 readings every 4 seconds. From these readings temperatures at 8 heights and information on cloud cover and water vapour content can be deduced to provide twice daily a complete global picture. Every temperature measurement made from the satellite, which orbits at about 1100 kilometres ($\approx$600 nautical miles) above the earth, is accurate to within 2 degrees Celsius.

The data are relayed directly from the satellite to Riccarton for analysis via the data receiving station at Fairbanks in Alaska, the Goddard Space Flight Centre in Washington and the Oxford research unit.

AWARDS

L. G. Groves Memorial Prizes and Awards

The 26th award of prizes was made on Friday, 8 December 1972, at the Ministry of Defence, Whitehall, by Major and Mrs K. G. Groves. The Assistant Chief of the Air Staff (Operations), Air Vice Marshal D. G. Evans, C.B.E., presided and the ceremony was attended by the Director-General of the Meteorological Office. (See Plates III — V.)

The 1972 Aircraft Safety Prize has been awarded to Master Air Electronics Operator M. B. Dane, M.B.E., formerly of Royal Air Force Akrotiri, with the following citation :

> 'Master Air Electronics Operator M. B. Dane has been employed on Search and Rescue duties, a role in which he has had considerable experience. Apart from the requirements of his normal duties, however, Mr Dane has consistently taken an active interest in all aspects of flight safety, and his personal enthusiasm, industry and imagination have led him to put forward many practical ideas. Over a period of time, his suggestions have embraced matters such as helicopter cliff rescue, illuminating flares, the recovery of injured survivors into single seat dinghies and the concept of Crash Rescue Quick Reference Cards.
>
> The Quick Reference Cards provide, for rescue teams, vital and quickly assimilated information on access points for a range of aircraft, and could be instrumental in saving time and lives in the event of a crash. These Cards have been adopted by the Ministry of Defence and they typify Mr Dane's involvement with safety.

Overall, the number of constructive and practical schemes devised by Mr Dane, has made an invaluable contribution to flight safety.'

The 1972 Meteorology Prize has been awarded to Mr P. R. Rowntree, Principal Scientific Officer, Meteorological Office, with the following citation :

'Mr P. R. Rowntree has studied over several years the effects which variation of the ocean temperatures in the equatorial Pacific may have on the large scale circulation of air over the Northern Hemisphere. It had earlier been surmised by Professor J. Bjerknes that sea temperatures in the Pacific exert a significant control over long term weather regimes over wide areas. In a paper published in the last year Mr Rowntree has calculated quantitatively the effects to be expected, and has shown that they are similar to those observed. This is the first time that quantitative numerical methods have been applied successfully to explain long-period weather variations.'

The Meteorological Observer's Award has been awarded to Mr J. Findlater, Senior Scientific Officer, Meteorological Office, with the following citation :

'Mr J. Findlater has carried out a unique series of observations through a band of exceptionally strong winds (a low-level jet stream) which he had earlier located from meteorological observations over East Africa as a regular summer occurrence. The observations were made from a light aircraft and were planned by Mr Findlater to disclose the cloud structure and wind circulation associated with the phenomenon.'

The Second Memorial Award for 1972 has been awarded to Mr J. I. P. Jones, Senior Scientific Officer, Meteorological Research Division, CDE, Porton Down, with the following citation :

'Mr J. I. P. Jones has over many years contributed a wide variety of ingenious ideas to the design of the mechanism and electronics of wind vanes and anemometers. Without his contributions the instrumentation now in use in the study of atmospheric turbulence would not have achieved its present high degree of accuracy and sensitivity.'

Owing to Mr J. Findlater's further service with the East Africa Meteorological Department, his award was collected on his behalf by Mr J. Crabtree.

REVIEWS

Foundations of climatology, by E. T. Stringer. 260 mm × 190 mm, pp. xiii + 586, *illus.*, W. H. Freeman and Company, 58 Kings Road, Reading, RG1 3AA, 1972. Price: \$17·50.

Techniques of climatology, by E. T. Stringer. 260 mm × 190 mm, pp. xiii + 539, *illus.*, W. H. Freeman and Company, 58 Kings Road, Reading, RG1 3AA, 1972. Price: \$17·50.

The first of these two volumes, *Foundations of climatology*, is a text written from the view point of classical physics for the serious student of climatology, who needs more than the purely descriptive treatment of atmospheric phenomena found in most books on climatology. It is a stimulus and a challenge to a newcomer to the subject of climatology when he is made to realize, as here, that for proper understanding of the subject he needs to know a great deal about physical, dynamical and synoptic meteorology as well as geography, and to be able to apply statistical methods to summarize and analyse data meaningfully.

It is not possible for anyone to know all there is to know about the topics dealt with by Dr Stringer under the six chapter headings: 1. The Atmosphere; 2. Atmospheric Properties and Processes; 3. Atmospheric Turbulence and Diffusion; 4. The General Circulation of the Atmosphere; 5. Scientific Inference in Climatology; 6. The Synoptic Method; but certainly anyone who has mastered this book and followed up the excellent set of references will be able to hold his own in good meteorological company.

The second volume, *Techniques of climatology,* is a manual for those who have mastered the first volume and wish to apply the techniques of the meteorologist, the mathematical statistician and the geographer to the solution of specialist problems in a great variety of disciplines, e.g. engineering, medicine, agriculture, physical and biological sciences, etc. The first three chapters discuss the making of climatological observations, instrumentation and required networks; the interpretation and statistical analysis of data; and physical and mathematical models of phenomena of weather and climate. The remaining five chapters discuss the applications of these basic techniques to radiation climatology, temperature, clouds and climate, visual climate and optical climatology, and geographical climatology.

Anyone reading *Techniques of climatology* and following up the references will know how to tackle the most difficult problem of all for climatologists: how to assemble, analyse and interpret climatic data.

These two volumes make a very valuable addition to climatological literature, and I am sure that most climatologists and those in other professions who have to tackle or understand climatological problems would wish to have them within easy reach.

A. F. JENKINSON

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LETTER TO THE EDITOR

Rule for reading the rain measure

Since observers in the British Rainfall Organization have been making their returns of rainfall in millimetres, they have used taper measures graduated in tenths as far as 10·0 mm. When there is more water in the rain-gauge than can be measured by one filling of the measure, they follow the advice given in section 7 of *Rules for rainfall observers* (Met O Leaflet No. 6). The metric equivalent of this rule is that the glass should be filled nearly to the 10·0 mark and the reading noted. The contents are emptied into a jug and the glass is filled again as often as is necessary; the reading is noted each time. The individual amounts are added together to give a total measurement, e.g. $9{\cdot}7 + 9{\cdot}5 + 9{\cdot}9 + 5{\cdot}1 = 34{\cdot}2$.

I submit that the measuring procedure would be facilitated if the graduations on the measure were extended as far as 11·0 or even 12·0, and the advice on measuring large quantities of rain modified to read: 'the glass should be filled to just beyond the 10·0 mark . . .'. In this way the foregoing fall of rain might be measured as follows: 10·2 + 10·1 + 10·4 + 3·5 = 34·2.

Not only would the summation be easier but often fewer fillings of the measure would be required.

Artetech International
Botley, Oxford
G. T. MEADEN

Reply by the Meteorological Office:

There are several factors which influence the most cost-effective size of rain measures: a 10-mm glass measure was standardized as a reasonable compromise between one too long and therefore expensive, inconvenient and fragile, and one so short as to require many fillings to measure the average amount of rain-water collected in the rain-gauge.

It does appear possible, however, that the graduations could be extended above the 10-mm mark, and this point will be examined at the time when further rain measures are ordered.

M. J. BLACKWELL AND L. S. CLARKSON

HONOURS

The following honours were announced in the New Year's Honours List, 1973:

C.B.

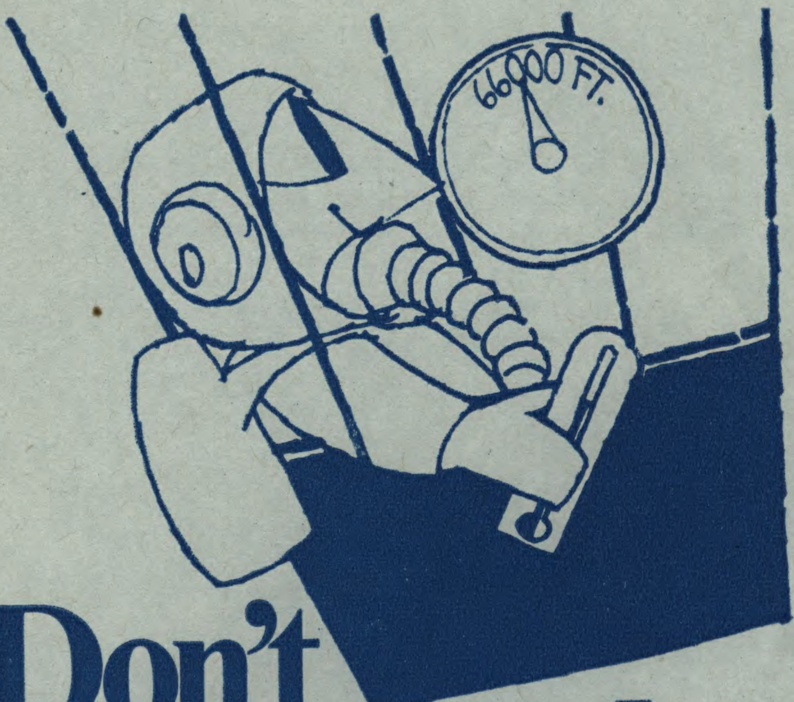
Dr B. J. Mason, F.R.S., the Director-General of the Meteorological Office.

I.S.O.

Mr R. K. Pilsbury, F.R.P.S., formerly of the Telecommunications Branch, Meteorological Office, Bracknell.

OBITUARY

It is with regret that we have to record the death of Mr R. P. Johnson, Higher Scientific Officer, Met O 2, on 30 November 1972.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Met.O.860

METEOROLOGICAL OFFICE

the meteorological magazine

APRIL 1973 No 1209 Vol 102
Her Majesty's Stationery Office

SCIENTIFIC PAPERS

No. 31 The three-dimensional analysis of meteorological data

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

37½p (40p by post)

No. 32 The Bushby-Timpson 10-level model on a fine mesh

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

55p (57½p by post)

METEOROLOGICAL OFFICE Met.O.860

THE METEOROLOGICAL MAGAZINE

Vol. 102, No. 1209, April 1973

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ERRORS IN 48-HOUR MOVEMENT AND DEVELOPMENT OF COMPUTER-FORECAST 500-MILLIBAR TROUGHS AND RIDGES: AMERICAN AND BRITISH MODELS COMPARED

By M. J. DUTTON

Summary. Although it is known that computer-forecast troughs and ridges suffer generally from slowness in west-to-east translation, very little quantitative work has been done on this subject. This paper summarizes some of the results of an analysis of errors in movement and development of 48-hour forecast 500-mb troughs and ridges (at 50°N from 110°W to 40°E) as forecast by the British 3-level 'vorticity' model (at the Meteorological Office, Bracknell) and the American 6-level primitive equation (PE) model (at the National Meteorological Center, Washington). The period of the analysis was June to November 1970.

Although the results reveal that there is little apparent significant difference in performance between the two models, the movement-error statistics do indicate a slight overall superiority of the 6-level PE model, more particularly over the North American and European continents. Differential biasing of the development errors by a mode of error dependent on the efficiency of the surface modelling obscures the issue in any direct comparison of the mean development errors, but by introducing a 'developmental efficiency' term, which is independent of the biasing, it can be shown that here again, the 6-level PE model is superior.

Glossary of symbols used and definitions.

Subscript T is used to refer to trough parameters.

Subscript R is used to refer to ridge parameters.

x = Horizontal west-to-east co-ordinate.

L = Longitude.

M = 48-h movement of trough/ridge axis at 50°N.

D = 48-h development in trough/ridge axis at 50°N (defined as the change in contour height at trough/ridge axis).

E_{ij} = Grid-point contour-height error (forecast minus observed contour height).

$(E_{ij})_s$ = Stationary mode component of E_{ij}.

E_m = Error in 48-h movement of trough/ridge axis at 50°N.

E_d = Error in 48-h development of trough/ridge axis at 50°N.

Δ = Development efficiency. $\Delta = \overline{E_d}(\text{AM}) - \overline{E_d}(\text{RE})$, where $\overline{E_d}(\text{AM})$ is mean development-error for amplifying systems and $\overline{E_d}(\text{RE})$ is mean development-error for relaxing systems.

$\overline{E_m}$, $\overline{E_d}$ etc. represent time-meaned quantities (usually 6-monthly means).

σ_m = Standard deviation of movement error.

MET = Abbreviation used to refer to the British 3-level model.

NMC = Abbreviation used to refer to the American 6- level model.

Introduction. Over the past 15 to 20 years, results of numerous investigations concerning verification of forecasts made by numerical weather prediction (NWP) models have clearly indicated that in all the models forecast troughs and ridges suffer typically from three main defects :

(a) *Slowness in evolution.* This defect is particularly evident in forecasts of 48 hours or more in situations where a local change from high to low zonal index (or vice versa) takes place. In such situations the numerical model will usually forecast adequately the change in type but will just as usually underestimate the rate of change of type.

(b) *Slowness in west-to-east translation.* In general the greater the phase speed of the system the 'slower' the numerical forecast (trough and ridge axes are moved eastward too slowly in the forecast). Slow-moving features or, more particularly, long-wave large-amplitude features do not normally suffer from this defect; in many cases the phase speed of such systems is overforecast.

(c) *Lack of amplitude.* This feature, which is more often associated with amplifying systems, is usually a direct consequence of the slowness in evolution ((a) above); the greater the rate of amplification the greater the amplitude error.

Mainly because of the largely subjective nature of the work involved, little has been done in the past to investigate quantitatively the slowness in eastward translation of individual forecast troughs and ridges. The majority of NWP verification reports have been restricted to the examination of monthly or seasonally meaned contour-height-error charts at various levels. Although useful in the diagnosis and (only occasionally) subsequent correction of some systematic errors, such investigations often prove to be of limited direct use to the human forecaster in his interpretation and modification of the daily computer product.

This report is mainly concerned with the errors in eastward translation (at 50°N latitude) of individual 48-hour forecast 500-mb troughs and ridges as computed by the British (Meteorological Office, Bracknell) and American (National Meteorological Center, Washington) operational NWP models. The British model is a 3-level 'filtered' vorticity model (Bushby and Whitelam[1]) and the American model is a 6-level primitive-equation model (Shuman and Hovermale[2]).

An investigation of errors in development of individual troughs and ridges is incorporated in this report which summarizes some of the results obtained over a period of 6 months from June to November 1970.

Summary of some previous verification results. The majority of verification reports on these two NWP models have been concerned mainly with subjective examination of monthly or seasonally meaned contour-height-error charts of which Figures 1 (a)–(d) are examples. They show mean observed 500-mb contour height and the associated mean 48-h prognostic error in the British 3-level (referred to as MET in this report) and the American 6-level (referred to as NMC) models for January and July of 1968. Seasonal variations in such error fields can be considerable, but certain features stand

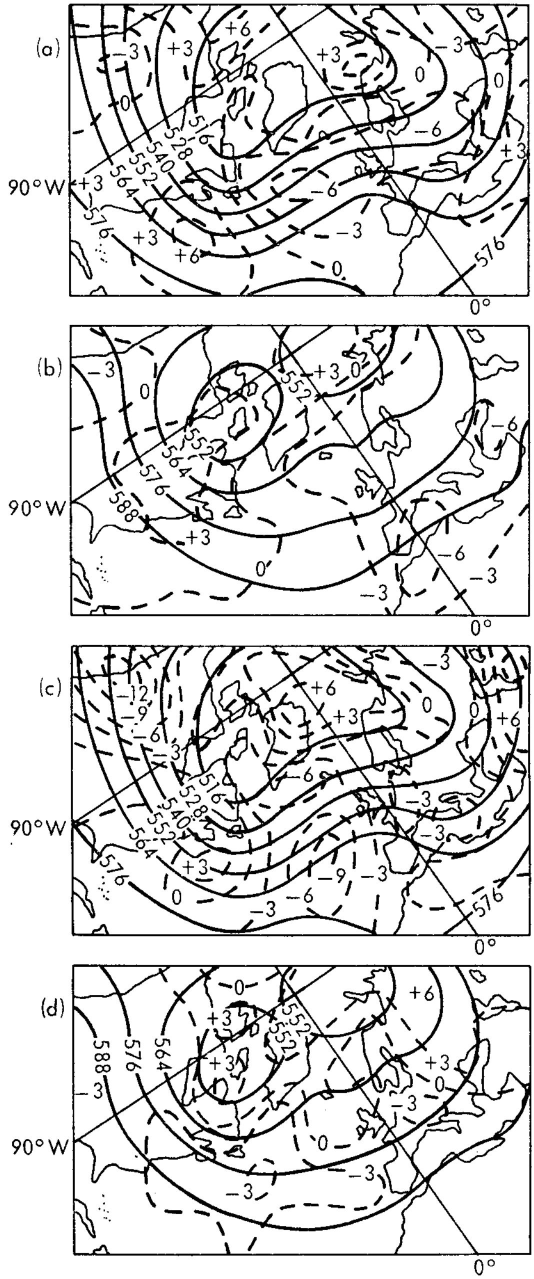

FIGURE 1—MEAN OBSERVED 500-MILLIBAR CONTOUR HEIGHT AND 48-HOUR PROGNOSTIC MEAN 500-MILLIBAR CONTOUR-HEIGHT ERROR

(a) Three-level (MET), January 1968. (b) Three-level (MET), July 1968.
(c) Six-level (NMC), January 1968. (d) Six-level (NMC), July 1968.
[(a) and (b) after R. M. Morris, 1970, (c) and (d) after J. F. Andrews.[4]]
Heights are in decametres. Error is forecast minus observed contour-height, in decametres.

out under subjective examination (Fawcett,[3] Andrews,[4] and an unpublished paper by R. M. Morris).

Basically the error fields can be regarded as a superposition of a number of modes of error. A stationary mode, $(\overline{E_{ij}})_S$, determined by the efficiency of the modelling at or near the surface boundary, is usually discernible by its apparent association with continental-scale variation in the nature of the surface boundary. Particular examples of this mode of error can be found by examination of a series of 48-h 500-mb mean-height-error charts; they can be recognized as features which are apparently independent of the local mean circulation type and appear to be solely dependent on the large-scale nature of the surface boundary. Similarly a non-stationary mode of error dependent on the local mean circulation type can be recognized; in 48-h forecasts (at 500 mb) negative contour-height errors tend to persist in mean ridges while positive errors dominate mean troughs (contour-height error is defined as the forecast minus the observed contour height). This circulation-dependent mode of error is usually more evident in MET than in NMC. In the latter the positive error associated with mean troughs tends to be situated farther to the north than it is in MET, usually to the north of the mean jet-stream, and in many cases negative error dominates the base of the mean trough. The magnitude of this type of error is normally simply dependent on the amplitude of the corresponding mean trough/ridge system; the greater the amplitude the greater is the magnitude of the error. In both MET and NMC much of the North Atlantic is dominated by negative stationary-mode error (which is normally considerably accentuated by the negative non-stationary-mode error associated with the existence of a local mean ridge). In MET this area of negative error extends eastward, increasing in magnitude to dominate the European continent and much of the Mediterranean. The magnitude of this type of error is normally greatest over the winter months and smallest over the summer months.

In some cases, where mean circulation types are strongly allied to particular areas at certain seasons of the year (so-called 'anchored' features) it is difficult to determine to what extent either of these two main modes of mean error is dominant. One classic example of such a case is the large area of positive contour-height error associated with the Canadian trough over the winter months (the areal extent and amplitude of this positive error in the Canadian trough are invariably substantially greater in MET than in NMC). In isolated areas adjustment to the modelling at and near the surface boundary can significantly reduce, if not eliminate entirely, the magnitude of the stationary-mode error; in September 1968 substantial adjustments to the modelling of the Rocky Mountains in NMC led to the virtual elimination of a large area of negative error which had previously dominated western Canada (Fawcett[3]).

The main limitation of this type of subjective examination of monthly meaned error fields is that it can give no indication of errors in movement or in amplitude of individual troughs and ridges. Hence, in addition to an investigation of movement errors, this report incorporates an analysis of development (or amplitude) errors in individual 48-h forecast troughs and ridges at 50°N (at the 500-mb level).

The data and analysis. The trough and ridge movement and development data (observed and forecast) were extracted from the following charts :

(a) 00 GMT 1:30 million 500-mb analysis (subjective, Central Forecasting Office, Bracknell),
(b) 00 GMT 1:30 million 500-mb 48-h forecast (MET),
(c) 00 GMT 1:30 million 500-mb 48-h forecast (NMC).

From June to November 1970, current data were collected for all wavelengths of troughs and ridges, except for very short-wavelength, low-amplitude, non-amplifying systems.

The position of a trough or ridge was taken as the point of intersection of its axis and the 50°N latitude circle; the contour height associated with the trough or ridge was taken as the contour height at this point. The observed 48-h movement, M, (to the nearest whole degree of longitude) and development, D, (to the nearest whole decametre) of troughs and ridges, and the corresponding movement and development errors, E_m and E_d, in the NWP models' forecast systems, are then directly obtainable.

The analysis was divided areally into three parts :

(a) area A 110°W–50°W (Rockies to Newfoundland)
(b) area B 50°W–00° (North Atlantic)
(c) area C 00° –40°E (western and central Europe).

The movement-error statistics were categorized in terms of the observed 48-h movement, M, of individual troughs and ridges. The five categories of M are :

(a) $M \leqslant 9$°L (including retrogressive systems)
(b) $10 \leqslant M \leqslant 19$°L
(c) $20 \leqslant M \leqslant 29$°L
(d) $30 \leqslant M \leqslant 39$°L
(e) $M \geqslant 40$°L.

Mean values of E_m and corresponding standard deviations, σ_m, are given for each M category (for each of the three areas) (Tables I, II, III and Figure 2(a), (b) and (c)). Table IV, showing movement-error frequencies, gives for the three areas A, B and C the percentages of troughs and ridges (of all values of M) with :

(a) $|E_m| < 5$°L (forecast movement correct to within 4°L)
(b) $E_m \leqslant -5$°L (forecast movement more than 4°L 'slow')
(c) $E_m \leqslant -11$°L (forecast movement more than 10°L 'slow')
(d) $E_m \geqslant +5$°L (forecast movement more than 4°L 'fast').

Development-error statistics for each of the three areas are subdivided into two main categories :

(a) Amplifying systems (AM)
(b) Relaxing systems (RE)
(Tables V, VI, VII).

Results are also given for the combination of all areas (Tables VIII, IX and Figure 2(d)).

In all the tables and figures the British 3-level vorticity model is referred to as MET, and the American 6-level PE model as NMC. These abbreviations are arbitrary and are used for ease of reference, they bear no other significance.

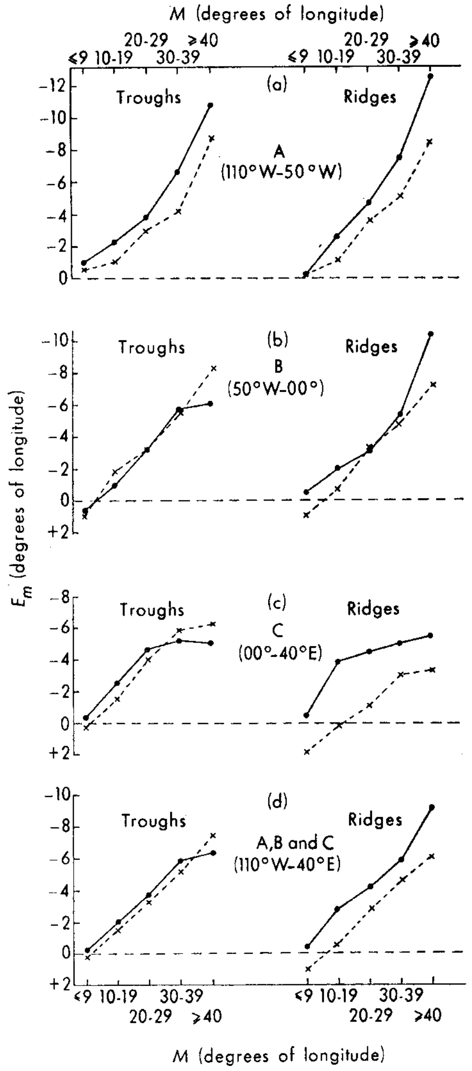

FIGURE 2—MEAN 48-HOUR MOVEMENT ERRORS, JUNE–NOVEMBER 1970

●——● British three-level model (MET). x - - - x American six-level model (NMC).

General discussion of results. The results for each area will be discussed separately but initially it may be useful to indicate in general terms the type and magnitude of movement and development errors that existed over the entire area of this analysis (110°W to 40°E).

The analysis confirmed that, in general, the greater the observed phase speed of the system, the 'slower' the corresponding forecast system (Tables VIII and IX and Figure 2(d)). For both MET and NMC models, mean movement-errors for forecast troughs vary from about 0°L (standard deviation $\approx$4°L) for the slowest-moving systems ($M_T \leqslant 9$°L) to about 10°L (standard deviation $\approx$7°L) for the fastest systems ($M_T \geqslant 40$°L). For ridges, mean movement-errors vary similarly with phase speed but NMC forecast ridges tend to be significantly less slow than corresponding MET ridges. The movement-error frequencies (Table IV) also indicate that, for trough movement, there is no significant difference between MET and NMC mean performance from 110°W to 40°E; for ridge movement the difference between MET and NMC is reflected in the percentages of ridges more than 4°L slow — these are 34 per cent for MET and significantly less, 23 per cent, for NMC.

Although the mean development-error statistics may serve as a general guide in any modification of the models' forecasts, useful discussion of these results is limited, particularly in a general context, by the biasing effect of the stationary-mode component of $\overline{E_{ij}}$ (i.e. $(\overline{E_{ij}})_s$) described earlier, especially since these $(\overline{E_{ij}})_s$ fields are not easily determinable. Rough estimates of the $(\overline{E_{ij}})_s$ values applicable to each area over the period June–November 1970 can be determined from the mean development-errors. These are :

	Area A	Area B	Area C
		decametres	
MET	+3·0	−1·5	−3·5
NMC	−1·0	−2·5	+0·5

One obvious general conclusion which can be drawn from the mean development-errors is that, in both models, amplifying troughs and relaxing ridges contain positive error (contour height overforecast) while relaxing troughs and amplifying ridges contain negative error (contour height underforecast).

As a simple method of bypassing the difficulty of not having more precise values of $(\overline{E_{ij}})_s$, the quantity Δ is introduced here as a measure of 'developmental efficiency' and is defined as :

$$\Delta = \overline{E_d}\,(\mathrm{AM}) - \overline{E_d}\,(\mathrm{RE})\,,$$

where $\overline{E_d}$ (AM) is the mean development-error for amplifying systems and $\overline{E_d}$ (RE) is that for relaxing systems. Δ is considered a reasonable measure of developmental efficiency since it is independent of the biasing effect of the $(\overline{E_{ij}})_s$ fields. If this stationary mode of error was the only one present in the models, then at any one position along 50°N both amplifying and relaxing systems would contain the same sign and magnitude of mean error (namely the mean stationary-mode error associated with that position) and Δ would be zero. In reality, however, the stationary-mode component is obviously not the only component of $\overline{E_{ij}}$; as already pointed out, positive error tends to occur in amplifying troughs and relaxing ridges and negative error in relaxing troughs and amplifying ridges. Δ is therefore invariably positive for troughs and negative for ridges, and the greater the magnitude of Δ the less efficient (developmentally) is the model. Table X lists values of Δ for each area; these figures are derived directly from values of $\overline{E_d}$ in Tables V, VI, VII and IX.

For the three areas A, B and C taken as a whole the values of Δ indicate an overall superiority of NMC in the handling of both trough and ridge development (i.e. development as defined in this context).

It is worth pointing out at this stage that just as the development-error statistics are biased by $(\overline{E_{ij}})_s$, so the movement-error statistics are subject to

TABLE I—MOVEMENT ERRORS, E_m, FOR AREA A (110°W–50°W), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	≤9	−1·0	3·6	−0·5	3·8	33
	10–19	−2·3	4·1	−1·0	4·2	61
	20–29	−3·8	4·3	−3·0	3·4	46
	30–39	−6·7	6·6	−4·2	5·6	19
	≥40	−10·8	*	−8·5	*	4
Ridges	≤9	−0·2	4·2	−0·2	3·9	41
	10–19	−2·6	5·3	−1·1	4·6	49
	20–29	−4·7	4·6	−3·4	3·6	44
	30–39	−7·5	2·8	−5·0	2·9	12
	≥40	−12·5	*	−8·5	*	4

* Sample too small for standard deviation to be significant.
An explanation of the symbols is given in the glossary.

TABLE II—MOVEMENT ERRORS, E_m, FOR AREA B (50°W–00°), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	≤9	+0·6	4·0	+0·9	3·6	48
	10–19	−1·1	3·9	−1·9	3·6	39
	20–29	−3·2	3·4	−3·2	3·5	42
	30–39	−5·8	4·3	−5·4	5·9	31
	≥40	−6·1	7·7	−8·1	9·1	20
Ridges	≤9	−0·5	4·2	+1·0	3·8	52
	10–19	−2·0	3·6	−0·7	3·6	48
	20–29	−3·0	3·0	−3·1	4·3	36
	30–39	−5·4	6·2	−4·8	5·3	25
	≥40	−10·5	*	−7·2	*	6

* Sample too small for standard deviation to be significant.
An explanation of the symbols is given in the glossary.

TABLE III—MOVEMENT ERRORS, E_m, FOR AREA C (00°–40°E), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	≤9	−0·4	3·1	+0·1	3·9	53
	10–19	−2·5	3·0	−1·7	4·0	42
	20–29	−4·7	3·7	−4·1	3·6	28
	30–39	−5·2	4·5	−5·8	3·8	14
	≥40	−5·0	2·9	−6·2	4·2	12
Ridges	≤9	−0·5	3·3	+1·9	3·4	63
	10–19	−3·9	3·5	+0·2	3·7	40
	20–29	−4·5	3·4	−1·0	3·8	24
	30–39	−5·0	*	−2·9	*	9
	≥40	−5·7	*	−3·3	*	6

* Sample too small for standard deviation to be significant.
An explanation of the symbols is given in the glossary.

bias by $\partial(\overline{E_{ij}})_s/\partial x$, the west-to-east gradient of the mean stationary-mode error along the 50°N latitude circle. If, for instance, a positive west-to-east gradient of $(\overline{E_{ij}})_s$ exists locally, axes of forecast troughs would be systematically displaced westwards and those of forecast ridges eastwards. Amounts by which the axes are displaced are normally insignificant for the majority of troughs and ridges and this aspect is discussed in a little more detail in the discussion of results for area C, where this effect is most marked.

Results for area A (110°W–50°W). Differences in performance between MET and NMC were more consistently marked in this area over the North American continent (at 50°N) than in either of the other two areas, B and C. Better handling (movement *and* development) of troughs and ridges by NMC was usually the case.

(a) *Movement errors* (Table I and Figure 2(a)). Although NMC mean movement-errors were consistently smaller in magnitude than those of MET, the most significant differences arose for systems with $M \geqslant 30$°L (mainly short-wave systems). By consideration of systems over the entire range of phase speeds, Table IV shows, for instance, that the percentage of forecast troughs which were more than 10°L slow (i.e. $E_m \leqslant -11$°L) was 2 for NMC and 9 for MET; the corresponding figures for ridges were 3 (NMC) and 8 (MET). The performance of MET in this area was noticeably worse than its performance in either of the other two areas; the opposite is true for the NMC, its performance here being slightly better than in the other areas.

(b) *Development errors* (Table V). Area A development errors in MET are positively biased by the extensive area of positive $(\overline{E_{ij}})_s$ usually associated with much of the North American continent downwind of the Rockies; in NMC the corresponding mean biasing-error is usually negative but of negligible magnitude. Values of the developmental efficiency, Δ (Table X), for this area indicate a marked superiority of NMC for both trough and ridge development.

Certain aspects of the superiority of NMC over MET in this area can probably be attributed to effects arising from the closer proximity of the western and southern lateral boundaries of the forecast area in MET and the greater efficiency of the Rockies modelling in NMC.

Results for area B (50°W–00°). In this area over the North Atlantic there were few significant differences in performance between the two models.

(a) *Movement errors* (Table II and Figure 2(b)). From the statistics obtained over this 6-month period MET forecasts appear to have had a slight edge over NMC forecasts for trough movement; for ridge movement this situation was reversed, NMC being slightly the better. It is interesting to note that the slowest-moving troughs (usually long-wave systems) have positive mean movement-error in both models' forecasts (i.e. forecast troughs 'fast').

The movement-error frequencies in Table IV illustrate the degree of similarity in the performance of the two models; the percentage of all forecast troughs with movement error more than 4°L slow (i.e.

TABLE IV—MOVEMENT-ERROR FREQUENCIES FOR THE THREE AREAS, JUNE–NOVEMBER 1970

Troughs/ridges with :			Area A (110°W–50°W)	Area B (50°W–00°)	Area C (00°–40°E)	All three areas
				per cent		
$\lvert E_m \rvert < 5$°L	Troughs	MET	64	63	70	65·5
		NMC	67	63	65	65
	Ridges	MET	50	59	71	60
		NMC	60	66	74	67
$E_m \leqslant -5$°L ('slow')	Troughs	MET	32	30	27	29·5
		NMC	27	31	31	29·5
	Ridges	MET	43	34	25	34
		NMC	30	26	13	23
$E_m \leqslant -11$°L ('very slow')	Troughs	MET	9	7	1·5	6
		NMC	2	9	3	5
	Ridges	MET	8	4	2	4·5
		NMC	3	3	nil	2
$E_m \geqslant +5$°L ('fast')	Troughs	MET	4	7	3	5
		NMC	6	6	4	5·5
	Ridges	MET	7	7	4	6
		NMC	10	8	13	10

TABLE V—DEVELOPMENT ERRORS, E_d, FOR AREA A (110°W–50°W), JUNE–NOVEMBER 1970

		Number sampled		$\overline{E_d}$	$E_d \geqslant +5$	$\lvert E_d \rvert < 5$	$E_d \leqslant -5$	$\lvert E_d \rvert \geqslant 11$ dam
				dam	Percentage of troughs/ridges with : *per cent*			
Troughs	MET	AM	106	+6·0	58	37	5	17
		RE	57	−0·1	23	61	16	
	NMC	AM	106	+1·6	31	56	13	12
		RE	57	−0·4	24	52	24	
Ridges	MET	AM	55	+0·9	17	76	7	9
		RE	95	+4·3	41	57	2	
	NMC	AM	55	−1·7	12	63	25	3
		RE	95	−1·1	14	67	19	

An explanation of the symbols is given in the glossary.

TABLE VI—DEVELOPMENT ERRORS, E_d, FOR AREA B (50°W–00°), JUNE–NOVEMBER 1970

		Number sampled		$\overline{E_d}$	$E_d \geqslant +5$	$\lvert E_d \rvert < 5$	$E_d \leqslant -5$	$\lvert E_d \rvert \geqslant 11$ dam
				dam	Percentage of troughs/ridges with : *per cent*			
Troughs	MET	AM	86	+3·5	35	60	5	15
		RE	96	−4·5	8	46	46	
	NMC	AM	86	+2·1	29	55	16	12
		RE	96	−2·8	11	49	40	
Ridges	MET	AM	78	−4·4	2	47	51	8
		RE	89	−1·4	12	65	23	
	NMC	AM	78	−5·2	nil	36	64	7
		RE	89	−2·7	5	57	38	

An explanation of the symbols is given in the glossary.

$E_m \leqslant -5°L$) were 30 for MET and 31 for NMC; the corresponding figures for ridges were 34 (MET) and 26 (NMC).

(b) *Development errors* (Table VI). As in area A, mean development-errors are directly biased by the mean stationary-mode error, $(\overline{E_{ij}})_s$, which is negative over much of the North Atlantic in both MET and NMC.

A comparison of the Δ values in Table X indicates again that NMC was the more efficient in the handling of trough development although this superiority was not as great as it was in area A. For ridge development this is the only area in which the Δ figures of MET compare favourably with those of NMC.

The fact that Δ values for this area over the North Atlantic exceed the corresponding values in both areas A and C (except in the case of MET ridges) is probably largely due to the greater development-rates usually associated with this area, particularly the western half, and the relative sparsity of observations contributing to greater uncertainty in the initial objective analyses. This latter characteristic of area B probably also explains the high degree of similarity in performance between the two models in that it is generally accepted that the performance of the simpler vorticity-type models usually compares very favourably (up to 48 hours) with that of the more sophisticated multi-level PE models in areas where initial data are sparse, particularly at the 500-mb level.

Results for area C (00°–40°E).

(a) *Movement errors* (Table III and Figure 2(c)). As in area B, there was little to choose between MET and NMC in the handling of trough movement in area C, the mean movement-errors for both ranging from about 0°L for the slowest-moving troughs to about 6°L for the fastest. The figures for ridge movement, however, showed a marked difference in handling between MET and NMC. Most of the discrepancy can be explained in terms of the local west-to-east gradients of $(\overline{E_{ij}})_s$ (i.e. $\partial(\overline{E_{ij}})_s/\partial x$). In NMC (for the period June–November) the mean stationary-mode error changes rapidly from negative to positive from about 10°W to 40°E($\partial(\overline{E_{ij}})_s/\partial x > 0$). In MET, by direct contrast, the gradient is negative. The overall effect of these contrasting gradients is a systematic westward displacement of MET forecast ridge axes with respect to their NMC counterparts; for forecast troughs the relative displacement is eastward. As mentioned earlier the magnitudes of such displacements would be small ($< 1°L$) in the majority of cases, but for broad troughs and ridges, and particularly for blocking ridges, it may exceed 3° or 4°L and would probably be of sufficient magnitude in the mean to account for a large part of the discrepancy between MET and NMC mean ridge-movement errors. For troughs the effect is reversed and MET forecast troughs would be expected to be less slow than their NMC counterparts. The fact that this is not evident may indicate an *intrinsic* superiority of NMC for both trough and ridge movement. In the hypothetical absence of the existing contrasts in $(\overline{E_{ij}})_s$ gradients in the two models, the performance of NMC would probably be consistently superior to that of MET for both trough and ridge movement.

TABLE VII—DEVELOPMENT ERRORS, E_d, FOR AREA C (00°–40°E), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	Percentage of troughs/ridges with: $E_d \geqslant +5$	$\|E_d\| < 5$	$E_d \leqslant -5$	$\|E_d\| \geqslant 11$ dam
				dam	*per cent*			
Troughs	MET	AM	79	−0·7	20	57	23	17
		RE	70	−5·0	2	48	50	
	NMC	AM	79	+1·4	35	43	22	9
		RE	70	−0·4	16	60	24	
Ridges	MET	AM	55	−5·6	nil	41	59	5
		RE	87	−2·0	7	67	26	
	NMC	AM	55	−0·3	15	68	17	6
		RE	87	+0·9	25	62	13	

An explanation of the symbols is given in the glossary.

TABLE VIII—MOVEMENT ERRORS, E_m, FOR THE THREE AREAS COMBINED (110°W–40°E), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	$\leqslant 9$	−0·2	3·6	+0·2	3·9	134
	10–19	−2·0	3·8	−1·5	4·0	142
	20–29	−3·8	3·9	−3·3	3·5	116
	30–39	−5·9	5·2	−5·1	5·5	64
	$\geqslant 40$	−6·3	6·7	−7·5	7·3	36
Ridges	$\leqslant 9$	−0·4	3·9	+1·0	3·8	156
	10–19	−2·8	4·3	−0·6	4·0	137
	20–29	−4·1	4·0	−2·7	4·0	104
	30–39	−5·9	5·3	−4·5	4·7	46
	$\geqslant 40$	−9·2	5·6	−6·1	5·2	16

TABLE IX—DEVELOPMENT ERRORS, E_d, FOR THE THREE AREAS COMBINED (110°W–40°E), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	Percentage of troughs/ridges with: $E_d \geqslant +5$	$\|E_d\| < 5$	$E_d \leqslant -5$	$\|E_d\| \geqslant 11$ dam
				dam	*per cent*			
Troughs	MET	AM	271	+3·1	39	51	10	16
		RE	223	−3·8	10	50	40	
	NMC	AM	271	+1·7	32	52	16	11
		RE	223	−1·4	16	53	31	
Ridges	MET	AM	271	−3·1	6	54	40	7
		RE	188	+0·4	21	62	17	
	NMC	AM	271	−1·9	9	54	37	5
		RE	188	−1·1	15	62	23	

TABLE X—DEVELOPMENTAL EFFICIENCY, Δ, FOR THE THREE AREAS

		Area A 110°W–50°W	Area B 50°W–00°	Area C 00°–40°E	All three areas
			decametres		
Troughs	MET	+6·1	+8·0	+4·3	+6·9
	NMC	+2·0	+4·9	+1·8	+3·1
Ridges	MET	−3·4	−3·0	−3·6	−3·5
	NMC	−0·6	−2·5	−1·2	−0·8

[$\Delta = \overline{E_d}$ (AM) $- \overline{E_d}$ (RE)]

In real terms, however, the slowest-moving ridges were better handled by MET ($\overline{E_m} = -0{\cdot}5°L$ for $M_R \leqslant 9°L$), the corresponding NMC-forecast ridges being too fast ($\overline{E_m} = +1{\cdot}9°L$). For all other ridges ($M_R \geqslant 10°L$) NMC performed much the better (by about 3°L in the mean). Percentages of forecast ridges with movement error greater than 4°L slow (Table IV) were 25 for MET and only 13 for NMC.

(b) *Development errors* (Table VII). The direct biasing by the mean stationary-mode error was again evident; for NMC $(\overline{E_{ij}})_s$ is small but positive in area C, and for MET it is negative and of appreciable magnitude. The direct biasing of this mode of error is illustrated in the mean development errors for this area where the most significant errors occurred in MET amplifying ridges where $\overline{E_d} \approx -6$ decametres compared with the NMC figure of $-0{\cdot}3$ decametres. The handling of ridge development by NMC was very good in this area particularly in cases where amplifying ridges evolved to form blocking highs. The local biasing conditions obviously favour NMC in amplifying-ridge cases since the negative non-stationary-mode error associated with amplifying ridges is usually balanced by positive $(\overline{E_{ij}})_s$ in NMC and accentuated by negative $(\overline{E_{ij}})_s$ in MET. In MET, 59 per cent of amplifying ridges were underforecast by more than 4 decametres compared with the corresponding NMC figure of only 17 per cent.

The Δ figures for area C (Table X) again illustrate the superior developmental efficiency of NMC for both troughs and ridges.

Conclusions. A slight overall intrinsic superiority of the 6-level PE model (NMC), both in movement and development, was evident in areas A (Rockies to Newfoundland) and C (western and central Europe).

In area A the intrinsic superiority of NMC was almost certainly considerably enhanced by superior Rockies modelling.

In area B there was little or no significant difference between the two models except in trough development (where NMC was better). The relative sparsity of initial data in this area makes the performance of the simpler 3-level vorticity model (MET) difficult to better.

In area C the modification of the apparent intrinsic superiority of NMC by the contrasting mean stationary-mode error fields and their west-to-east gradients was such that, in real terms, there was little to choose between the models for trough movement, while for ridge movement NMC was considerably less 'slow' than MET.

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GLIDER FLIGHT IN THE LOWER STRATOSPHERE ABOVE CUMULONIMBUS CLOUDS

By T. A. M. BRADBURY

Summary. On 9 May 1971 Mr Michael Field, flying an 18-m-span glider, climbed to nearly 8700 m in a cumulonimbus cloud between Swindon and Oxford. He then flew upwind of the cloud and climbed in wave lift to 12 960 m, about 4 km above the tropopause. Radar observations showed no sign of lee waves in the troposphere below 5 km and it appears that the high-level waves used by the glider were caused by the convective clouds extending up into a layer of strong winds near the tropopause.

Account of the flight. Mr Field, flying a Slingsby Skylark 4 glider, left Booker airfield, near High Wycombe, at 12 GMT on 9 May 1972 and was aero-towed upwind to an area clear of the airways radiating from London. At about 13 GMT he reached 11 520 ft (3511 m) in a large cumulus cloud and was then able to fly farther upwind to a large bank of cumulonimbus. He reached this cloud at Cricklade, about 5 miles ($\approx$8 km) north-north-west of Swindon, and, after penetrating some distance into cloud, located the region of upcurrents. This part of the climb began at about 3100 ft (945 m) and continued up to 28 520 ft (8693 m).

When the rate of climb decreased to zero and the cloud became lighter Mr Field steered west-south-west to reach clear air. The outside of the glider was by then covered with ice. Inside the cockpit the condensation had frozen, covering the canopy and instruments with hoar-frost. The artificial horizon had been kept clear by constant scraping of the glass but other instruments were obscured at this time and as a result the pilot at first misread his height as about 18 000 ft when in fact it was 28 000 ft.

The canopy ice prevented the pilot from observing just when clear air had been reached. The glider has clear-vision panels but the ice was too thick for these to be opened. As a result the pilot could not give any description of the appearance of the clouds, nor could he note his position in relation to them. This lack of visual observation is a severe handicap in analysing the remainder of the flight.

When the glider had descended to 26 000 ft (8077 m) it reached an area of smoothly rising air which the pilot recognized as wave lift. He then began a series of wide 'S' turns keeping to an average heading of west-south-west. This is a pattern of flight commonly used in wave soaring when the forward speed of the glider is greater than the horizontal wind speed. Since the air-speed indicator was not functioning then, the pilot trimmed the glider to a speed which seemed comfortably above the stall. At 30 000 ft the true air-speed is estimated to have been between 80 and 90 kt (40–45 m/s), which was much more than the environmental wind at that level.

At 36 000 ft (nearly 11 000 m) the pilot lost the area of lift and began a search to regain it. During this search he descended to 34 500 ft (about 10 500 m). At this level he experienced about a minute of severe 'cobblestone' turbulence. The true airspeed at this level was probably between 90 and 100 kt (45–50 m/s). When the turbulence ceased the glider entered strong lift. The rate of climb seemed rapid at first, but soon decreased to a slower rate than before. When the rate of climb became negligible the pilot abandoned the ascent at a height which was later confirmed as 42 520 ft (12 960 m) above sea level.

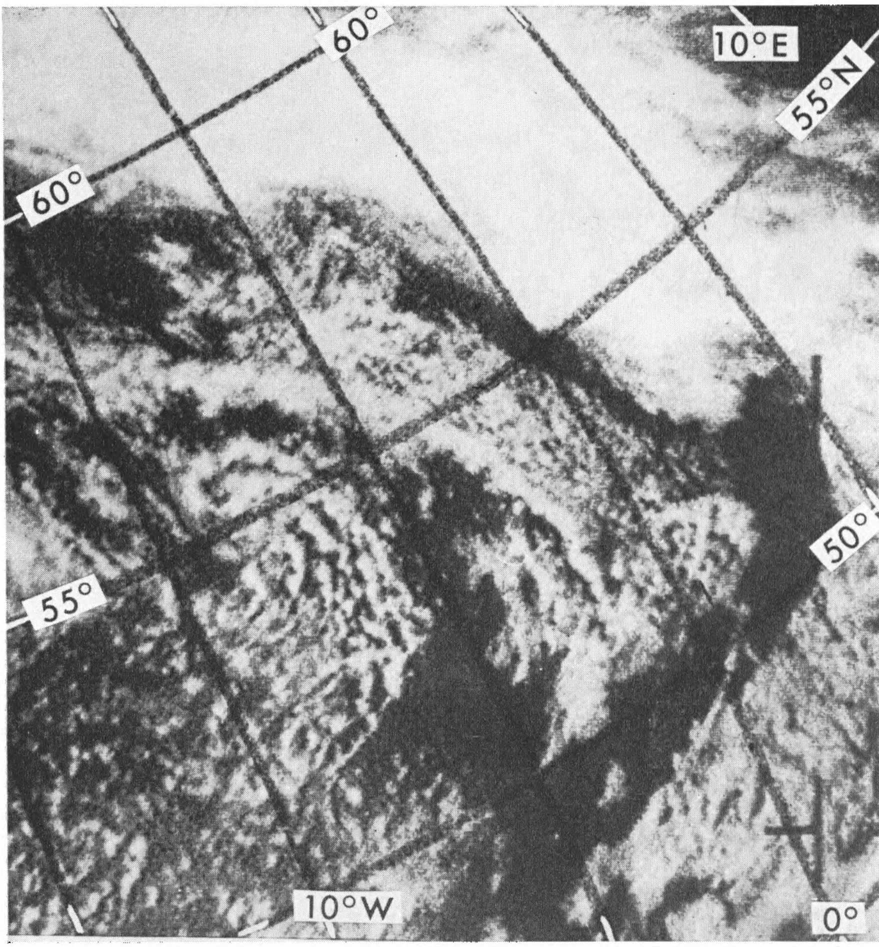

PLATE I—SATELLITE PHOTOGRAPH OF CLOUD PATTERN OVER THE BRITISH ISLES AT 12 GMT, 9 MAY 1972

See page 113.

Photograph by D. Tribble

PLATE II—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking north-west at approximately 1700 GMT. See page 120.

Photograph by D. Tribble

PLATE III—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking west at approximately 1730 GMT. See page 120.

Photograph by D. Tribble

PLATE IV—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking north-west at approximately 1730 GMT. See page 120.

During the descent, but while still above the freezing level, the tailplanes were twice struck by pieces of ice which, it is assumed, had broken away from the wings. The air-brakes were in use to increase the rate of descent and it may be that the buffeting and vibration they caused shook off some of the ice. The freezing level was about 4000 ft (1220 m) and consequently the ice did not clear completely before landing. Since the forward view was still too poor for the pilot to return to the airfield he made a landing in a field at the foot of the Chilterns several miles north-west of Booker.

Vertical currents encountered during the climb. The rates of climb achieved by the glider have been calculated from a copy of the barograph trace provided by Mr Field. The original trace shows only the pressure curve; heights and times have been superimposed after calibration (Figure 1).

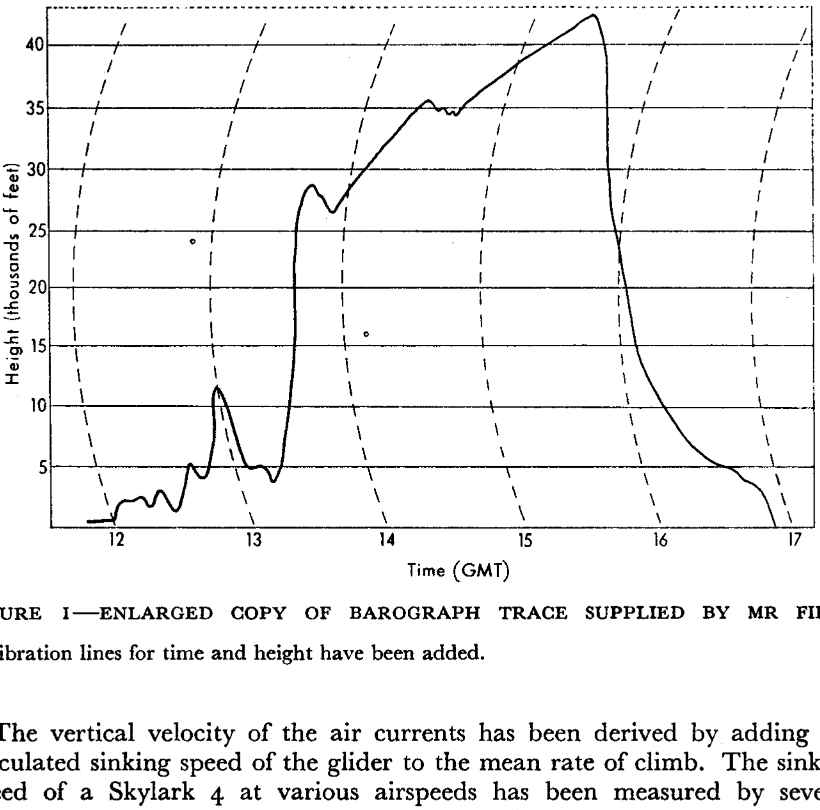

FIGURE 1—ENLARGED COPY OF BAROGRAPH TRACE SUPPLIED BY MR FIELD

Calibration lines for time and height have been added.

The vertical velocity of the air currents has been derived by adding the calculated sinking speed of the glider to the mean rate of climb. The sinking speed of a Skylark 4 at various airspeeds has been measured by several independent test groups in recent years and the curves show a satisfactory measure of agreement. Figure 2 shows the calculated sinking speed of a Skylark 4 flying straight, at an indicated airspeed of 55 kt, at altitudes from sea level up to about 55 000 ft. The full curve is for a glider in clean condition, the pecked curve is the result of adding 50 per cent to the sinking speed to allow for the effect of ice. Unfortunately there are no figures published for gliders in this condition. Various glider pilots were consulted and this estimate was thought to be reasonable. In view of the uncertainty no additional

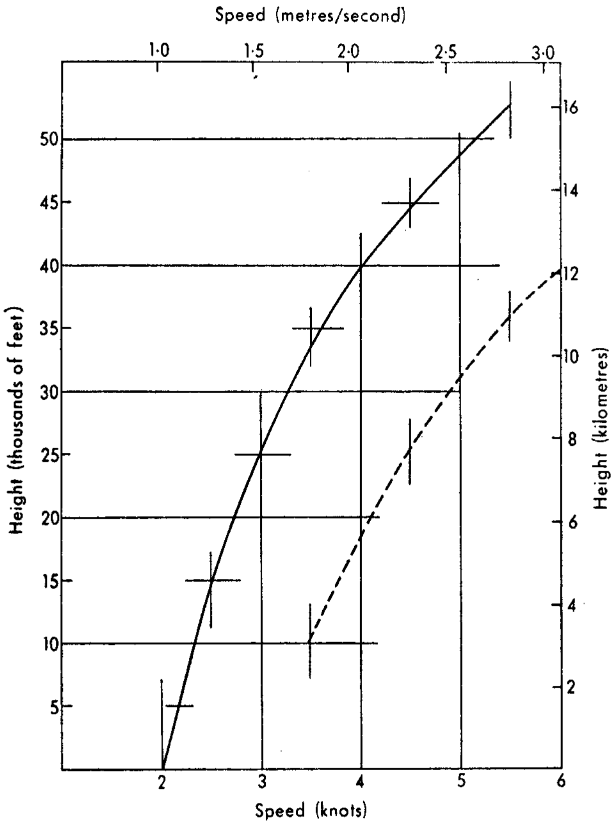

FIGURE 2—CALCULATED SINKING SPEED OF SKYLARK 4 GLIDER FLYING AT AN INDICATED AIRSPEED OF 55 KNOTS AT VARIOUS ALTITUDES

——— Glider in clean condition. — — — Estimated performance when ice had formed.

correction was made for the change of Reynolds number. It has been estimated that this would only amount to about 5 per cent decrease in glider performance at levels near the tropopause.

The average rate of climb for the ascent inside the cumulonimbus works out at about 9·5 kt, indicating vertical currents of at least 13 kt (6·5 m/s). However, the rate of climb was less than this at the beginning and end of the climb in cloud. Between the heights of 10 000 and 25 000 ft (3000 to 7600 m) the rate of climb was about 15 kt (7·5 m/s) suggesting upcurrents of at least 19 kt (9·5 m/s). These rates of climb are not remarkable for the size of cloud and suggest that the glider was not in the strongest lift.

In clear air the vertical currents were much weaker. From 26 000 to 36 000 ft (7925 to 10 970 m) the rate of climb averaged 3 kt (1·5 m/s). This probably represents a vertical current of about 8 kt (4 m/s).

The final part of the climb from 34 000 ft (10 360 m) to the top showed an average rate of ascent of 1·8 kt (0·9 m/s) but allowing for the greater rate of sink the vertical velocity of the air was probably again about 8 kt (4 m/s).

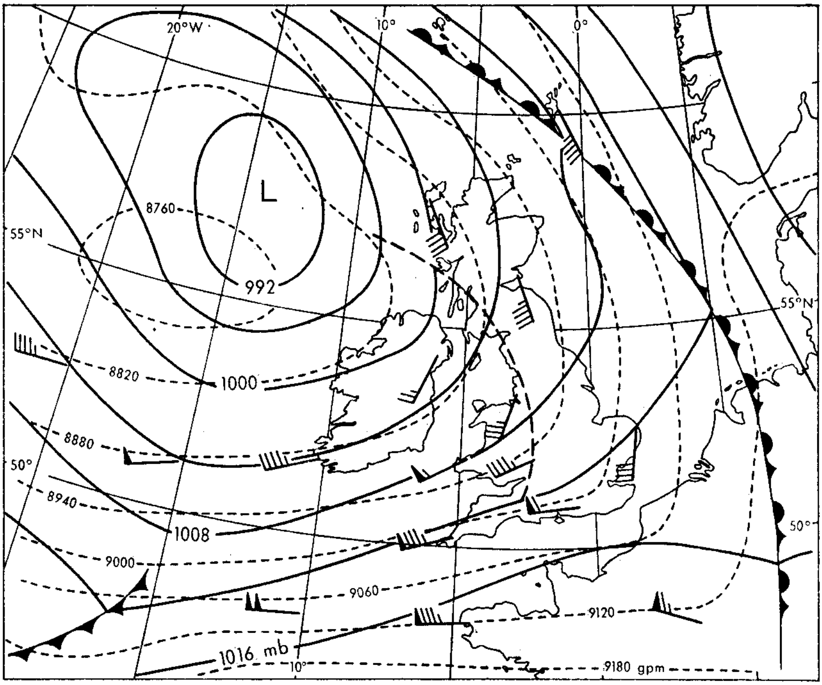

FIGURE 3—SURFACE CHART FOR 12 GMT, 9 MAY 1972, WITH 300-MILLIBAR CONTOURS AND WINDS ADDED

——— Surface isobars. - - - - 300-mb contours. — — — Line of shower cloud.

Meteorological conditions in the area of the flight. The midday chart (Figure 3) shows a depression west of the Hebrides with an unstable south-westerly airflow over England. Minor troughs were moving north-east across the country and one of these troughs produced a continuous line of shower cloud which may be seen in the satellite photograph (Plate I). Arrows showing the winds reported at 300 mb have been added to the surface chart to indicate the presence of a jet-stream which was extending towards Brittany. Figure 4 shows cross-sections of the upper winds along a line from Long Kesh in Northern Ireland to Camborne in Cornwall, and also from Long Kesh to Crawley in Sussex. These cross-sections are approximately at right angles to the wind, and show the edge of the jet-stream. The mean winds for the climb were estimated from these cross-sections.

Movement of shower clouds. The radar at the Meteorological Research Unit, Malvern, recorded the pattern and movement of numerous showers which occurred over the Midlands and southern England that afternoon. The long band of cloud shown on the satellite photograph appeared on the radar as a number of separate showers. The cloud mass visible over Devon and the Bristol Channel on the photograph was later tracked by radar. Its movement is shown in Figure 5. From the times given by Mr Field it appears that this was the cloud mass in which the glider began its big climb.

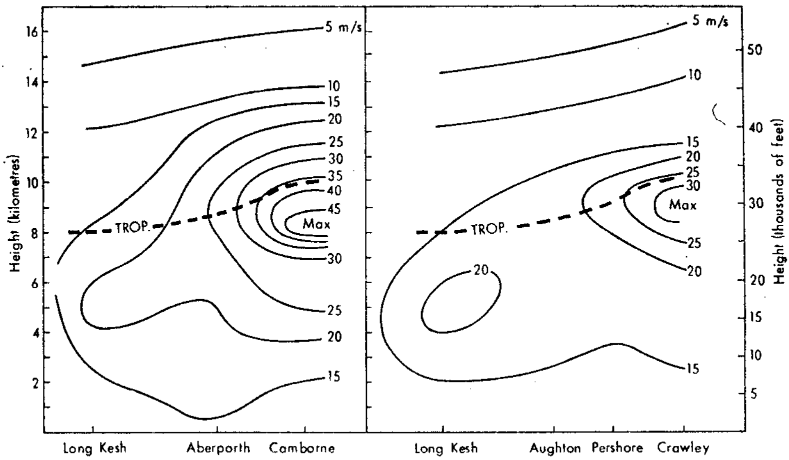

FIGURE 4—CROSS-SECTIONS OF WIND SPEEDS AT 12 GMT, 9 MAY 1972: LONG KESH TO CAMBORNE AND LONG KESH TO CRAWLEY

Aberporth winds are from the 11-GMT sounding and Pershore winds are from the 10-GMT sounding.

The pattern of cloud cells could be tracked for up to two hours and showed that the average speed was 24 kt ($\pm$ 2 kt) from a direction of 240°.

Vertical extent of cumulonimbus clouds. Although cloud tops had been measured by radar that morning there were no height readings for the afternoon and it was necessary to estimate the vertical extent. The height to which convective clouds can rise is partly dependent on their distribution;[1] large masses of cumulus are often found to extend higher than isolated clouds. The cloud mass in which the glider climbed formed part of a very active system several miles wide and about 70 miles ($\approx$113 km) long. The radar echoes photographed at Malvern were so strong that a number of cells could still be seen when the attenuation had been increased to 40 db. It seems likely that tops reached the tropopause which was between 28 000 and 30 000 ft ($\approx$8500–9100 m). Figure 6 shows the Aberporth 11-GMT radiosonde ascent which was the most representative sounding.

Vertical wind shear and 'thermal waves'. Figure 7 shows the vertical wind shear plotted in relation to the speed of the clouds together with the assumed airflow over the cumulonimbus in which the glider climbed.

It has been observed that cumulus containing powerful convective up-currents are able to rise through a layer of stronger winds aloft without experiencing the tilting or distortion of the clouds which occurs with weaker convection. When such a vigorous cumulus cloud extends into a faster-moving airstream aloft the upcurrents act as an obstruction to the horizontal flow aloft. Some of the surrounding air is probably entrained into the expanding cloud but the rest of the flow is deflected round or over the cloud.

Kuettner[2] suggests that for a vertical wind shear of 3 kt per 1000 ft (5 m/s per km) a glider may be able to ascend in clear air close to the upwind side of a cumulus at about 2 kt (1 m/s). The technique is very similar to that used for hill soaring.

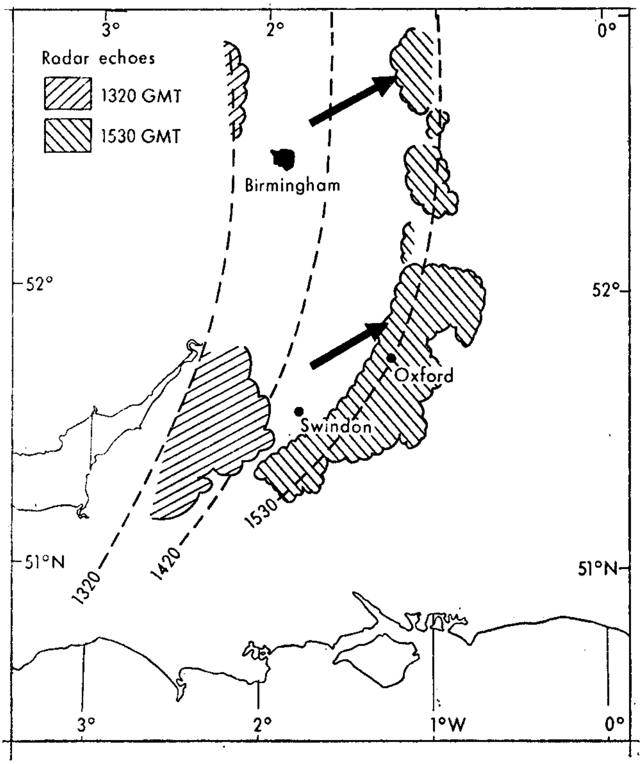

FIGURE 5—MOVEMENT OF CUMULONIMBUS BELT DURING THE PERIOD OF THE GLIDER'S CLIMB, AS SHOWN BY MALVERN RADAR

Hatching shows the eastern edge of the cloud echo at 1320 and the entire area of echo at 1530 GMT. Arrows show movement of echoes.

When the air between and over the cumulus clouds is relatively stable most of the flow is likely to be deflected round rather than over the clouds. This seems to be confirmed by the observations of glider pilots that it is rarely possible to climb much above the top of scattered cumulus. However, long lines or 'streets' of cumulus clouds appear to influence the airflow to greater heights. Jaeckisch[3] gives examples where cumulus formed long streets beneath an inversion with stable air above. The wind at cloud level was parallel to the cumulus streets but above the inversion the wind had a component at right angles to the streets. A wave-like flow was observed in the stable air aloft and gliders were able to climb several thousand feet above the cloud tops.

This wave-like flow over cumulus clouds has been termed 'thermal waves' or 'cumulus waves' to distinguish it from the orographically caused lee waves.

Thermal waves or lee waves? The conditions under which thermal waves can form are similar to those for the development of lee waves and it may be difficult to separate the two processes. There are many observations of the effect of lee waves on the distribution of convective clouds. These show

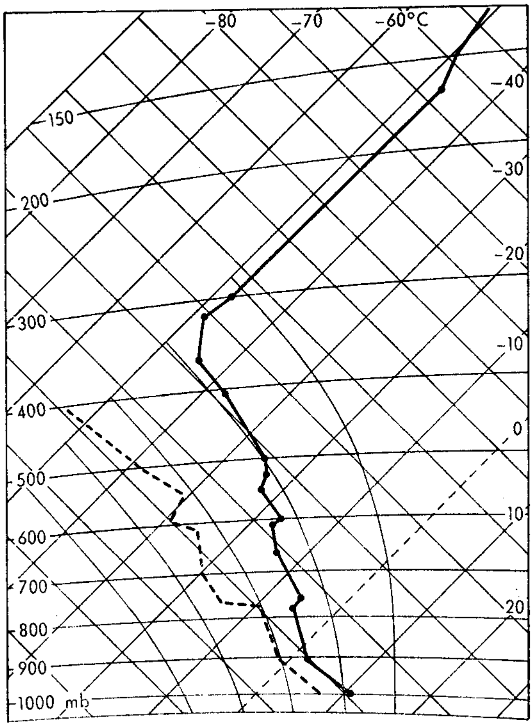

FIGURE 6—TEPHIGRAM OF THE ABERPORTH RADIOSONDE ASCENT AT 11 GMT, 9 MAY 1972

•——• Dry bulb. - - - - Dew-point.

that cumulus clouds are suppressed in wave troughs and enhanced under wave crests. There are at present relatively few observations of waves produced exclusively by the underlying thermal activity. However, Townsend[4] has shown that convective currents can produce wave motion in the stable layer above.

The great depth of instability on 9 May 1972 makes the development of lee waves seem unlikely. The possibility cannot be excluded for that reason alone because there are now a number of observations of large cumulus and even of cumulonimbus extending up through levels at which gliders were soaring in lee waves. These observations show that lee waves can occur in close proximity to large convective clouds. The likelihood of lee waves on this occasion can be ruled out by the report from Malvern.

The high-powered radar at Malvern is able to detect waves in the troposphere.[5] A few hours before the glider began its climb the Malvern radar had been scanning the sector upwind towards Wales. The range/height pictures showed more than one quasi-horizontal layer in the mid troposphere and if wave flow had occurred it should have been visible as an undulation in one of these layers. The radar records show the development of convective clouds, with one top reaching the 5-km level, but no sign of wave flow.

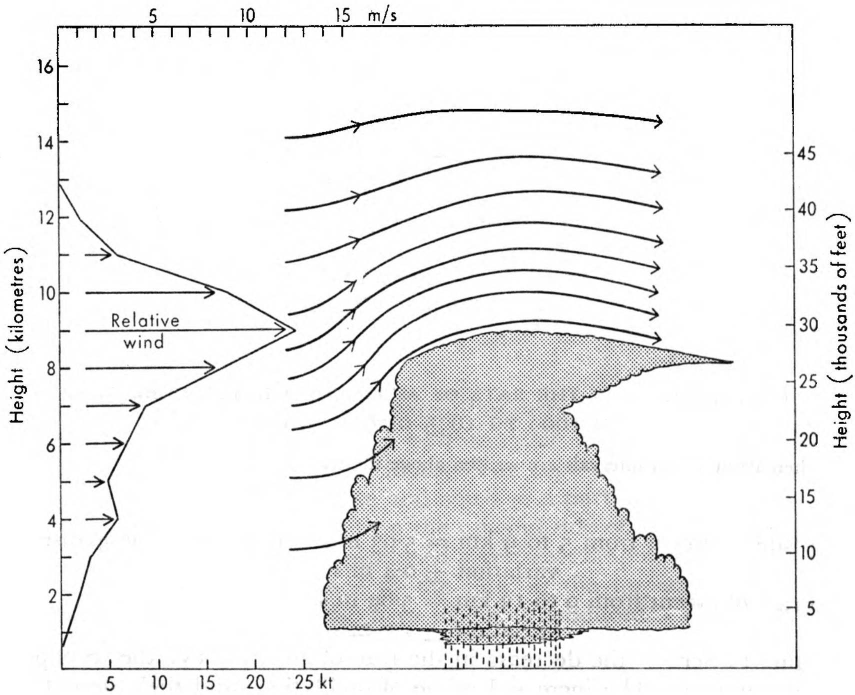

FIGURE 7—VERTICAL WIND SHEAR IN RELATION TO THE CUMULONIMBUS WITH ASSUMED PATTERN OF AIRFLOW OVER IT

Other gravity waves. Where jet streams exist the conditions of stability and vertical wind shear often favour the development of gravity waves. Kuettner[6] considered the possibility of such waves being used by a glider. Satellite photographs have revealed a number of examples of transverse waves on the long bands of jet-stream cirrus. Roach[7] has given examples of waves at high level far out over the Atlantic in regions where there was a strong upper flow ahead of a developing depression.

The situation on 9 May 1972 showed some similarity to the examples quoted by Roach. The Pershore 10-GMT radiosonde ascent was therefore examined to see if the balloon showed any periodic variations in the rate of ascent which might indicate wave motion.

Existence of high-level waves indicated by the balloon sounding. A radiosonde was launched from Pershore about two hours before the glider took off. The height of the balloon was measured at 20-s intervals and from these values the rate of ascent was plotted. Figure 8 shows the observed variations from about 5 km upward. Values below 5 km are not included here because it was considered that convective currents influenced the upward velocity.

In the diagram time is plotted on the *x*-axis and the rate of ascent is plotted on the *y*-axis. The actual heights at 4-min intervals are written above the curve. The results are summarized overleaf.

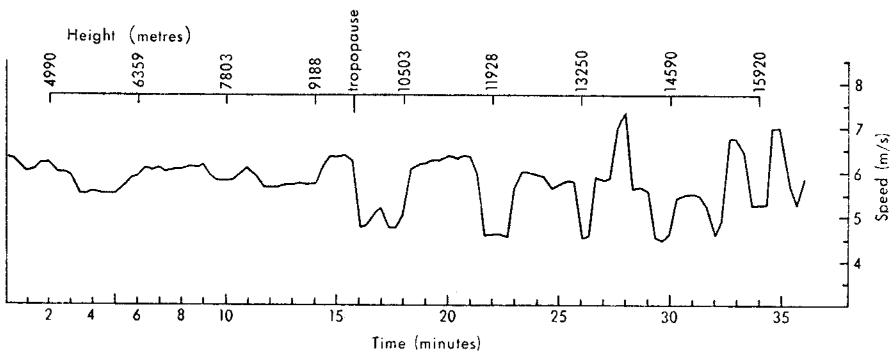

FIGURE 8—VARIATIONS IN THE RATE OF ASCENT OF THE PERSHORE RADIOSONDE FROM 1000 TO 1035 GMT, 9 MAY 1972

Actual heights at 4-min intervals are written above the trace.

Mean rate of ascent from 5 to 9 km = 5·93 m/s (below the tropopause)
variation $\pm$ 0·4 m/s
Mean rate of ascent from 9 to 13 km = 5·69 m/s
variation $\pm$ 1·0 m/s

According to Scrase[8] the decrease in the rate of ascent above the tropopause is not uncommon. The increased range of oscillations and their period may however be significant. The period of the first oscillation is about 320 s; subsequent periods grow shorter with increasing altitude.

These oscillations may represent weak waves in the lower stratosphere, but if so the associated vertical currents are very much weaker than those found by the glider a few hours later.

Stratospheric wave and the underlying cumulonimbus. While the glider was ascending in the lower stratosphere its average cross-country speed was not much less than the speed of the cumulonimbus beneath. It is probable that the two stages of the ascent above the tropopause used two different waves which moved in phase with the clouds beneath.

If it is assumed that the period of 320 s was close to the natural period of oscillation of the air just above the tropopause and the wave kept in phase with the cloud below moving at 24 kt (12 m/s) then the wavelength would be nearly 4 km.

Clear-air turbulence (CAT). It is not unusual to experience CAT close to areas of wave flow particularly if there is strong wind shear in the vertical. Radar studies[revealed that CAT developed when large-amplitude Kelvin–Helmholtz billows with wavelengths up to 4 km broke down.

The glider experienced about one minute of severe 'cobblestone' turbulence at about 34 500 ft ($\approx$10 500 m) after which the air was found to be rising rapidly. It seems possible that the glider flew through a breaking wave at this stage. The Richardson numbers, calculated for layers of depth 200 m and 400 m from the Pershore sounding a few hours earlier, showed no sign of the very low values of Ri normally associated with this class of turbulence. There were however no strong vertical currents when the balloon ascended into the lower stratosphere. The development of the strong upcurrents may have produced local concentrations of wind shear which did not exist at the time of the sounding.

A special investigation into CAT was being undertaken on this day and a large number of aircraft reports were available. There was only one report, from a large military jet aircraft, which coincided fairly closely in time and height with the glider observation. The jet flew from west to east at 35 000 ft just north of the area of the climb. No turbulence was observed there although light turbulence had been encountered during the climb through the tropopause farther west. This negative report, together with the fact that the glider only once encountered turbulence, suggests that the CAT was a very local phenomenon, probably associated with the altered airflow above the cumulonimbus.

Conclusions. A jet stream was extending eastwards over Brittany, and the strengthening upper winds on the northern side of this jet passed over an irregular line of cumulonimbus clouds. The tops of these clouds extended up to the base of the stratosphere and acted as a partial barrier to the strong upper winds. As a result the air on the upwind side of the clouds was forced to rise over the cloud tops and produced a vertical component of air of at least 8 kt (4 m/s). The disturbance to the flow in the upper troposphere also extended into the lower stratosphere where it produced a wave-like motion at least 4 km above the tropopause.

By flying out of the cumulonimbus cloud at high level and on the upwind side the glider entered a region of ascending air and was able to climb through the tropopause and well into the lower stratosphere.

This is the first report of such a phenomenon at high level but there have been a number of observations of similar phenomena on a smaller scale when cumulus developed in a vertical wind shear.

The turbulence encountered in clear air above the cumulonimbus cloud suggests a localized breakdown of the wave flow. This type of CAT may be a regular occurrence when wave flow develops over cumulonimbus clouds but if so it probably only affects small areas.

Acknowledgements. The thanks of the author are tendered to the staff of the Meteorological Research Unit at Malvern who provided a very large number of tracings from radar plan-position-indicator photographs, computed a radiosonde ascent of exceptional detail, and supplied a series of radar range/height-indicator photographs showing airflow over and to lee of the Welsh mountains.

The author is also grateful to Mr S. G. Cornford, Meteorological Office, Bracknell, who provided data from reports of CAT and to Dr J. P. Kuettner, World Meteorological Organization, for information on 'thermal waves'.

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AN EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

By E. N. LAWRENCE

Plates II, III and IV show an unusual display of cirrus cloud. The pictures were taken on 6 August 1954, south of Kitzbühel (approximately 47½°N, 12½°E) in the Austrian Tirol.

At the time, there was a pre-sunset sky of crimson red, particularly at the lower or lighter part of the sky, illuminated by the sun behind the silhouetted ridge in the photographs.

Surface charts show that the cirrus did extend well to the north-east and south-west of the Tirol however and its more general development was probably caused by ascending motion in the upper troposphere associated with the approaching trough at 300 mb (see Figure 1). The eastern edge of this band of cirrus is estimated to have cut latitude 50°N at longitude 5°–10°E at 18 GMT on 5 August and at 10°–15°E 24 hours later, when the eastern part of the band passed through or rather to the north-west of Kitzbühel.

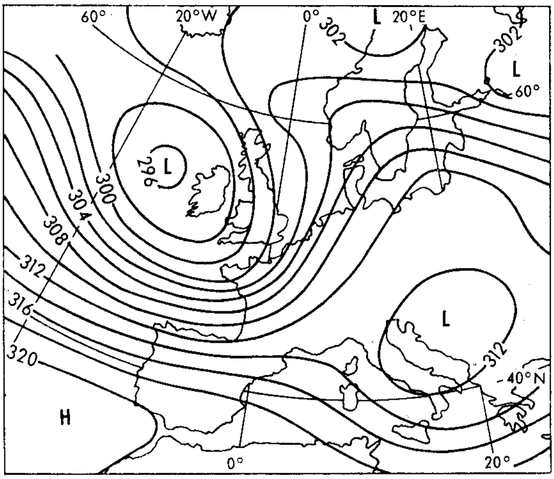

FIGURE 1—CONTOUR CHART OF THE 300 MILLIBAR SURFACE AT ABOUT 15 GMT, 6 AUGUST 1954

Contours at 200-ft intervals

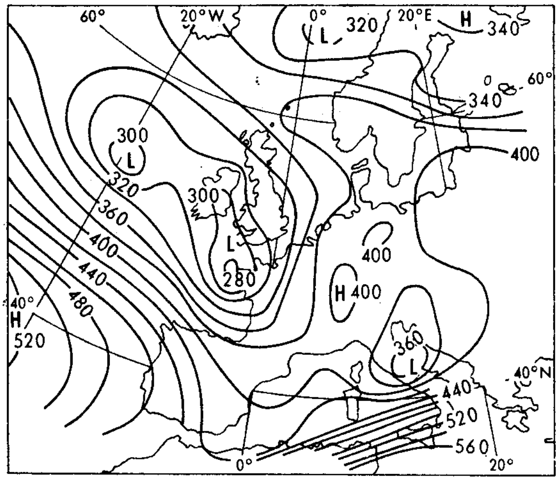

FIGURE 2—CONTOUR CHART OF TROPOPAUSE HEIGHT AT ABOUT 15 GMT, 6 AUGUST 1954

Contours at 2000-ft intervals, values are in hundreds of feet.

Weak pressure gradients rather eliminate the possibility of orographic cirrus but the 'isolated' shower in the region on the previous day suggests the possibility of some residual cirrus.

A striking feature of the upper-air patterns was the strong south-westerly gradient (about 1 in 50 over 150 miles (≈240 km)) of the contour lines of the height of the tropopause over northern Italy and the northern Adriatic Sea at 15 GMT on the 5th. By 15 GMT on the 6th this gradient had moved south to Tunisia, Sicily and southern Italy, leaving a high cell centred at 48°N, 8°E (see Figure 2).

REVIEWS

Profiles of wind, temperature, and humidity over the Arabian Sea, by F. I. Badgley, C. A. Paulson and M. Miyake. 282 mm × 222 mm, pp. 62, *illus.*, University of Hawaii Press, 535 Ward Avenue, Honolulu, Hawaii 96814, 1972. Price: $7.50.

This volume has two parts, the first describing and presenting the observations and the second analysing them. The measurements were made in late February and early March 1964 at locations around 19°N 72°E, 20°N 69½°E, and 20½°N 71½°E, in the Arabian Sea. The equipment used consists of a stabilized floating carrier known as 'Mentor' which supports an 8·5-m mast and which, in use, is kept well upwind of the tending ship by means of a sea-anchor. The instrumented boom projects into wind and is mounted on a carriage which runs up and down the mast, stopping at six selected levels for sampling times of about 15 seconds each. A complete sequence of measurements takes about 2 minutes and was repeated as often as possible during each test run of about 40 minutes, the outputs (wind speed, air temperature and wet-bulb depression) being recorded on magnetic tape. Checked data from 118 test runs, consisting of mean values for six levels between 114 and 815 cm of wind speed, temperature and specific humidity, are presented. Also included are wind direction and sea surface temperature during each run and SHIP and PILOT SHIP observations made from the escorting ship at main synoptic hours on the days on which profiles were measured.

In Part 2 an analysis is carried out of 110 sets of data, the other 8 being excluded because fetches were less than 50 km. Possible errors in the measurements are first considered in some detail. It is shown that errors due to buoy motion, to study which special measurements were made of pitch, roll and vertical acceleration, could be safely ignored. Interference due to the buoy pontoons is believed to have caused anomalous (low) wind speeds at the lowest sampling level but it is concluded that the resulting errors in computing friction velocities from the profiles could be neglected. The main uncertainty arose from sampling error, each level being sampled for only about one-eighth of the time, and this is discussed at some length. It was minimized by comparing the readings of the travelling probe with those from a fixed probe at the 4-m level and by adjusting the raw data accordingly. The standard deviations of the differences between the readings at the 4-m level indicated sampling errors of about 1·3 per cent in wind speed, 0·012 degC in temperature and 0·04 degC in wet-bulb temperature. Wave-generation theories predict that profiles over water should be different from those over solid surfaces, at least in the lower layers. To test this, 21 selected wind and humidity profiles, restricted to the higher speeds and near-neutral conditions, were combined but there were no major peculiarities in the mean profiles which could be attributed to wave-generation processes. Such effects could of course have been present below the lowest sampling level or might become more apparent at higher wind speeds than those encountered, all of which were below 9 m/s. Computed fluxes of momentum, heat and water vapour are tabulated for each run. The observations are shown to be well represented by the Businger–Dyer model for unstable conditions and by the log-linear equation for stable conditions; the profiles are thus indistinguishable from those measured over land. A drag coefficient of about 0·0014 for wind speeds in the range 2–8 m/s, but increasing slowly with increasing wind speed, is indicated. Finally, comparisons of the computed water-vapour fluxes, on some occasions with areal evaporation estimates based on simultaneous observations from aircraft, show reasonably good agreement. As the authors themselves remark, observations at higher wind speeds would be very desirable in future measurements of this type.

The work is the sixth in the series of International Indian Ocean Expedition meteorological monographs and maintains their high standard of presentation. A few minor errors were noted, however, the most important being that Figure 9 is printed over the caption for Figure 8 and vice versa.

H. C. SHELLARD

Geography from space, by E. C. Barrett. 290 mm × 210 mm, pp. 98, *illus.*, Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, 1972. Price: 95p.

The outstanding feature of this book is the extremely high quality of the many coloured photographs, mostly taken from satellites. They may be awe-inspiring, as the view of the Earth from the Moon (Plate 1.1) and of the Kashmir Himalayas from GEMINI V (Plate 17.11); or strikingly informative, as the GEMINI IV view of the Nile delta (Plate 7.1); or of tranquil beauty, as the conventional photograph of convective cloud off the coast of southern Queensland, Australia (Plate 11.2).

The title of the book is rather misleading, the subtitle 'modern readings in physical geography' being a better description of the contents. Approximately half of the book is concerned with weather and climate (including hurricanes and the south Asian monsoon) and there are also chapters devoted to ocean currents, the Nile delta, structure of coasts, the polar regions, regions of high relief, patterns of erosion, and the use of land. Every chapter is illustrated by one or more excellent satellite photographs including examples of varicoloured maps (made with an infra-red radiometer) of the sea surface temperature in the vicinity of the Gulf Stream (Plate 11.1), and of different types of land surface such as forest, farmlands and rivers (Plates 19.1, 19.2, 19.3).

The text is clearly written and is interspersed with stimulating questions for the benefit of geography students, but even though the treatment of the meteorological sections is elementary, the author could have improved on the definition of isobars on weather maps (page 18) and of advection (page 72). Also in explaining the formation of rain (page 8) he mentions only the coalescence mechanism.

The book is recommended as an introduction to the study of weather and climate from a modern 'space-age' standpoint.

F. E. LUMB

NOTES AND NEWS

History of Eskdalemuir Observatory

The Superintendent, Eskdalemuir, who is bringing up to date a history of the Observatory, has asked if there are any pre-war Eskdalemuir staff still in the Office who might have interesting photographs (including pictures of themselves) taken at that time.

There may also be a number of retired members who served at the Observatory and who still receive the *Meteorological Magazine*. The Superintendent would like to obtain copies of any pictures not already available to him and, of course, he would arrange the copying.

Readers having suitable photographs are invited to get in touch with Mr P. R. Robinson, Superintendent, The Observatory, Eskdalemuir, Langholm, Dumfriesshire PG13 0QW.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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VISIT TO THE METEOROLOGICAL OFFICE BY H.R.H. THE DUKE OF EDINBURGH

On the afternoon of 16 February 1973, the Meteorological Office was honoured by a visit from His Royal Highness the Duke of Edinburgh, K.G., K.T., O.M., F.R.S., who came to see something of the operational work in the new Richardson Wing of the Headquarters building.

His Royal Highness was greeted on arrival at the entrance of the FitzRoy Wing by Dr B. J. Mason, the Director-General, and Mr Ian Gilmour, M.P., Minister of State for Defence. His Royal Highness then proceeded to the Director-General's office where he was introduced to Mr J. M. Wilson, Permanent Under Secretary (Administration) in the Ministry of Defence, Mr P. J. Meade, Director of Services, Mr J. S. Sawyer, Director of Research, and Mr H. E. Davies, Secretary of the Meteorological Office, and he was then invited to sign the Visitors' Book.

After a brief talk by the Director-General on the work of the Office, His Royal Highness was escorted round the Richardson Wing. In the Central Forecasting Office he showed a deep and detailed interest in the techniques used for producing the daily forecast and, in particular, the way in which the computer products are used. He was shown an impressive selection of satellite photographs, the development of several heavy showers on the radar display, and ships being routed across both the Atlantic and Pacific Oceans. In the Telecommunication Centre, His Royal Highness showed considerable interest in the methods by which meteorological data are collected and disseminated both by the teleprinter network and the facsimile system and was shown the computer-controlled message-switching system, linking Bracknell with Washington, Paris and Offenbach, that had become operational only a few days before. In the Computing Laboratory he saw part of an operational forecasting suite being run on the IBM 360/195 computer and was particularly interested in the automatic production of charts on the high-speed line-printer and cathode-ray-tube plotter.

His Royal Highness then returned to the Director-General's office where he took tea with the guests and senior members of the staff and initiated a very lively discussion with Dr Mason and Mr Sawyer on the possible influences of man-made activities on weather and climate. He appeared thoroughly to enjoy his visit which lasted for about two hours, showed a real interest in and understanding of what he saw, and spoke to several members of the staff during his tour.

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MONTHLY MEAN WIND PATTERNS AT 40 000 FEET OVER AUSTRALIA

By T. R. HEALY
School of Geography, University of New South Wales, Australia.

Summary. Processing of the most comprehensive set of data yet available for the Australian region led to the compilation of new monthly mean vector-wind charts for 40 000 feet. Inspection of the charts gives rise to the inference of a preferred location or quasi-permanent trough in the upper-tropospheric westerlies centred about 150°E over eastern Australia. A complementary mean ridge was found to be present over central Australia at about 125°E. The amplitude of the mean trough–ridge system was between 4° and 8° of latitude.

Introduction. Preliminary upper-tropospheric monthly mean wind statistics for the Australian region were derived by Phillpot,[1] Gabites and Porter,[2] and Phillpot and Reid[3] in the early 1950s. Later, in response to the demand for upper-wind information upon the introduction of high-flying jet aircraft, Phillpot,[4] using data collected to 1956, analysed the wind fields at all levels to 60 000 ft.* Unfortunately the resulting charts were constructed from data which were inhomogeneous both in time and in method of observation and were thus considered 'provisional'. Accordingly, for this study it was decided to construct new vector mean wind charts in order to take advantage of both the increased data network and the enlarged time span of homogeneous observations. These charts are expected to show with greater precision the monthly patterns of vector mean wind flow and the behaviour of the maximum westerlies and Australian subtropical jet stream (STJ) as depicted by monthly mean upper-wind flow. Because upper winds over Australia are measured at fixed altitudes, the level chosen for analysis was 40 000 ft, this being the closest to 200 mb and the recognized level of the upper-tropospheric maximum westerlies.[5]

Data network. Most of the stations selected supposedly possessed an unbroken set of records for the 12-year period 1956–67, although some stations had been in continuous operation for only the 6-year period 1962–67. Unfortunately the method of wind finding varied at a number of stations during these periods because of the introduction of new wind-finding radars.

Distribution of the upper-wind stations used in this study is illustrated in Figure 1. Distribution shows a bias of concentration in the eastern zone (east of 145°E) which possesses 26 of the 53 stations. The central zone (125°–145°E) contains 16 stations while the western zone contains only 11 stations. Oceanic stations are few, and this study suffers — as have all to date — from the acute lack of observations over the Indian and Antarctic Oceans. Nevertheless, the upper-wind network used here is the densest of any study so far attempted for this region (cf. Phillpot:[4] 21 stations). Of the 53 upper-wind stations used (including the 5 New Zealand stations and Nandi, Fiji) 31 were pilot-balloon theodolite stations in 1956. Throughout the period under consideration the number of stations using visual methods of upper-wind recording steadily decreased until in December 1967 only 14 remained, whereas the number of radar-wind stations increased from 16 in 1956 to 39 by 1968.

* 1000 ft ≈ 300 m.

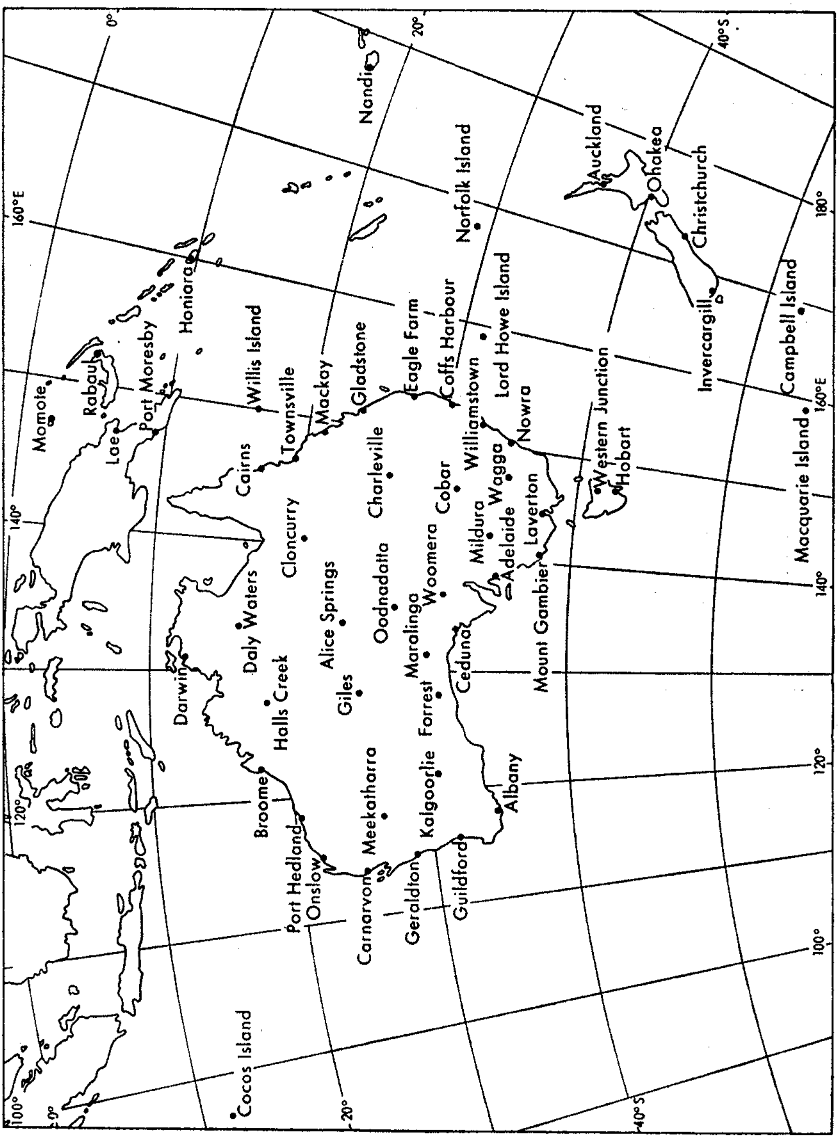


FIGURE 1—DISTRIBUTION OF UPPER-WIND STATIONS IN THE AUSTRALIAN REGION

Data source. All upper-wind observations made by the Commonwealth Bureau of Meteorology are stored on punch-cards.[6] Wind observations at fixed heights for each station are extracted from the original wind sounding. Direction and magnitude are recorded in units of 10 degrees and knots respectively. These data, for the years 1956–67, were obtained from the Bureau of Meteorology in the form of card images on magnetic tape.

Problems in the analysis. A number of problems arose in the analysis of the raw data supplied by the Bureau of Meteorology. These principally related to the checking and homogeneity of the data, and they were solved as follows:

(a) Checking of the raw data for embedded blanks, incorrect punching and illegal characters was carried out within the Bureau of Meteorology. However there is no safeguard against mistakes in the original wind observations. The complete set of original observations were not checked in detail although random checks of two flights per month per station are made, prior to punching, in the Weather Statistics section of the Bureau of Meteorology. A number of checks for correct data were incorporated in the program (e.g. correct card, times of flight, etc.) but no curve-fitting or smoothing of individual upper-wind soundings was included.

(b) Although it was originally proposed to utilize a homogeneous set of records complete for 12 years for 56 upper-wind stations, this proved impracticable. A number of stations were converted from pilot-balloon to radar methods of measurement during that period, and truly reliable wind records thus date from that event. Frequently pilot-balloon observations reaching 40 000 ft were too few per month to consider for inclusion in computation of the statistics. Thus the aim of obtaining a long period of homogeneous upper-wind records was to a certain extent frustrated.

(c) Although some stations (e.g. Laverton) undertake four flights per day, for standardization and to reduce serial correlation only the 23-GMT observations have been utilized for this study.

(d) The problem of the influence of diurnal variation in wind flow, which can be detected in the vector means up to levels of about 10 000 ft,[4] is not considered significant at 40 000 ft and was disregarded in this study.

(e) The final charts are not completely objective in that a certain amount of smoothing of the isotachs was necessary to allow for disparate values of adjacent stations, arising as a function of the wind-measuring device.

(f) Sources of errors in upper-wind observations, and assessment of the reliability of Australian data, are discussed in detail by Spillane.[7]

New Zealand stations and Fiji. Statistics for the New Zealand stations (Campbell Island, Invercargill, Christchurch, Ohakea and Auckland) and Nandi, Fiji, were extracted directly from de Lisle.[8] All statistics for these stations were based on 10–12 years of observations made by wind-finding radar. Although normally four flights per day are made, the statistics presented are also computed from the 00-GMT observations only, in order to decrease serial correlation. Otherwise, treatment of the data is the same as that outlined by Maher and McRae.[9]

Construction of the charts. The monthly vector mean wind and standard vector deviation were calculated for each station on the CDC 3200 and Burroughs B 5500 computers at the Monash University Computer Centre. Unless the number of observations at 40 000 ft for each station exceeded 10, that month was excluded from the computation. The vector mean winds and standard vector deviations for most of the stations have been plotted on the 12 charts constituting Figure 2 and the remainder are presented in Table I. Although the original aim was to base these upper-wind statistics on 6–12 years of continuous records this was not always possible. Choice of stations was restricted to those at which at least 3 years of observations contributed to the computations, as suggested by Phillpot.[4]

On the charts isotachs have been drawn. As with Phillpot's charts[4] some smoothing was inevitable so that the mean flow patterns resulting are somewhat subjective. For this reason, the analysis has been confined to the areas with a relatively high density of upper-wind stations. Little attempt has been made to interpolate over the data-sparse regions.

On most charts it was possible to locate an isotach maximum (of jet-stream strength) for the months April–November. The axis of the upper-tropospheric mean maximum westerlies is also indicated.

TABLE I—VECTOR MEAN WINDS AND STANDARD VECTOR DEVIATIONS AT 40 000 FEET OVER THE AUSTRALIAN REGION: STATION DATA OMITTED FROM THE CHARTS OF FIGURE 2 BECAUSE OF SPACE LIMITATIONS

	Port Hedland		Onslow		Meeka-tharra		Maralinga		Ceduna		Woomera	
	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*
January					264/34	30					244/33	36
February					266/33	32	251/37	33			247/37	34
March							254/41	39	252/34	40		
April	269/45	31					262/57	40			259/51	39
May			254/53	41			264/56	43			262/61	49
June							262/74	47			262/80	50
July			268/57	32			268/87	44			264/95	47
August							259/95	46			259/95	44
September							260/76	42			263/75	42
October					269/73	42	262/73	40			260/69	43
November							267/53	38				
December							257/46	34			258/46	36

	Mildura		Laverton		Mount Gambier		Coffs Harbour		Townsville		Mackay	
	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*	Wind *deg kt*	σ *kt*
January	249/37	39	262/39	44			262/35	39			272/30	31
February	253/36	39	258/39	43			269/37	46	272/17	28		
March	253/45	41	259/39	42			266/40	40			272/35	31
April	252/34	37	264/36	37			272/50	38			278/55	29
May	260/47	45	262/42	40			266/56	42			272/71	40
June	264/59	43	263/43	38			270/76	56	272/55	37		
July	262/80	43	264/53	39					272/51	30		
August	262/74	45	262/51	37					269/50	32		
September	262/65	44	264/49	39			263/79	42	272/48	33		
October	264/53	41	265/46	38					271/49	30		
November	258/49	36			264/53	40	261/48	41	268/47	31		
December	257/40	40	264/40	41			264/46	37	268/39	28		

σ = Standard vector deviation.

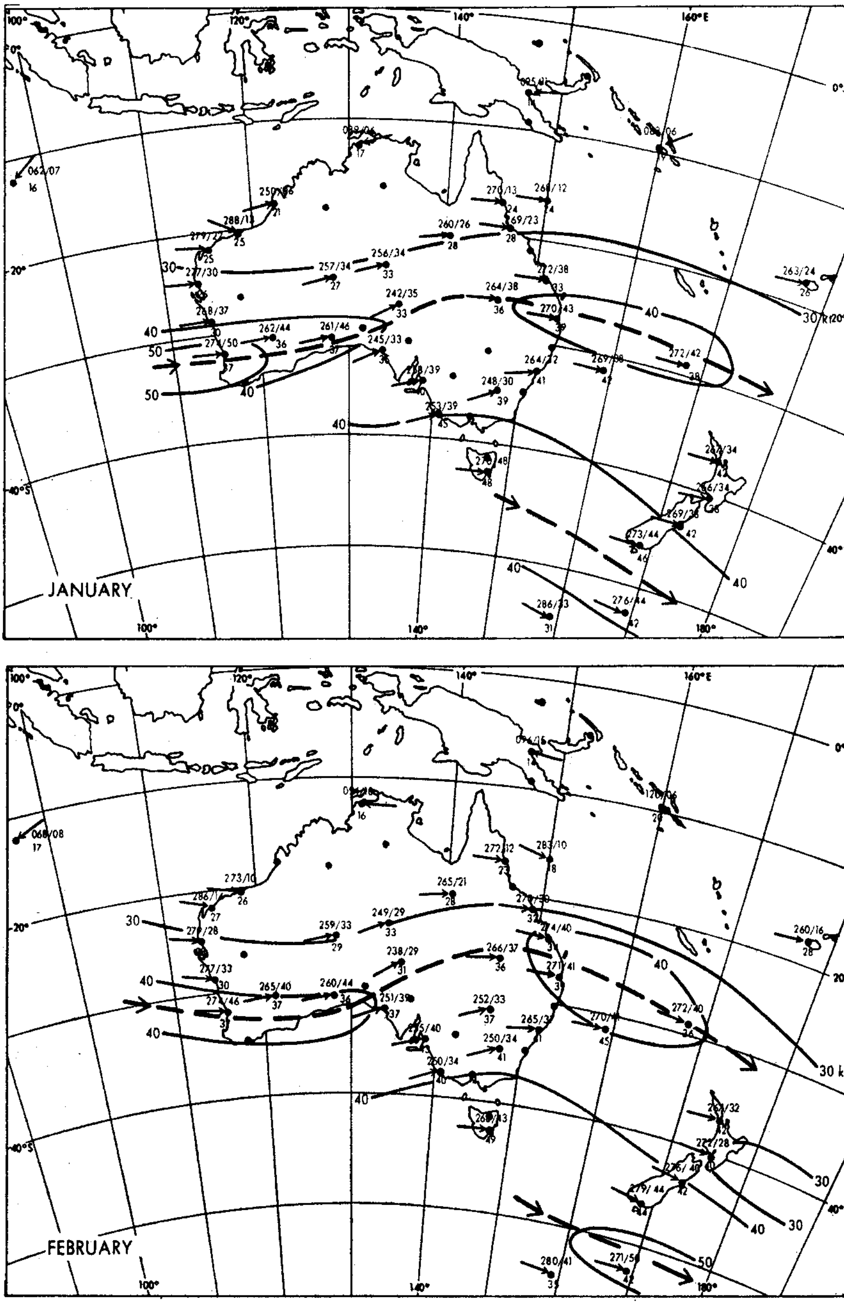
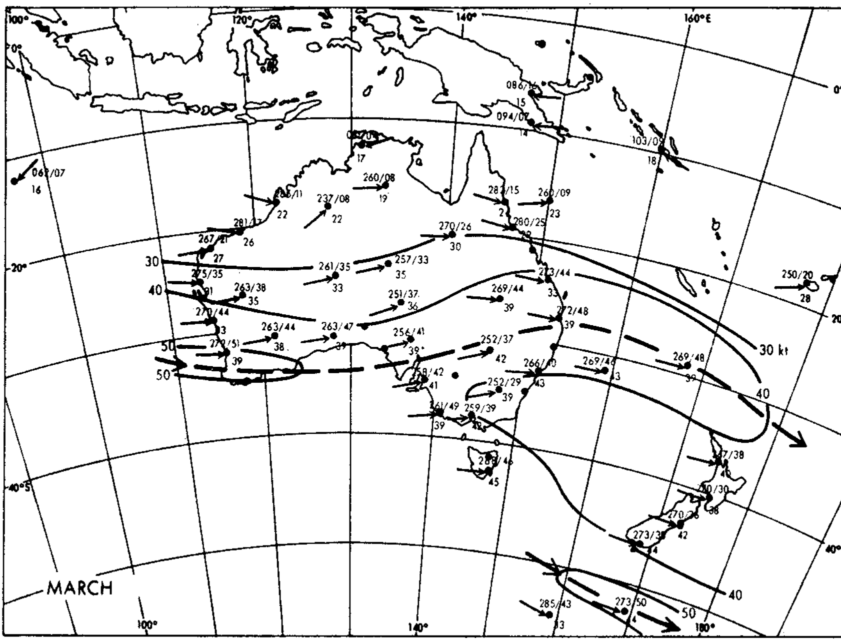
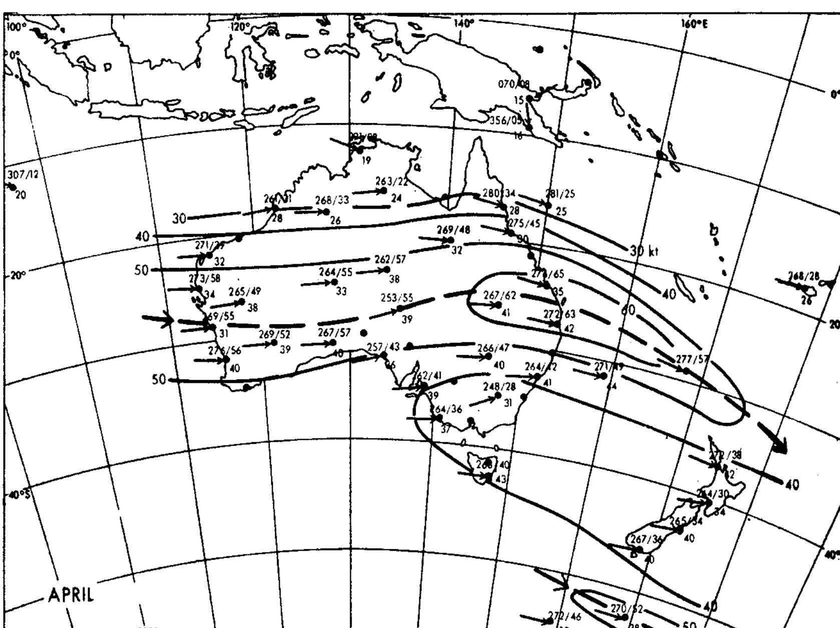


FIGURE 2—MONTHLY VECTOR MEAN WINDS AT 40 000 FEET IN THE AUSTRALIAN REGION

— → Mean maximum wind axis ——— Isotachs at 10-kt intervals
Directions are given in degrees and speeds in knots above the station circles; standard vector deviations are given in knots below them.
See Table I for data omitted from the charts because of space limitations.





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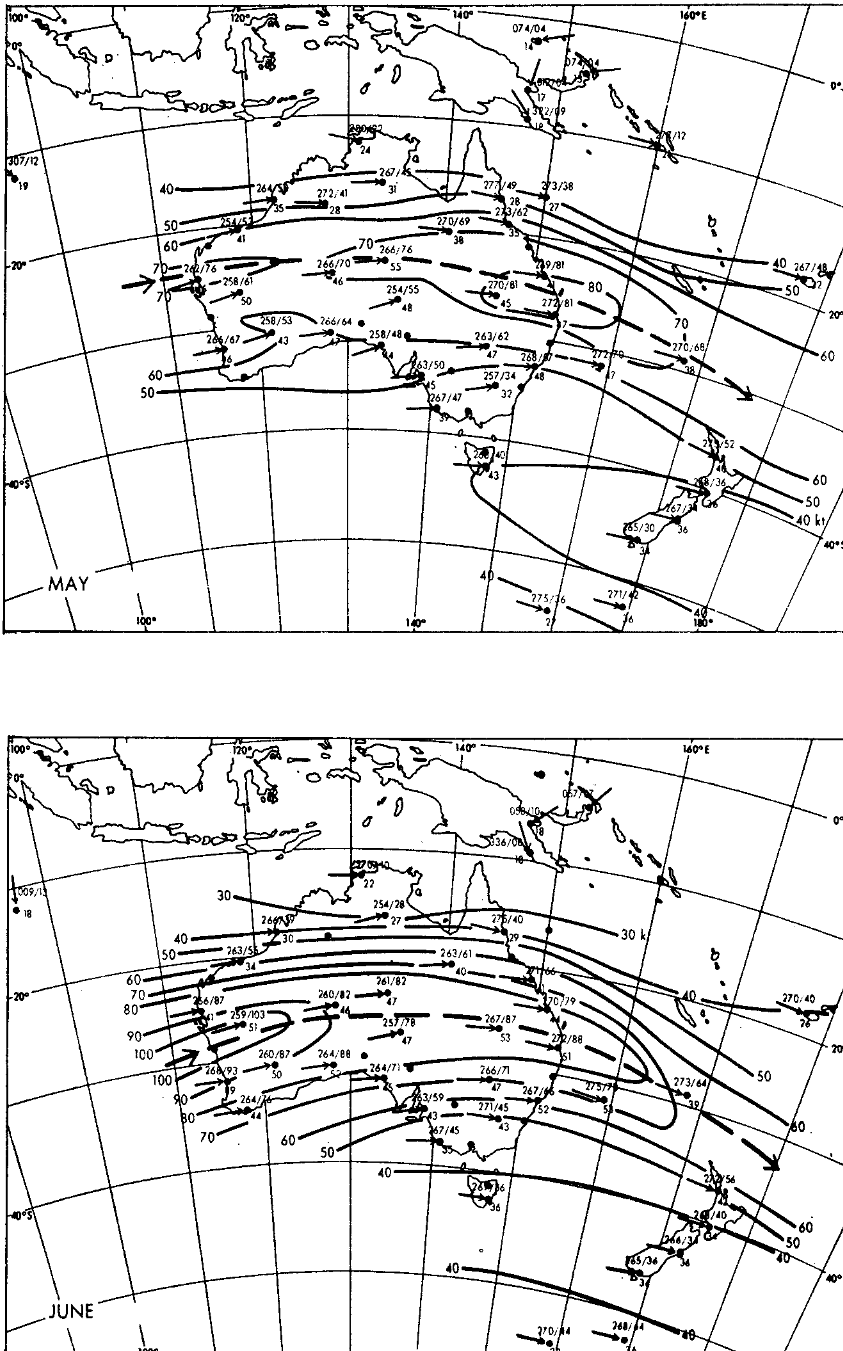

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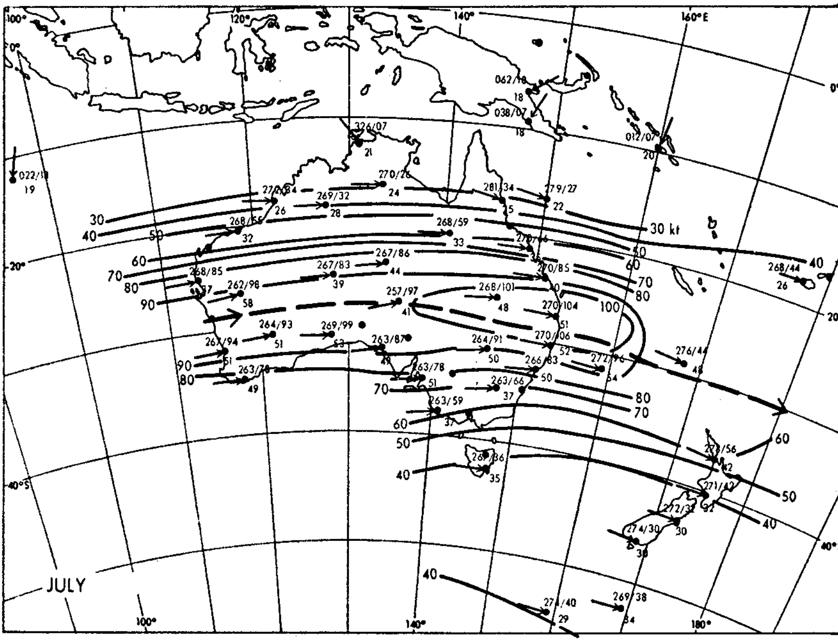

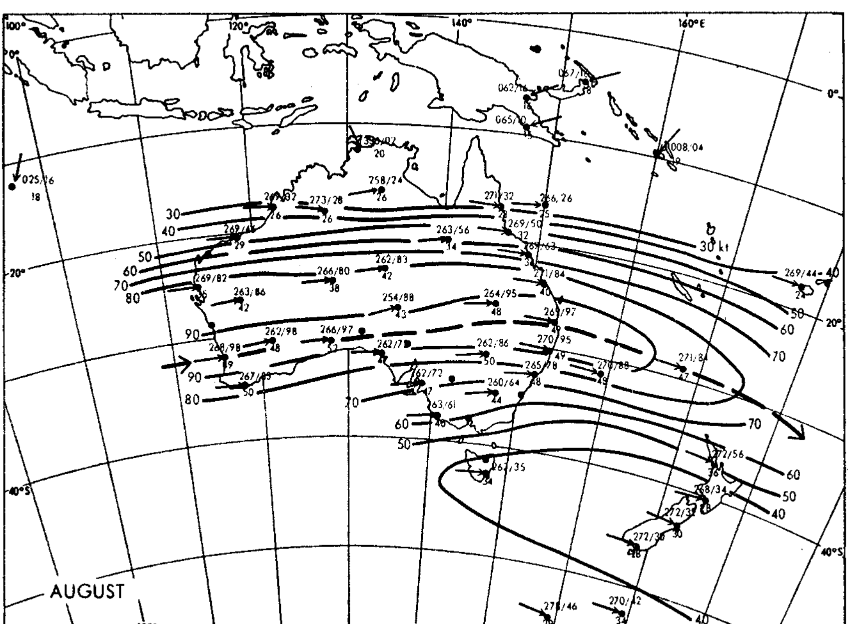

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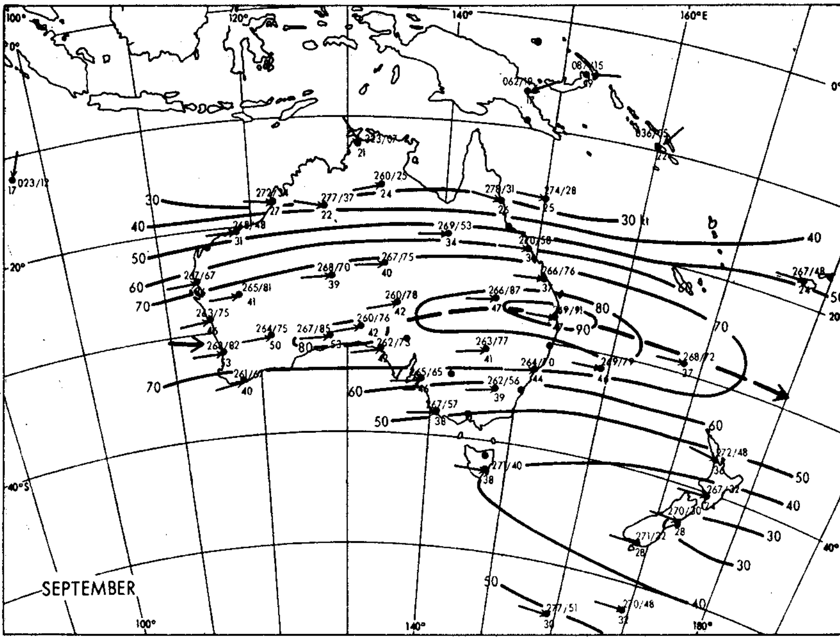


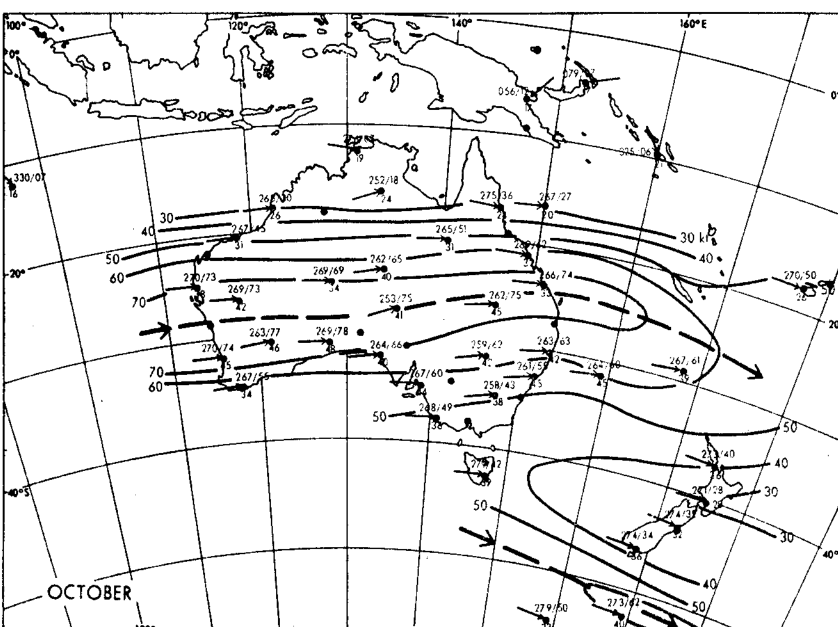
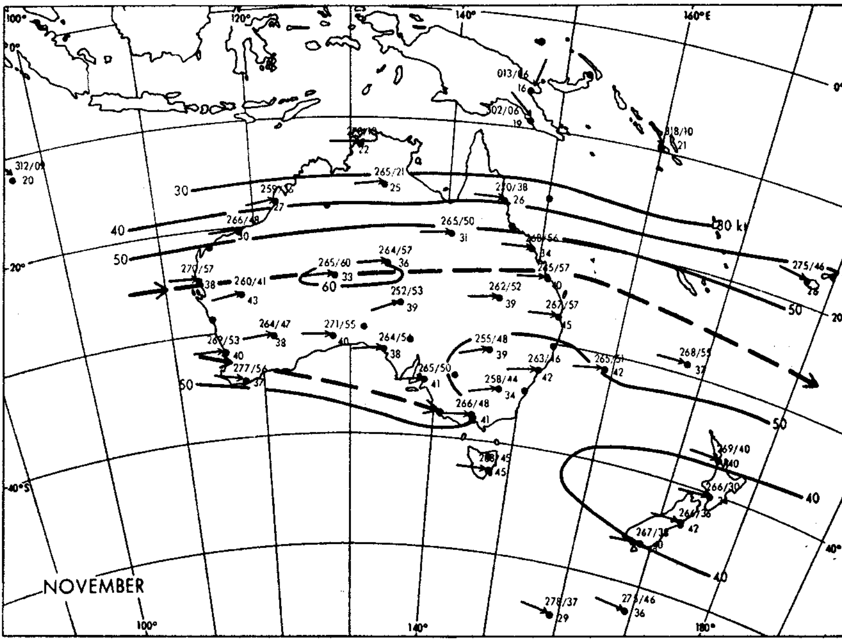


FIGURE 2—*continued*



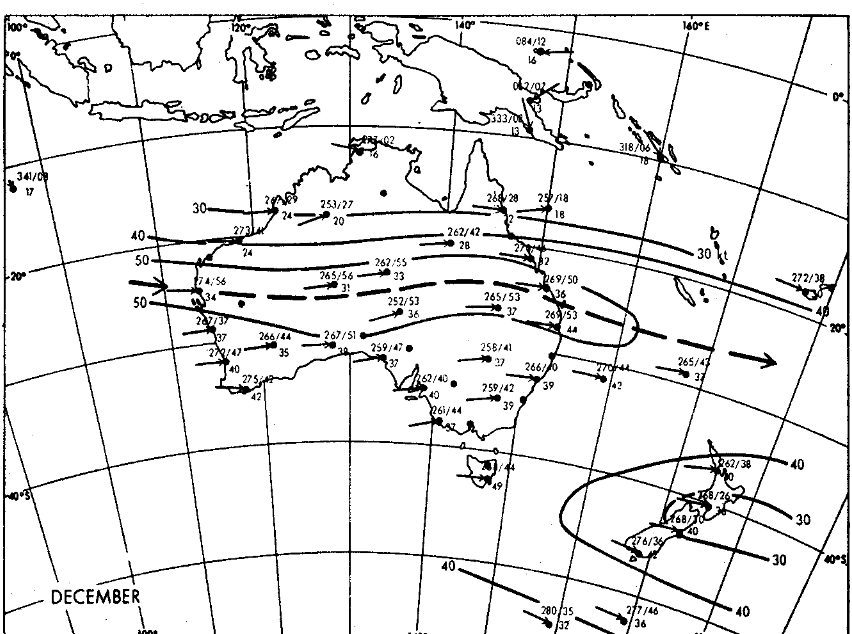


FIGURE 2—*continued*

Monthly mean flow patterns at 40 000 ft. A number of general points arise from the monthly mean flow patterns illustrated in Figure 2. Discussion is limited to those areas covered by the data network.

(a) In contrast to the mean charts presented by Phillpot,[4] much greater deviations from mean zonal flow are evident in the present charts. Phillpot shows that from March to November the mean flow is directly zonal. In contrast, of the charts constructed for this study only three months exhibit mean flow which is directly zonal (i.e. within 2–3 degrees of latitude over 100 degrees of longitude).

(b) Isotach maxima are generally lower than those calculated by Phillpot[4] for the autumn, winter and spring months, but are about the same as his values for the summer months. For example the highest isotach value shown here (100 kt*) occurs over eastern Australia in July whereas Phillpot shows a zone of 110 kt traversing the continent during that month.

(c) Mean jet-stream speeds (>60 kt) are evident from April to November (cf. Phillpot: April to December).

(d) Wind flow at 40 000 ft is well above the frictional influence of the earth's surface.[10,11] Hence it can be assumed that the wind flow at 40 000 ft will follow the 200-mb geopotential contours and that the isotachs will roughly define a mean contour trough or ridge. This assumption is implicit in the following discussion.

Strongest mean wind and direct zonal flow are exhibited in July. An isotach maximum of 100 kt is located between 140°–160°E and 25°–30°S. However, the extraordinarily light wind computed for Norfolk Island probably reflects either the unreliability of the Metox radiotheodolite for measuring strong winds at 40 000 ft or, alternatively, mistakes in the data. A minimum with mean speeds of less than 40 kt is located over the South Island of New Zealand and apparently extends across to Tasmania. This minimum coincides with the area marked by Lamb[12] as an area of blocking anticyclones. It is also shown by Karelsky[13] as an area of maximum anticyclonicity. Grant[14] and Radok and Grant[15] indicate that the region of wind minimum may extend south of the Australian continent at about 40°S. This minimum appears to be evident only in the Australian region of the hemisphere.[16] North of the minimum there is an incipient weak mean trough with an axis located between 150° and 160°E.

August shows a similar pattern. The eastern mean trough centered at 150°E becomes evident with an amplitude of 4–5 degrees of latitude. Mean maximum wind speed over Australia is between 95 and 100 kt (cf. Phillpot:[4] 110 kt). September and October are similar with mean maximum wind decreasing to about 75 kt over the continent in the latter month. The minimum extending over southern New Zealand and the south Tasman Sea remains, although a distinct current from 280° appears over Macquarie Island with a constancy of 77 per cent.

By November only a small area of mean wind exceeding 60 kt remains over the continent. In December a mean ridge appears over the central and western parts of the continent and the amplitude of the eastern mean trough increases. Mean maximum vector-wind speed over Australia is about 55 kt.

* 1 kt ≈ 0·5 m/s

In January, February and March the mean wind trough–ridge system over the continent attains its greatest amplitude (8 degrees of latitude) although the mean wind speeds associated are low — less than 50 kt. During February–April a mean west-north-westerly stream exceeding 50 kt is located in the vicinity of Macquarie and Campbell Islands. By April a mean maximum, reaching jet-stream speeds (>60 kt), appears in the eastern trough at the eastern coastline. This increases to 80 kt in May, and flow becomes nearly zonal again in June with a maximum of 100 kt located over Western Australia. A minimum zone extends longitudinally between 40° and 50°S although its cell-like character is lost.

The information presented here indicates that the mean trough found by Lamb[12] centred at 120°E at 500 mb does not seem to extend to 200 mb. On the other hand the evidence supports the existence of an eastern mean trough as suggested by Muffatti.[17]

In summary, the major features of upper-tropospheric monthly mean subtropical jet (STJ) flow seem to be :

(a) Mean STJ speeds greater than 60 kt prevail over the continent from April to November.

(b) A mean trough, with axis near 150°E over eastern Australia, is clearly discerned from October to April but is also incipiently developed from May to September (Figure 2).

(c) A complementary mean ridge, centred about 125°E, is evident in the summer months from December to March.

(d) A cell of minimum wind speed appears situated over southern New Zealand and the south Tasman Sea as far west as Tasmania. The minimum seems to be bounded to the south by a westerly stream over Macquarie Island.

Discussion: implications for the mean circulation. The mean west to west-north-westerly stream over Macquarie Island may bear little relation to the STJ. Instead this stream may be explained by the presence of a mid- to high-latitude jet, possibly the southern polar-front jet, troughing slightly to the west of Macquarie Island. Alternatively this stream may indicate a preferred region of STJ diffluence which, presumably, would be located either near the south-western tip of the continent or in the zone of the mean ridge south of the continent. The origin remains problematical[18] and, indeed, both interpretations may commonly feature on the synoptic 200-mb daily analysis charts prepared by the Bureau of Meteorology. The need for further research on the detailed structure of the jet streams over the southern oceans is obvious.

The existence of the mean STJ trough located in the vicinity of 150°E over the east coast of Australia was recently firmly established by Weinert[19] and indirectly by Campbell.[20] Mean troughs over the eastern sectors of continents are well-known phenomena.[21,22] Their origins are complex but are believed to be related to orographic[23] or thermodynamic influences[24] or perhaps to instability of the zonal baroclinic current.[25,26] Although an orographic influence may be applicable to the North American situation, there is no barrier in Australia comparable to the Rockies.

Thermal influences superimposed on the basic zonal current seem the most appropriate for the Australian situation. In summer the zonal current is

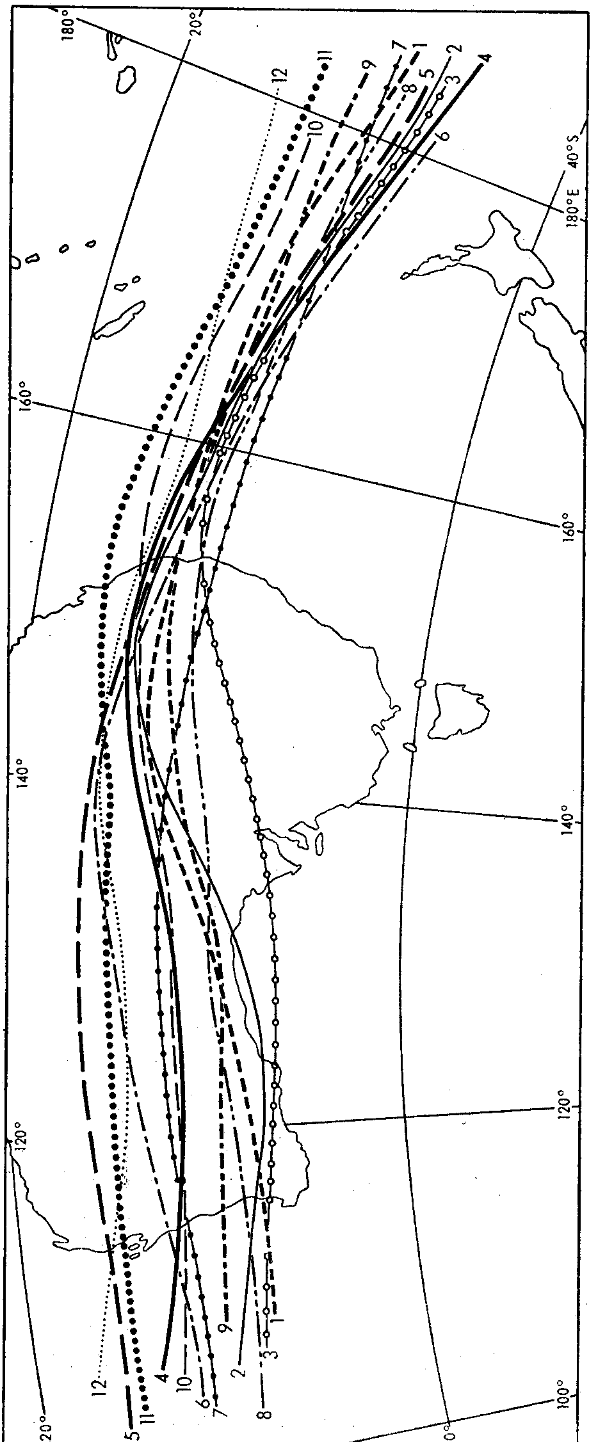


FIGURE 3—MONTHLY MEAN TRACKS OF THE AUSTRALIAN UPPER-TROPOSPHERIC MAXIMUM WESTERLIES

1 = January, 2 = February, 3 = March, 4 = April, 5 = May, 6 = June, 7 = July, 8 = August, 9 = September, 10 = October, 11 = November, 12 = December.

much less intense and the continent acts as a secondary heat source. Pressures higher than the latitudinal average tend to build up in the upper troposphere over the continental heat source. Over the surface layers of the heat 'low' a tendency for mean cyclonic circulation would be expected with a tendency for anticyclonic circulation in the upper troposphere. On either side of the heat source anticyclonic circulation should be maintained at lower levels with cyclonic flow aloft. Since the intensity of the zonal current increases with height, the resulting pattern at upper levels should have a wave-like structure with upper troughs over areas of lower temperatures at the surface and upper ridges over areas where the air is heated from below.

The above model seems fitting for the Australian continent in all seasons except winter when flow is strong and closely zonal. In winter the continent is cooler than the oceans,[27-29] and a mean trough may be expected over the continent. However, the land–sea thermal contrast is relatively less and hence the features of the wave pattern at upper levels do not change essentially from winter to summer (Figure 3).

Conclusion. Although it was hoped to compile new charts of vector mean wind for 40 000 ft, based on 12 years of complete and homogeneous records, this was not found to be practicable. Only 35 stations consistently gave reliable monthly statistics (cf. Phillpot:[4] 21 stations). Notwithstanding this the mean winds at 40 000 ft computed in this study are based on the most homogeneous data and densest data network to date. Unfortunately construction of the mean isotach contours remains subjective and includes a certain amount of smoothing.

Despite these deficiencies, the mean charts do indicate a degree of 'pattern' of the Australian upper-tropospheric maximum westerlies. This is evident both as seasonal (climatological) variation and as deviation from direct zonal flow (Figure 3). The mean trough and ridge features determined are of only small amplitude however, which possibly suggests that Rossby-type perturbations evident on 200-mb synoptic charts tend to have a preference for certain locations, or alternatively they may reflect large-scale thermal influences.

Acknowledgements. The author is grateful to the Director, Commonwealth Bureau of Meteorology, for making available the upper-air data, and to Mr J. C. Langford (Southern Hemisphere Analysis Centre) and Mr A. Muffatti (Extended Range Forecasting), both of the Commonwealth Bureau of Meteorology, Melbourne, for critical discussion of an earlier draft of this paper. Financial assistance was provided by Monash Univeristy.

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RADIATION FOG AND STRATUS FORMATION AND FOG CLEARANCE IN TERMS OF GEOSTROPHIC WIND — SOME APPLICATIONS OF WIND MEASUREMENTS ON A HIGH MAST

By W. E. SAUNDERS

Summary. Wind data from the Belmont mast are used to show the upper limits of geostrophic wind speed above which radiation fog and low stratus are unlikely at Manby. Within the range of wind speed favourable for fog the geostrophic wind direction is shown to be of great importance. With regard to fog clearance due to insolation, it is shown that the stronger geostrophic wind speeds increase the chance of a lifted-fog phase before final clearance and that most commonly this is preceded by vertically thick fog (reported as 'sky obscured').

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Photograph by courtesy of the Bracknell News

PLATE I—HIS ROYAL HIGHNESS THE DUKE OF EDINBURGH IS GREETED BY THE DIRECTOR-GENERAL, DR B. J. MASON, AND THE MINISTER OF STATE FOR DEFENCE, MR IAN GILMOUR, ON ARRIVAL AT THE METEOROLOGICAL OFFICE HEADQUARTERS ON 16 FEBRUARY 1973

PLATE II—HIS ROYAL HIGHNESS SIGNING THE VISITORS' BOOK

PLATE III—HIS ROYAL HIGHNESS DISCUSSES THE FORECAST FOR THE NEXT DAY WITH THE SENIOR FORECASTER (MR R. M. MORRIS — BACK TO CAMERA)

PLATE IV—THE MEDIUM-RANGE FORECASTER (MR R. C. A. SUTHERLAND) EXPLAINS THE 48-HOUR AND 72-HOUR FORECASTS TO HIS ROYAL HIGHNESS

PLATE V—H.R.H. THE DUKE OF EDINBURGH DISCUSSES RECORDINGS OF A.P.T. PICTURES RECEIVED FROM THE AMERICAN ESSA 8 SATELLITE

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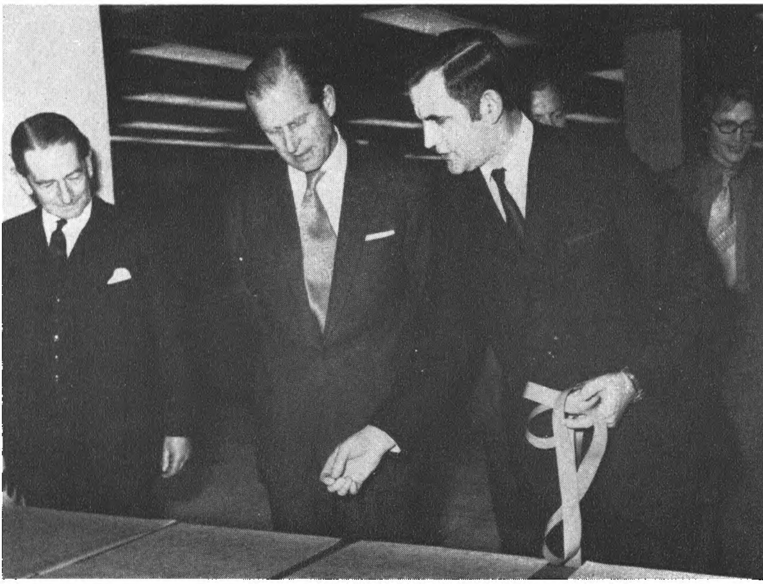

PLATE VII—THE 360/195 COMPUTER LABORATORY: HIS ROYAL HIGHNESS INSPECTING PLOTTED AND LINE-DRAWN CHARTS PRODUCED ON THE CALCOMP 1670 COMPUTER OUTPUT ON MICROFILM PLOTTER

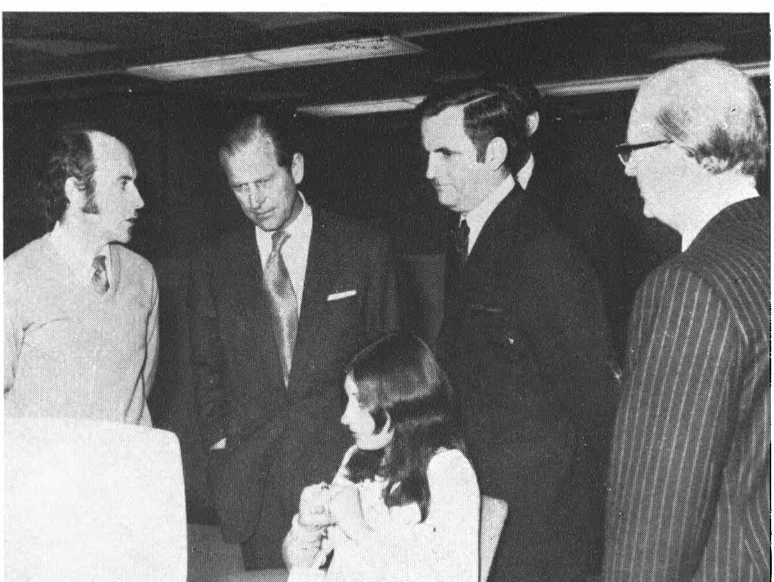

PLATE VIII—THE 360/195 COMPUTER LABORATORY: HIS ROYAL HIGHNESS AT THE TAPE/DISK CATHODE-RAY-TUBE CONSOLE WHERE MESSAGES CONCERNING MAGNETIC TAPE AND DISK REQUIREMENTS ARE DISPLAYED

Fog and stratus formation. It is common experience that during a radiation night wind speed above some limit prevents radiation fog formation but may permit the formation of stratus cloud with base a few hundred feet above ground. Above some higher limiting speed this form of low stratus also becomes unlikely. Little attempt appears to have been made to define these limits, either theoretically or experimentally. This note describes an attempt to derive these wind speed limits on the basis of actual observations.

Since September 1970 the forecast office at Manby, Lincolnshire, has been connected through a display panel (console) to a Munro Recorder, belonging to the Central Electricity Generating Board, at the Belmont mast of the Independent Broadcasting Authority. This is located 11 miles ($\approx$18 km) west of Manby, as shown in Figure 1. The site is 400 ft ($\approx$120 m) above m.s.l. An anemometer at 1275 ft ($\approx$390 m) above ground level has a clear exposure above the top of the mast.

C. A. S. Lowndes has made comparisons between the Munro Recorder readings and those taken at the Manby console. The comparisons showed that, for the 1275-ft wind speed, the mean difference (console minus Munro) was -1 kt, with standard deviation 1 kt. For wind direction, taken in units of 10 degrees, the mean difference was $-0{\cdot}4$, standard deviation 0·6. Comparisons have also been made, by Manby forecasters, between the console readings of the 1275-ft wind speed and the geostrophic wind speed measured from the hourly synoptic charts. These have shown that the mean difference (geostrophic wind minus console wind) is generally about 1–3 kt.

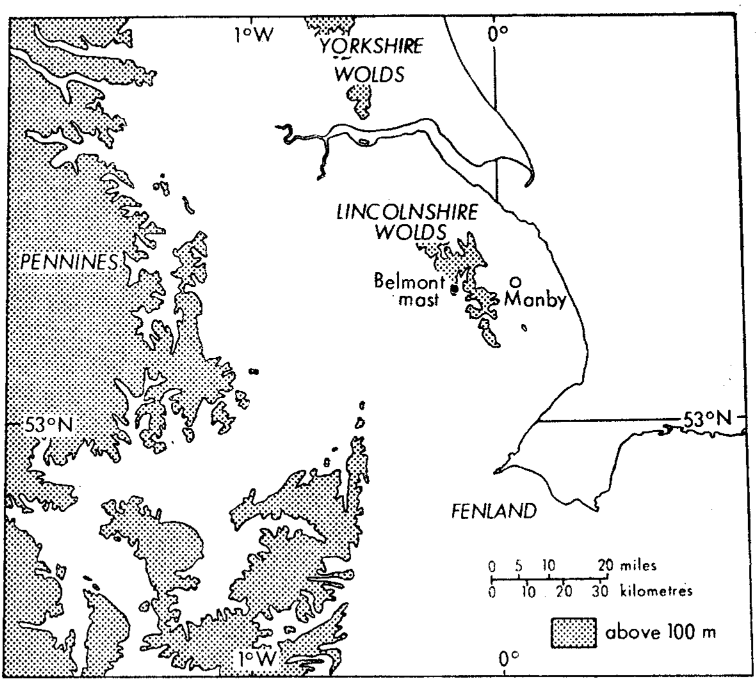

FIGURE 1—MAP ILLUSTRATING THE POSITION OF THE BELMONT MAST IN RELATION TO MANBY

It follows that the Belmont 1275-ft wind readings taken from the Manby console can be used with reasonable confidence as representative of the geostrophic wind. This is probably more true during a radiation night than in the day-time, because of the reduced depth of the friction layer at night. One advantage of having the Belmont winds available is that they are ready to hand on occasions when it is difficult to draw isobars accurately on that part of the chart which covers the Lincolnshire coast (e.g. when the geostrophic direction is nearly parallel with the coastline, coupled with the usual shortage of pressure readings over the North Sea). Another advantage is that the scrutiny of these wind readings taken at frequent intervals gives an indication of trends toward change in the geostrophic wind, perhaps before this is recognized from changes in the barometric tendency. This can be of great assistance in fog or stratus forecasting.

In the work described in this note, Belmont 1275-ft winds read from the Manby console were used. The wind speeds as read were corrected to accord with a calibration carried out by the Central Electricity Research Laboratory for the period up to 12 October 1971.

Manby observations for all radiation nights when Belmont data were available in the period from September 1970 to April 1972 were examined. The Belmont 1275-ft readings at the time of fog formation were extracted for occasions when radiation fog formed — visibility less than 1100 yd ($\approx$1000 m). Similarly, if low stratus cloud formed instead of fog the winds at the time of stratus formation were found. When neither fog nor stratus formed, the time of maximum relative humidity in the screen was noted and the wind at this time was extracted. The investigation was confined to radiation nights, and occasions of fog or stratus advection from the North Sea were omitted.

The results of this investigation are shown in Figure 2. When fog or stratus formed, the appropriate symbol has been entered against the geostrophic wind direction and speed at the time of formation. When there was no fog or stratus the small circular symbol has been entered against the geostrophic wind direction and speed at the time of maximum relative humidity. The height of the base of stratus and the value of the maximum relative humidity are shown for each occasion.

Examination of Figure 2 leads to the following conclusions :

(a) The upper limit of geostrophic wind speed for radiation fog formation is about 21 kt, but within the range 18–21 kt there is an increasing probability of stratus cloud forming at a few hundred feet instead of fog forming at the surface.

(b) There is no reliable lower geostrophic wind speed limit for fog.

(c) Geostrophic wind speed at the time of fog formation does not provide any guidance on whether or not the sky will become obscured during fog.

(d) Stratus at a few hundred feet is liable to form with geostrophic wind speeds mainly within the range 18–29 kt. At wind speeds above 29 kt there is generally a sharp fall in the screen-level maximum relative humidity reached, but note that in this sample all occasions of wind speed above 29 kt lie in the sector 210°–340°: a zone associated with lee effects. However, even within the wind speed limits which favour stratus formation this cloud forms on only a small proportion of the occasions.

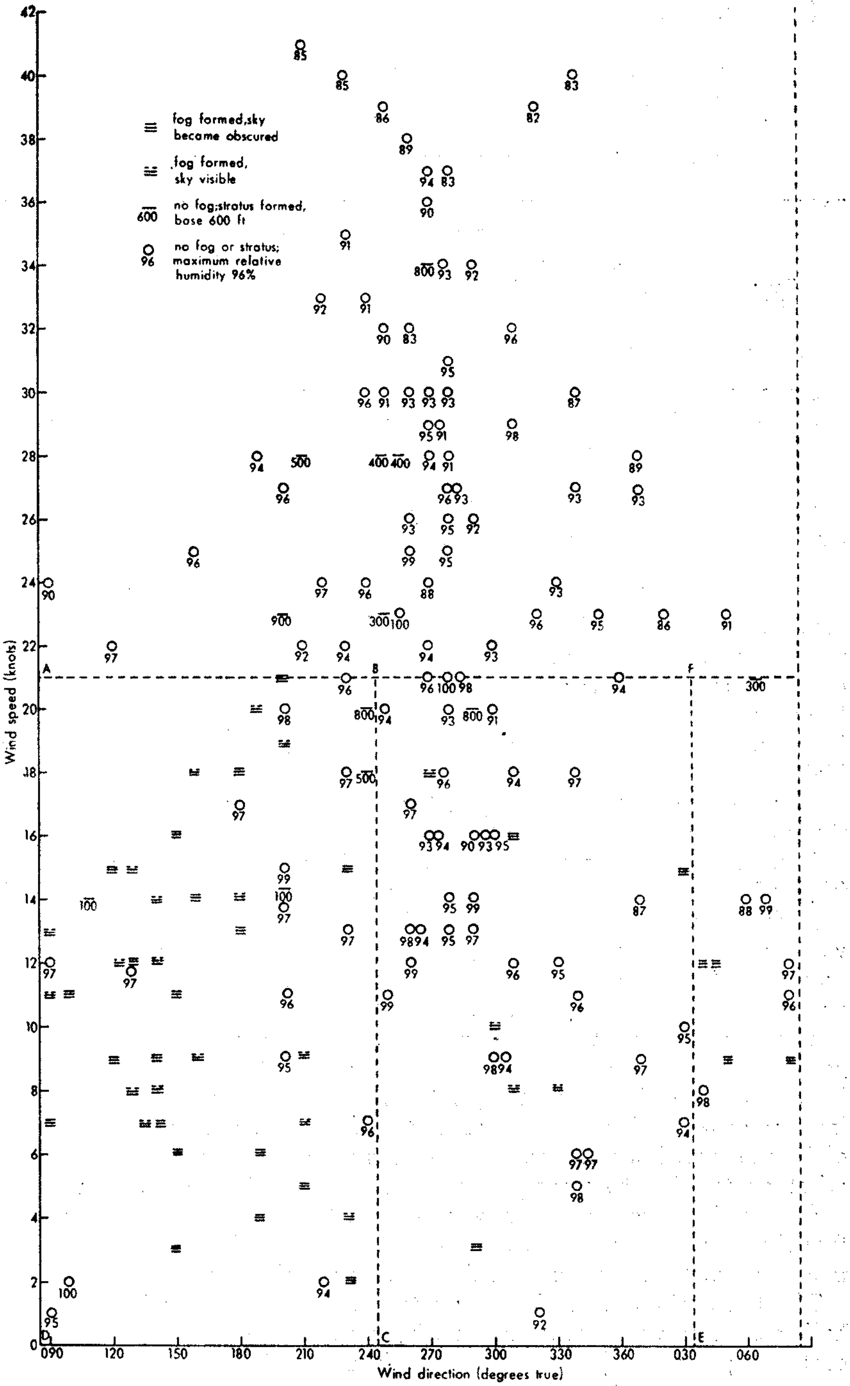

FIGURE 2—THE INCIDENCE OF FOG OR LOW STRATUS ON RADIATION NIGHTS AT MANBY IN TERMS OF WINDS ON A MAST 1275 FEET ABOVE THE GROUND AT BELMONT

(e) Geostrophic wind direction is clearly of importance. Scrutiny of Figure 2 suggests that below the critical wind speed limit of 21 kt the diagram may be divided into three zones, where AD, BC and EF have been placed to accord with changes in the fog or stratus frequencies. The differences between these zones are tabulated in Table I. The boundary BC is clearly of considerable significance.

TABLE I—FREQUENCIES OF FOG AND STRATUS WITH GEOSTROPHIC WINDS FROM SELECTED DIRECTIONS

Zone	No. of occasions	No. of occasions with : fog	stratus	Percentage of occasions with : fog and/or stratus
ABCD	56	37	4	73·2
BFEC	45	7	1	17·8
FADE	10	4	1	50·0

Some comments on the distribution of fog occasions follow :

Zone ABCD (*directions 085°–245°, through 180°*). The incidence of fog reaches a maximum with wind direction 140°–170°. The sample is small, but if confirmed over a longer period it implies that fog always forms on radiation nights when the geostrophic wind is in this sector. It is the situation in which air has moved from the Wash and the fen areas of south-east Lincolnshire towards Manby.

Examination of the 15 occasions when no fog or stratus formed showed that 12 were within the summer half-year, a season when the fog-point is sometimes not reached owing to the short length of night. On all 3 winter occasions saturation was not reached and the minimum temperature was below freezing, in the range −1 to −4°C, i.e. the fog-point was well below freezing. It follows that in the winter half-year the fog probability is very high indeed on a radiation night when the geostrophic wind falls within ABCD.

Zone BFEC (*directions 245°–035°, through 360°*). The outstanding feature is the low incidence of fog and/or stratus compared with that of zone ABCD.

In a large proportion of the occasions with no fog, the Manby surface wind followed a definite pattern, with the speed increasing towards the end of the night from some lower value to within the range 6–12 kt, and with the direction varying between 240° and 280°. The increased wind speeds referred to were around 50–80 per cent of the Belmont 1275-ft speeds at the same time. It was also found that as the geostrophic wind direction veers through north this nocturnal surface westerly wind at Manby still occurs, and does so until the geostrophic wind direction reaches at least 030°. This supports the placing of boundary EF on Figure 2 at 035°. There seems no doubt that the nocturnal increase of wind often prevents saturation being reached and is a main cause of the relatively low incidence of fog in this zone. It is possible that a katabatic effect is intensified by a component of geostrophic wind in the same direction.

Another factor which may have some effect in reducing the fog incidence is that the air will in its recent history have crossed high ground, i.e. the Welsh mountains or the Pennines, and then the Lincolnshire or the Yorkshire Wolds.

The 8 occasions when fog or stratus formed were all within the winter half-year. One was unusual for Manby, smoke fog (relative humidity 90 per cent at fog formation) forming in mid afternoon. On this occasion saturation was not reached until the temperature had fallen to −0·2°C. The Belmont 1275-ft wind speed was only 3 kt. On the other occasions the fog-point was always above 2·5°C, and the Belmont wind speed was 8 kt or above. Of the occasions with no fog or stratus, 19 were in winter, and on 7 of these the minimum temperature was above 2·5°C.

The main conclusions reached tentatively from this rather small sample, and subject to amendment as more occasions are recorded, are :

In summer : fog and stratus are unlikely.

In winter : the overall chance of fog and/or stratus is about 1 in 3, but is higher than this if the fog-point is above 2°C. If the fog-point is below 2°C the fog probability appears to be very low unless the geostrophic wind is unusually light (it is possible that with very light geostrophic winds the differences between the zones become negligible because of the general stagnation of the air mass; but the number of occasions is as yet insufficient to show whether this is true and to indicate the value of the lower limit).

Zone FADE (*directions 035°–085°*). Fog or stratus forms on half of the occasions. There were no significant seasonal variations. Probably the tendency for air with high fog-point to move in off the North Sea is in some cases offset by the advection of relatively warm air in this sector.

Fog and stratus clearance. In the clearance of radiation fog through insolation and turbulence there is frequently a lifted-fog phase before final clearance. To investigate the relation of this to geostrophic wind speed the Belmont 1275-ft winds were extracted for the times of Manby fog clearance. The only item observed as routine which gives some indication of the vertical depth of fog is the state of the sky, i.e. whether or not it is reported as obscured. The author has shown previously,* from Cardington data, that a report of 'sky obscured' probably corresponds to a fog depth of 300 ft or more.

In Figure 3 symbols have been entered showing the geostrophic wind at the time of Manby fog clearance, whether or not the sky was obscured before clearance and whether or not there was a lifted-fog phase, and the cloud base when the latter occurred. Occasions when small amounts of lifted fog, 1/8–3/8, were reported temporarily during the clearance were disregarded.

From Figure 3 it can be seen that :

(a) The likelihood of a lifted-fog phase increases as the geostrophic wind speed increases, as shown in Table II.

(b) A lifted-fog phase is nearly always preceded by a 'sky obscured' fog. However, a 'sky obscured' fog is not necessarily an indication that there will be a lifted-fog phase, especially if the geostrophic wind does not exceed 10 kt.

(c) The geostrophic wind speed gives no guidance on the likely cloud base when there is a lifted-fog phase.

TABLE II—RELATIONSHIP BETWEEN THE INCIDENCE OF A LIFTED-FOG PHASE AND THE GEOSTROPHIC WIND SPEED

Geostrophic wind speed	Fog clearance	
	With lifted fog	Without lifted fog
kt	*No. of occasions*	
0–10	2	17
over 10	16	9

* SAUNDERS, W. E.; Daytime fog clearance at Exeter Airport. *Met Mag, London*, **89**, 1960, pp. 261–263.

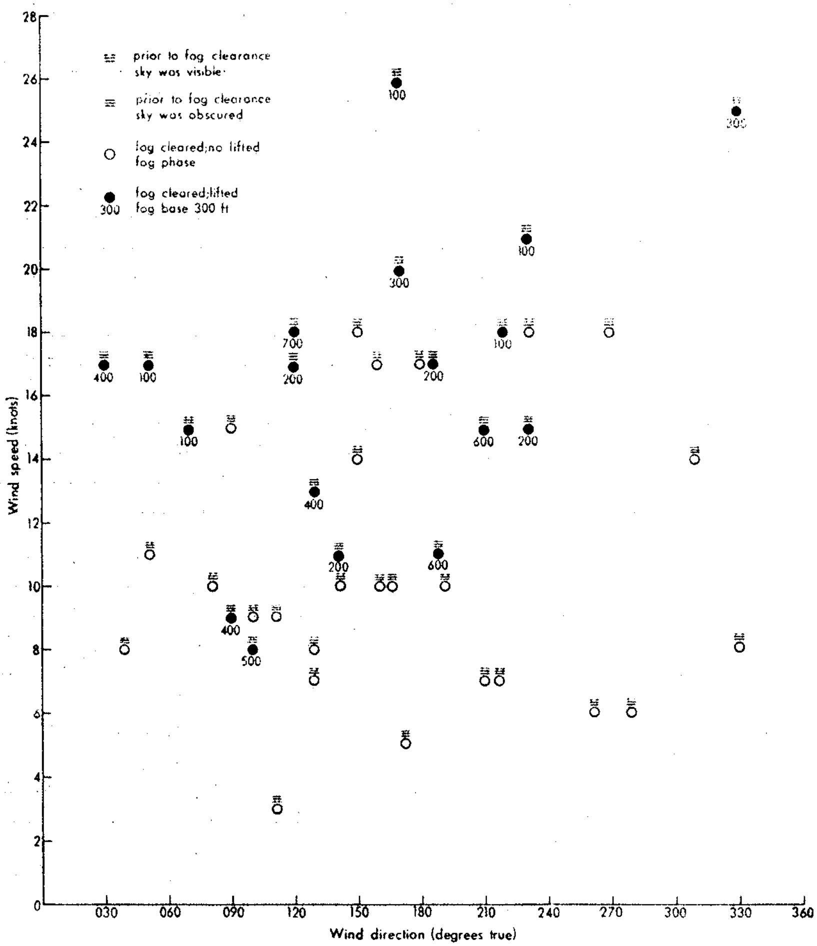

FIGURE 3—RADIATION FOG CLEARANCE AT MANBY IN TERMS OF WINDS ON A MAST 1275 FEET ABOVE THE GROUND AT BELMONT

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AN INVESTIGATION INTO A RELATIONSHIP BETWEEN UPPER-AIR RELATIVE HUMIDITY AND CLOUD COVER

By J. N. RICKETTS

Summary. An investigation was conducted to establish what relationships exist between cloud cover and relative humidity. It was instigated primarily to find a method of determining cloud cover from relative-humidity forecasts made by means of the 10-level model, in connection with the absorption of radiation by cloud and for forecasting cloud distributions. Relative humidity and total cloud cover were first compared, each being estimated over grid-square areas. A roughly linear association was apparent from this. Then the two variables for the individual stations concerned were compared so as to obtain more-definite relationships which took account of cloud at different levels. Two linear relationships, one each for low and medium cloud, were obtained.

Introduction. The filtering effect of the atmosphere upon radiation is increased by the presence of cloud. Radiation is absorbed or reflected by cloud according to its type and thickness, and there are great differences between the effects of low, medium and high cloud. Low cloud types exhibit the greatest variation in effect upon radiation, ranging from the high degree of absorption by thick stratocumulus to the high reflectivity of large cumulus. Medium and high clouds reduce the amount of radiation reaching and leaving the earth in proportion to their amount and thickness. An important factor in cloud formation is the relative humidity of the air, and this variable can be forecast numerically.

Designed in the context of the 10-level numerical model, the present work was intended to improve on the relationships given by Gadd and Keers.[1] They had compared 12-hour forecasts of relative humidity at the grid points of the 48 × 32-point rectangular (fine mesh) areas with the observed cloud distribution taken from synoptic charts. Earlier work by Smagorinsky[2] was based on comparisons between observed relative humidities and cloud-cover values. Gadd and Keers's relationships were similar to Smagorinsky's for medium and high cloud but rather different for low cloud. Both papers defined low cloud as having its base in the 1000–800-mb range but they defined the ranges for medium and high cloud slightly differently.

Initially, in the present investigation, smoothed values of relative humidity and total cloud cover over grid-square areas were compared, but there could be no attempt to discriminate between cloud levels on this basis. Total cloud cover and the highest relative humidity values over 100-mb layers (1000–900 mb, 900–800 mb, etc.) were compared, over grid squares, on the assumption that the predominant cloud would be in the moistest layer.

In a further analysis, low, medium and high cloud were compared separately with relative humidity in the three ranges 1000–800 mb, 800–500 mb and 500–300 mb respectively. Relative humidities were averaged vertically for 100-mb layers from 1000 to 300 mb. The amount of cloud in each of the three ranges was compared:

(a) with the highest average relative humidity of the 100-mb layers in the range (type A comparison), and

(b) with the mean relative humidity over the entire range (type B comparison).

Such an analysis could not be made over grid squares, so reported cloud amount was compared with observations of relative humidity taken at approximately the same time and place. The relationship between cloud type and mean relative humidities was briefly considered but a lack of time prevented a detailed investigation.

Collection of data. Periods of about a fortnight which were considered representative of each of the four seasons were chosen for the investigation. These were : 16–31 January, 16–30 April, 16–31 July, and 16–31 October 1969.

Relative humidity and cloud data for radiosonde stations in the United Kingdom only were used — Lerwick, Stornoway, Shanwell, Long Kesh, Aughton, Hemsby, Crawley and Camborne, with the addition of the supplementary stations : Aberporth, Shoeburyness, Larkhill and Eskmeals. Mean relative humidities over 100-mb layers were assessed by eye from Väisälä diagrams, which were obtained from each of the above stations.

The amount of data which could be used was limited because radiosonde observations, in general, are taken only at noon and midnight. However, since comparisons were being made with surface observations for standard times, care had to be taken to check the time of ascent. There were occasional late starts, and the supplementary stations often made soundings at other times. Only ascents made within two hours either side of 00 GMT or 12 GMT were considered.

Grid-square analysis. This need be mentioned only briefly since the final results came from the later work. Estimates of relative humidity and the corresponding cloud cover were made over the 100-km grid squares of the 10-level model which lay over land in the U.K. The estimates were divided into ranges of relative humidity and cloud cover, so any association found between them by this method would be fairly rough. An approximately linear relationship was found which varied inconsistently with time of year. There did appear, however, to be a consistent variation with time of day, although this was later found to be not significant. The approximate relationship did show that clear skies can be associated with much higher relative humidities and that the change from clear to cloudy conditions occurs in a narrower range of relative humidity values than either Smagorinsky or Gadd and Keers had indicated.

Direct analysis. So far, no discrimination between low, medium and high cloud had been attempted, but it was clearly necessary. As was mentioned in the Introduction, this could only be done in terms of individual stations and in the first instance three were used : Crawley, Shanwell and Long Kesh. Cloud reports were extracted from *Daily Weather Reports* for nearby surface stations: Gatwick, Leuchars and Aldergrove respectively. The upper-air stations were chosen for their position and because the nearby surface stations are airfields, from which good cloud reports might be expected. Each of the type A and type B comparisons, as defined in the Introduction, was subdivided to consider low and medium cloud separately (Table I). No useful comparisons could be made for high cloud since the data were inadequate.

It is obvious from Tables I (a) and (b) that occurrences of extensive cloud (7–8 oktas) become proportionately greater with increasing relative humidity, and the form of the distribution in Table I (a) and (b) does indicate an approximately linear relationship.

Unfortunately, the medium cloud distributions (Table I (c) and (d)) are unavoidably biased. Values of medium cloud amount are rarely reported when low cloud cover is greater than 6 oktas, and when low cloud is even moderately extensive they are more in the form of estimates. Tables I (c) and (d) show a disproportionate number of reports of small amounts of medium cloud and very few reports of moderate amounts. Clearly, more data are necessary before the regression lines corresponding to the distributions can be properly defined.

Humidity data from the radiosonde stations at Lerwick, Stornoway, Shanwell, Long Kesh, Hemsby, Aberporth and Crawley were assembled with cloud reports from the nearby surface stations, Gorleston being taken as the surface station for Hemsby. Reports of medium cloud were used only when there were 3 oktas or less of low cloud, except when medium cloud amount was greater than 6 oktas. The data were not grouped and scatter diagrams were compiled. Figures 1 and 2 for 16–31 July 1969 are typical of the diagrams for low cloud. Figures 3 and 4 give the complete distributions for medium cloud. It is evident from these diagrams that the type A analyses are more compact than the type B.

TABLE I—RESULTS OF COMPARISONS OF RELATIVE HUMIDITY AND CLOUD COVER FOR CRAWLEY, SHANWELL AND LONG KESH

(a) Low cloud — type A analysis

Cloud				Relative humidity (per cent)					
cover	< 20	20–29	30–39	40–49	50–59	60–69	70–79	80–89	≥90
oktas				*number of occasions*					
7, 8						4	31	103	22
5, 6							24	30	3
3, 4					1	4	24	16	1
≤2					8	28	62	15	2

(b) Low cloud — type B analysis

Cloud				Relative humidity (per cent)					
cover	< 20	20–29	30–39	40–49	50–59	60–69	70–79	80–89	≥90
oktas				*number of occasions*					
7, 8				1	1	15	52	73	9
5, 6					2	10	31	19	2
3, 4					2	10	27	9	1
≤2			1	6	26	32	40	9	1

(c) Medium cloud — type A analysis

Cloud				Relative humidity (per cent)					
cover	< 20	20–29	30–39	40–49	50–59	60–69	70–79	80–89	≥90
oktas				*number of occasions*					
7, 8					2	5	15	10	1
5, 6			2	4		2	5	3	
3, 4					2	2	2		1
≤2	13	12	20	26	31	27	21	2	1

(d) Medium cloud — type B analysis

Cloud				Relative humidity (per cent)					
cover	< 20	20–29	30–39	40–49	50–59	60–69	70–79	80–89	≥90
oktas				*number of occasions*					
7, 8			2	1	3	11	15	3	
5, 6		3	1	3	2	1	5		
3, 4			1		3	1	1	1	
≤2	17	29	34	36	26	10	5		

Of the statistics presented in Table II, only the humidity variances of the low cloud type A and B analyses were significantly different at the 5 per cent level. This provided statistical support for considering the type A analyses to be less scattered than those of type B. The bias in the medium cloud distributions made any statistical examination of them of little value. Figures 3 and 4 show that a disproportionately large number of observations of humidity were associated with zero cloud cover, and this gave regression lines for medium cloud which predicted less than 8 oktas cloud cover at 100 per cent relative humidity, which is obviously physically unreasonable.

In order to reduce this weighting effect, the type A distributions of low and medium cloud were analysed using means of cloud cover calculated over 10 per cent ranges of relative humidity. It was immediately noticeable

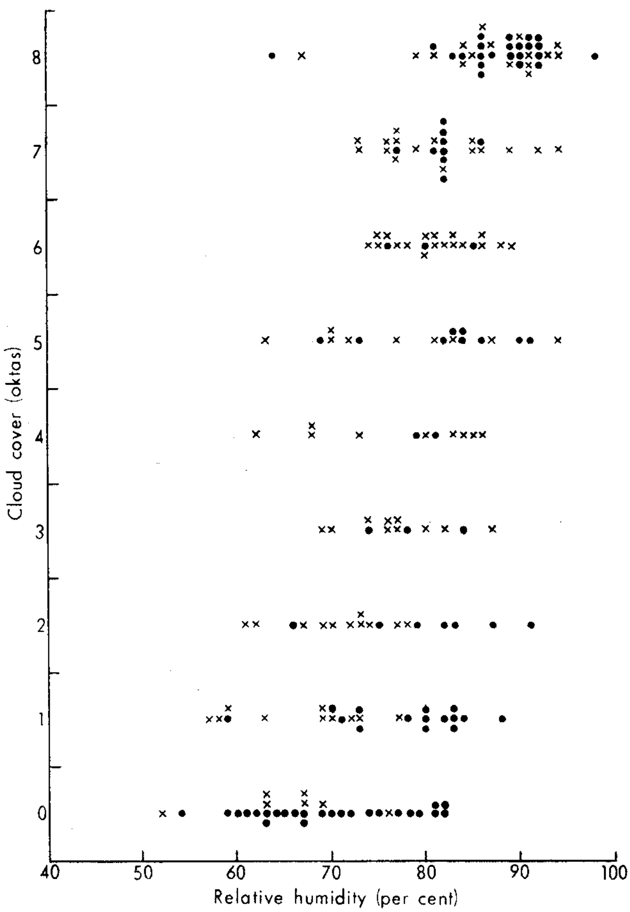

FIGURE 1—DISTRIBUTION OF LOW CLOUD (TYPE A ANALYSIS) AT 00 AND 12 GMT: SUMMER, 1969

● Night-time observation × Day-time observation

TABLE II—CORRELATION COEFFICIENTS AND VARIANCES FOR THE TYPE A AND B ANALYSES OF LOW AND MEDIUM CLOUD

	Type of analysis	No. of observations	Correlation coefficient	Variance of cloud cover	Variance of humidity
Low cloud	A	788	0·57	6·10	45.83
Low cloud	B	788	0·54	6·45	76·39
Medium cloud	A	293	0·59	6·66	253·44
Medium cloud	B	293	0·63	6·15	224·70
Medium cloud but ignoring points below 50 per cent relative humidity	A	192	0·59	7·24	76·74
Medium cloud but ignoring points below 50 per cent relative humidity	B	128	0·60	7·08	59·29

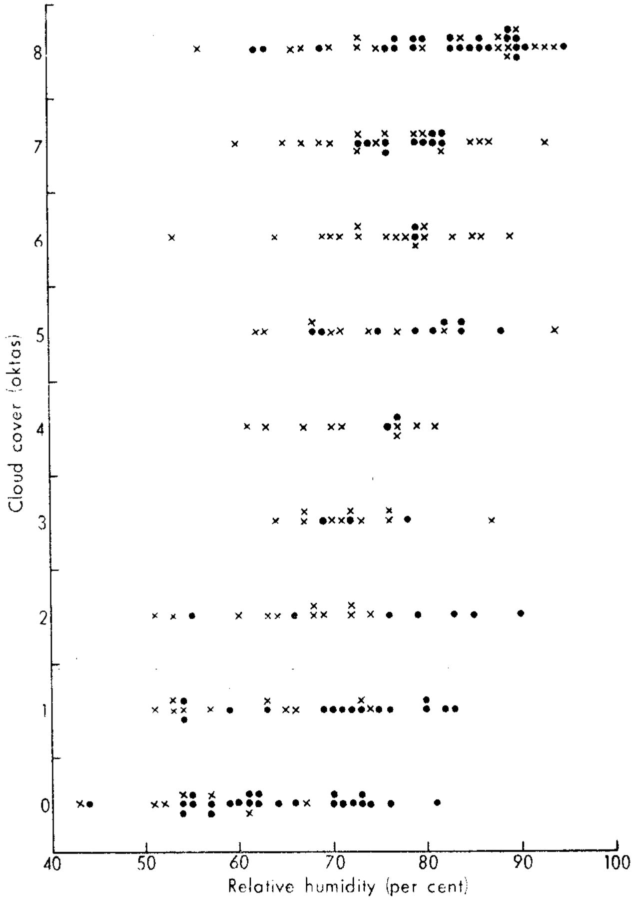

FIGURE 2—DISTRIBUTION OF LOW CLOUD (TYPE B ANALYSIS) AT 00 AND 12 GMT: SUMMER, 1969

● Night-time observation × Day-time observation

from the curves shown in Figure 5 that points below 50 per cent relative humidity are distributed differently from those above 50 per cent, particularly for medium cloud. Since, on the average, relative humidity values up to 50 per cent are associated with less than 2 oktas cloud amount, which would have little effect on radiation, this part of the distribution can be ignored. The regression lines for low and medium cloud were re-calculated on this basis and are also shown in Figure 5.

Application of results. With the exception of Crawley and Larkhill, the U.K. radiosonde stations are situated on or near coasts. Lerwick, in particular, is representative of a purely maritime station whereas airstreams affecting other stations could be either maritime or continental in character.

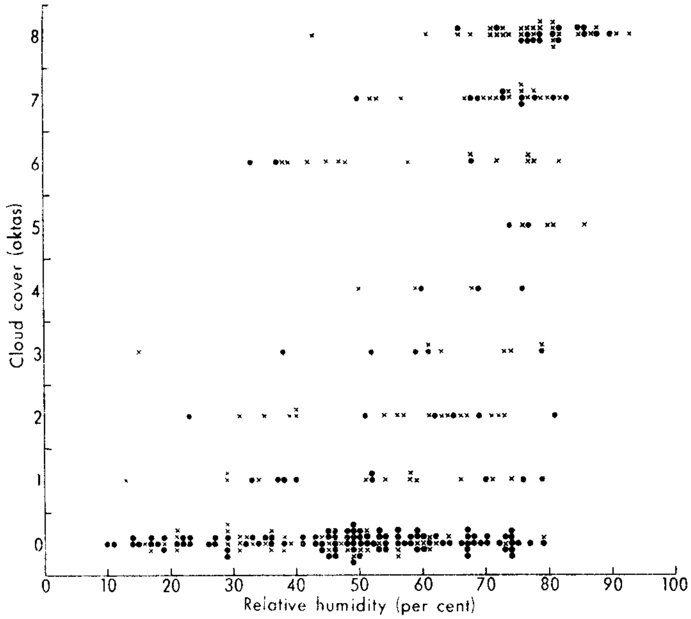

FIGURE 3—DISTRIBUTION OF MEDIUM CLOUD (TYPE A ANALYSIS) AT 00 AND 12 GMT: ALL SEASONS, 1969

● Night-time observation × Day-time observation

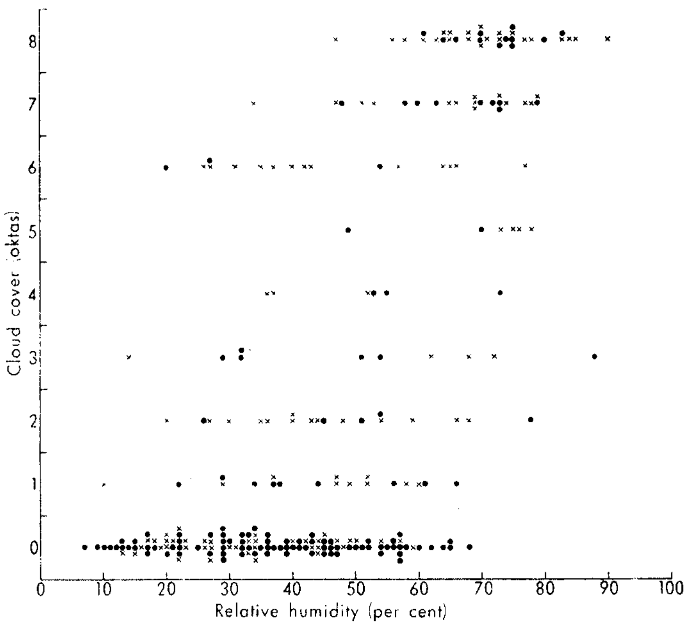

FIGURE 4—DISTRIBUTION OF MEDIUM CLOUD (TYPE B ANALYSIS) AT 00 AND 12 GMT: ALL SEASONS, 1969

● Night-time observation × Day-time observation

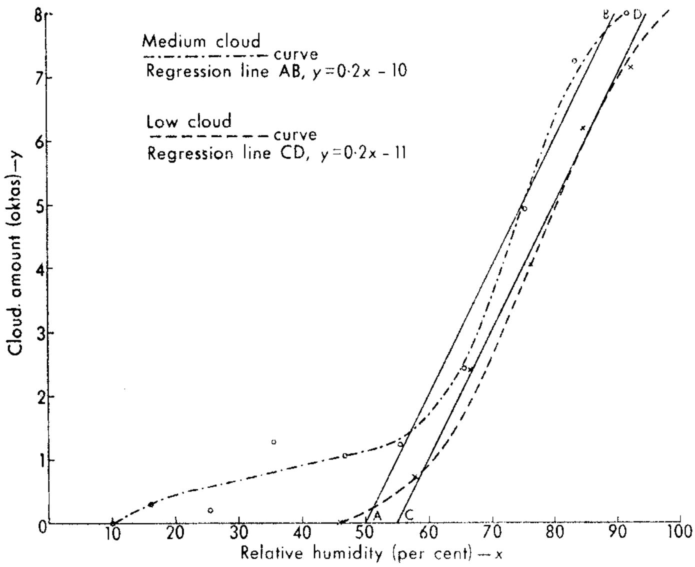

FIGURE 5—DISTRIBUTION OF LOW AND MEDIUM CLOUD (TYPE A ANALYSES) BASED ON MEANS OVER 10 PER CENT RANGES OF RELATIVE HUMIDITY

Included are the regression lines calculated after all points with relative humidity below 50 per cent were ignored.

However, there was no evidence to suggest any significant difference in distribution between one station and another. Also, the results for an area with much convective activity, such as the tropics, may be expected to be different from those for the U.K., where stratiform clouds tend to predominate. Any such difference should have been apparent between the distributions for each season, summer being a more convective time of year than winter. But seasonal differences were inconsistent, showing that there was no single predominant factor.

Conclusions. During the course of this work it became evident that any relationship between relative humidity and cloud cover would be rather indefinite. Even if humidity is assumed to be the only factor in cloud formation, no account was taken of cloud thickness, and type was defined only by the terms low, medium and high.

The relationship between medium cloud cover and relative humidity is approximately linear; that for low cloud is more definitely linear. Therefore, it is reasonable to estimate low and medium cloud cover from forecasts of the highest average relative humidity of the 100-mb layers in the two ranges 1000–800 and 800–500 mb.

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2. SMAGORINSKY, J.; On the dynamical prediction of large-scale condensation by numerical methods. *Geophys Monogr, Washington.* 1960, No. 5, pp. 71–78.

REVIEW

Review of forecast verification techniques, WMO Technical Note No. 120, by E. M. Dobryshman. 275 mm × 213 mm, pp. x + 51, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972. Price: Sw. Fr. 10.

The meteorologist may well think that his task is completed when a forecast has been issued, perhaps pausing to pat himself on the back when it turns out to be substantially correct or to consider the possible causes of failure if things go wrong. But there is a need for a more systematic assessment of many types of forecast in order to show, for example, whether the forecasts are providing useful guidance or whether a change in forecasting techniques brings about any improvement in accuracy, and most meteorological services carry out some kind of evaluation of at least some types of forecast. The aim of Professor Dobryshman's report is to make a systematic classification of the methods of forecast verification in use in various countries and to lay down guide-lines for future work in this field.

The review starts off with an excellent brief outline of the problem, with examples of the difficulties encountered. The second chapter gives an account of the types of verification methods in use, with a summary of their common and their desirable features. In just a few places in this chapter there are mistakes which are, however, readily spotted, while here and there the text is a little obscure. The third chapter, entitled 'Consideration of various types of forecast and possible methods of verification', is the one to which the reader will look for guidance on establishing a scheme for the verification of a particular type of forecast. The treatment is, however, rather disappointing, mainly because it does not really get down to fundamentals but also because there are one or two places where it is misleading. There are two, usually distinct, aspects to the assessment of a set of forecasts, viz :

(a) to check the accuracy of the forecasts themselves, i.e. verification or empirical evaluation; and
(b) to assess their usefulness to the customer; this is not strictly verification but may be termed 'operational evaluation'.

Although the author does talk about the two types of assessment he does not draw a sufficient distinction between them, and the reader is left with the impression that for certain types of forecast only the first aspect matters while for others only the second is important. A good deal could usefully be said about the purposes for which forecasts are assessed or evaluated, but this area still needs further exploration.

Two less general but still important points in this chapter require comment. Equation (5) on page 16 forms an index to indicate the 'degree of success' of a set of forecasts by averaging three quantities which are calculated in very different ways, and it is difficult to see how variations of the index can be related to the properties of the forecasts. The second point arises in the discussion of 'alternative' (black/white or yes/no) forecasts: the author suggests an index, Q, which appears to be new, but a few lines of simple algebra suffice to show that it is in fact identical with that put forward in 1884 by Peirce and criticized on the grounds that it unduly weights prefigurance (the ability of a set of forecasts to predict successfully the occurrence of a given state, regardless of the number of forecasts of that state which are not fulfilled).

A short chapter on 'Conclusions and recommendations' comes next, followed by two appendices giving detailed verification schemes for short-range weather forecasts and long-range forecasts. The schemes appear to be based on the needs and established practice of the author's home country and may not be as useful elsewhere. It would have been better to lay down the fundamental principles more thoroughly in Chapter III and leave the individual services or units to work out the details.

J. CRABTREE

551.501.3

LETTER TO THE EDITOR

SI units in the Meteorological Office

Mr Lumb,* in his article discussing the use of the International System of Units within the Meteorological Office states that 'A major problem arises with series of data over a long period of years including readings in different units . . . but with computer help there is little difficulty in using (the new unit) as the common unit. There may be other reasons for treating the series as two separate parts . . .'.

The purpose of this letter is to point out that in practice difficulties can arise when the original readings have been recorded to the nearest integer on the old scale and integers on that scale do not fall uniformly into unit bands of the new scale. It is then possible for uniform steps on the new scale to correspond to non-uniform steps on the effective scale of the converted data, with effects on the apparent frequency distribution. When a frequency analysis is carried out on such data alone the effect is usually obvious, but where the analysis is of mixed old and new data, the effect is sometimes less easy to see and can give rise to erroneous deductions.

As an example, temperature data originally recorded in degrees Fahrenheit rounded to the nearest degree for climatological purposes, on being converted to Celsius are distributed in such a way that two integral degree-Fahrenheit numbers fall into each unit degree-Celsius interval for four successive degrees Celsius, but only one such number falls into every fifth unit degree-Celsius interval. In consequence although intervals of 1 degC are apparently uniform in width, in fact every fifth interval is only half the width of the intervening four in terms of the effective unit of the data sample under analysis, and for such intervals a frequency count only about half that expected appears in the apparent analysis.

For analysis of mixed data originally recorded partly in degrees Fahrenheit and partly in degrees Celsius the depression of every fifth apparent frequency depends upon the relative numbers of old and new data encountered in the class and is not necessarily uniform.

* LUMB, F. E.; SI units in the Meteorological Office. *Met Mag, London,* **101**, 1972, pp. 366–368.

The problem is not of course confined to temperature. One way to overcome the difficulties is to carry out analyses in parts, using the units in which the data were originally recorded for each part and then expressing the results for each part in the new units.

Meteorological Office,
Bracknell,
Berkshire

C. L. HAWSON

OBITUARIES

It is with regret that we record the death on 6 January 1973, of Mr D. Girdwood, Higher Scientific Officer, Aberdeen Airport, and the death on 20 January 1973, of Mr D. R. Hoskin, Higher Scientific Officer, Met O 12.

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CONTENTS

NOTICES

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AN ANALYSIS OF MONTHLY RAINFALL TOTALS REPRESENTATIVE OF KEW, SURREY FROM 1697 TO 1970

By B. G. WALES-SMITH

Summary. A very long series of monthly rainfall data representative of Kew is analysed in terms of frequency distributions of annual and seasonal totals, and in terms of return periods of rainfall amounts for given months, sets of consecutive months, and on a yearly basis. Trends in seasonal and annual rainfall are discussed.

Introduction. Planners and many others frequently ask if there have been trends in the rainfall of London and of other places. They seek advice on the frequency of wet winters, dry summers and so on. Water engineers have two main problems; the satisfaction of the ever-increasing demand for fresh water and the avoidance, or at least the control, of flooding. Agriculturists, too, are vitally concerned with trends in and frequencies of rainfall. These problems require detailed studies of the regional characteristics of the water cycle. The meteorological aspects of the cycle are, of course, rainfall and evaporation. In this article further investigations are made into a very long series of monthly rainfall totals which formed the basis of an earlier paper by the present author.[1] Work on the preparation of a companion series of evaporation estimates and measurements representative of Kew, for a similar study and for study in association with this rainfall series is now nearing completion.

Homogeneity of the series of annual totals. Although, as will be shown later in this article, there are some interesting trends, the series of annual totals passes a rough test for homogeneity. The 'run' test was applied. The median value is 23·71 inches (602·2 mm), with 137 totals above and 137 totals below this value. There were 132 'runs' (i.e. sets of one total or more, taken in chronological order, above or below the median value). These criteria define a point lying comfortably between the lower and upper 0·10 significance limits.

Frequency distributions of annual and seasonal totals. Totals, in 1-inch ranges of amount, were tabulated for years and seasons from 1697 to 1970. The 4-month and 2-month seasons used are those suggested by A. Bleasdale as being especially appropriate to U.K. rainfall studies. Frequency diagrams are shown as Figure 1. The simple dashed-line construction helps the eye to recognize the generally convex (upwards) shape of the left-hand parts and the generally concave shape of the right-hand parts of the diagram.

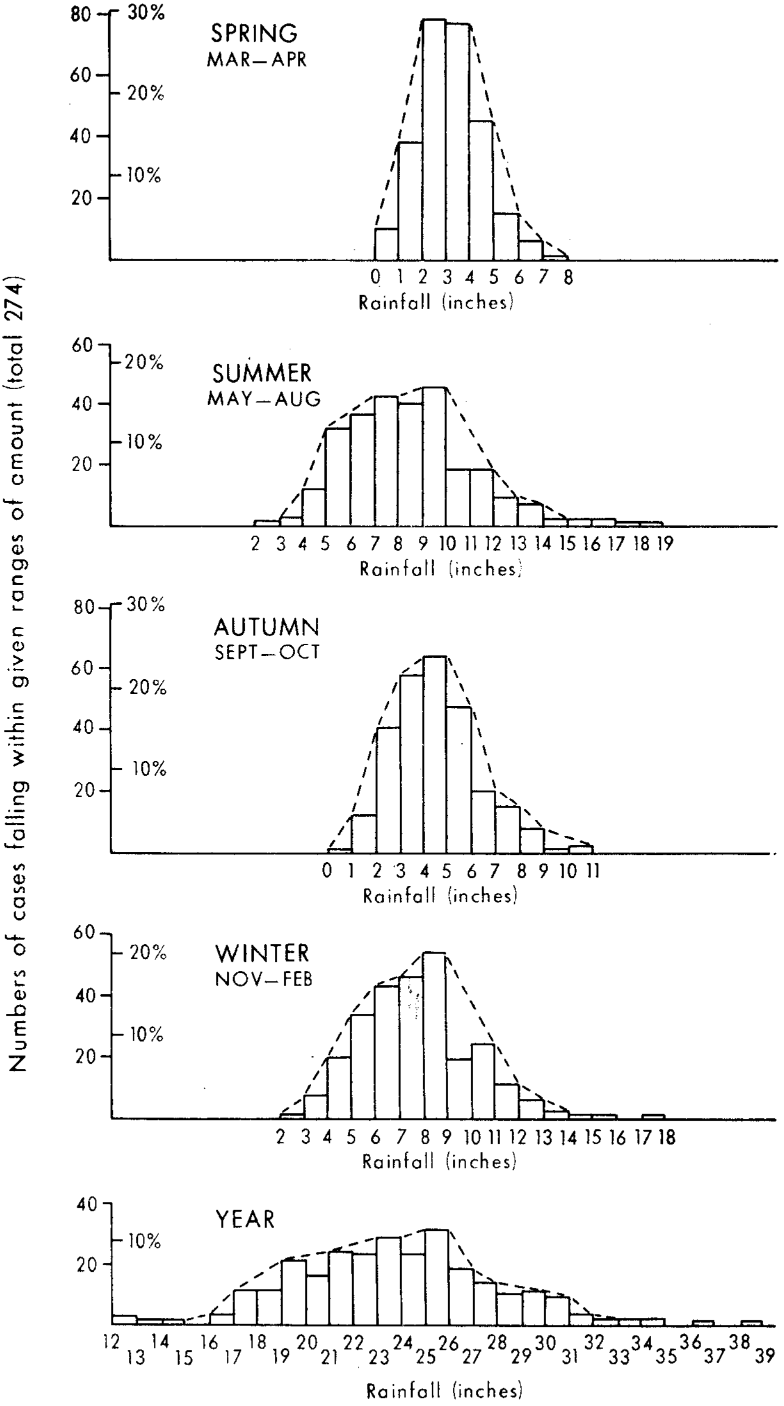

FIGURE 1—FREQUENCY DIAGRAMS OF SEASONAL AND ANNUAL TOTALS OF RAINFALL REPRESENTATIVE OF KEW, 1697–1970

Analysis by computer. The series was first analysed by a FORTRAN IV program designed and written by J. D. Bacon. The output consists of (a) the year numbers and rainfall amounts for the six wettest and six driest of each calendar month (ignoring change of calendar in September 1752) and (b) the same analysis for accumulations of months up to six, commencing with October and April. (The hydrologists' 'Water Year' begins with October.) In each of these 22 analyses the amounts likely (a) to occur or be exceeded and (b) not to be exceeded (on average), with return periods of from 5 to 200 years are obtained by empirical frequency.

The above analyses were carried out on the whole 274-year series and, for later study, on consecutive 50-year periods starting in 1721. Next the series was analysed by another FORTRAN IV program designed and written by K. Bruley. The output consists of frequency tables for desired periods. The table for the whole period was rewritten to give numbers of cases of less than stated amounts of rain and these figures were divided by 274 to give cumulative probability values.

Comparison of extreme values. The values of the six wettest and driest of each calendar month (a) in the whole series and (b) in consecutive 50-year sets were plotted. The generally random distribution of these extreme values through the series suggested that whilst the series might contain trends, it is, none the less, reasonable to subject it to frequency analysis.

Extreme-value analysis. Taking each month in turn, the 6 highest and 6 lowest values were plotted on extreme-value probability paper, using positions recommended by A. F. Jenkinson.[2]

$$P = \frac{m - 0{\cdot}31}{n + 0{\cdot}38}, \qquad \ldots (1)$$

where P is the cumulative probability plotting position, m is the ranking order, and n is the number of classes. In this case the value of n was 274 and m took values of 274 to 269 and 6 to 1.

The same procedure was followed with the 12 extreme values for sets of months beginning with October and April, for the 4- and 2-month 'seasons' May–August, September–October, November–February, March–April and for annual totals.

The empirical threshold estimates of monthly rainfall (obtained from Bacon's program) were plotted against their return periods (in years) and the cumulative probability values obtained from Bruley's table were plotted against the appropriate upper limits of classes. Lines of best fit were drawn by inspection through all the plotted points. There was little difficulty in fitting points up to 100 years' return period (probability 0·99) but rarer occurrences were, of course, hard to handle with any confidence. The method adopted was extreme caution in making estimates of 200-year events (i.e. to aim to err on the low side). Figures 2 and 3 show the estimates finally accepted. Envelopes to curves of values likely not to be exceeded, with given return periods, obtained by similar treatment on probability paper, are also shown. The 10 periods October–November through to October–March and April–May through to April–September were treated in the same way as the individual months. Because of the progressive increases in amounts, however, the

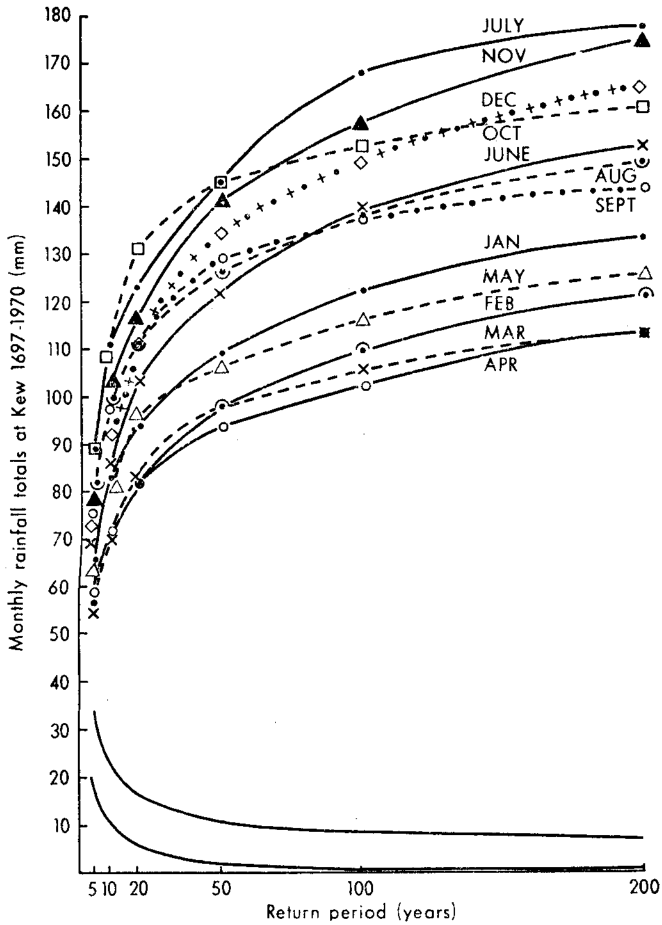

FIGURE 2—AMOUNTS OF RAINFALL LIKELY TO OCCUR OR TO BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS (UPPER CURVES) AND ENVELOPES TO MONTHLY CURVES OF RAINFALL AMOUNTS LIKELY NOT TO BE EXCEEDED, EACH MONTH, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

probability curves representing the winter and summer halves of the Water Year could be plotted on only two sheets and comparisons of adjacent curves were very helpful in dealing with rare events. In drawing the curves of amounts not likely to be exceeded with given return periods use was made of the six lowest totals in each case. Figures 4 and 5 show the values finally accepted. The annual and the 4-month and 2-month seasonal values were processed in the same way as the other totals. The results are shown in Figure 6.

By using the same principle of extreme caution as employed with 200-year events rough estimates have been made for 500- and 1000-year events and are given in Table I. These rough estimates have been made only because they may be of some value and because it was fairly simple to make them with all the working sheets readily available. The estimates for individual months are almost certainly the least trustworthy of all.

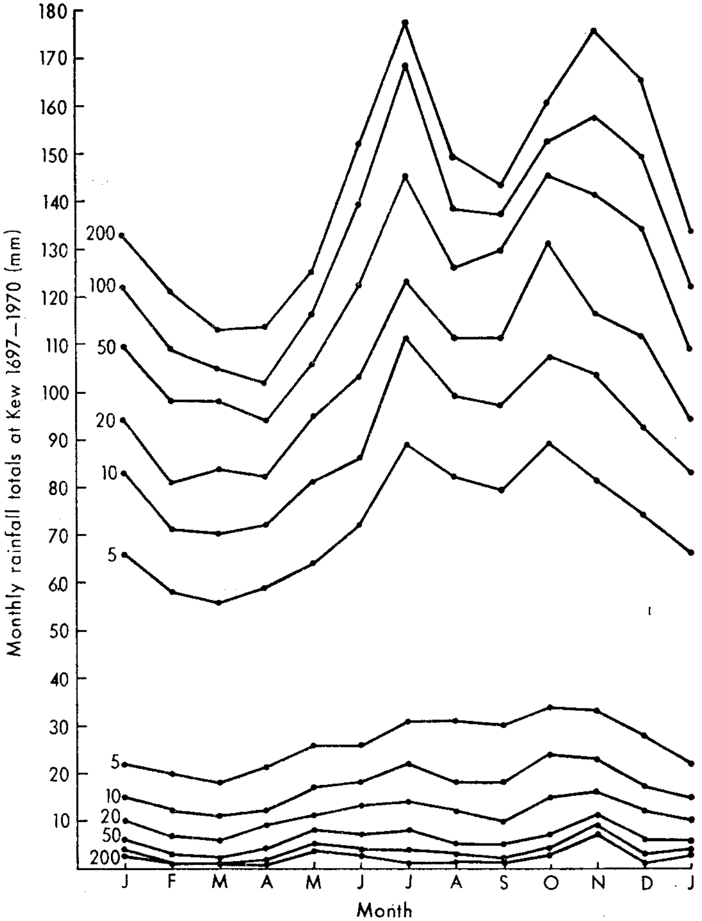

FIGURE 3—AMOUNTS OF RAINFALL LIKELY TO OCCUR OR TO BE EXCEEDED IN EACH MONTH OF THE YEAR (UPPER CURVES) AND AMOUNTS OF RAINFALL LIKELY NOT TO BE EXCEEDED (LOWER CURVES) FOR GIVEN RETURN PERIODS, AT KEW

Numbers to the left of the curves are return periods in years.

Dates of extreme events. The year dates of the six wettest and driest examples of (a) individual months, (b) given sets of months, (c) 'seasons' and years are given in Tables II, III and IV. It is interesting to note that the wettest and driest summers, autumns and winters in the 274-year series (Table IV) all occurred in the last 100 years, 1871–1970. This raises the often discussed question of whether very long sets of data should be analysed in terms of frequency. Perhaps the last 50 to 100 years belong to a population slightly but significantly different from the preceding century or so.

In an attempt to investigate this the 6 wettest and driest of each 'season' in the century 1871–1970 were tabulated (Table V). The numbers in brackets show the ranks of events in the whole 274-year series.

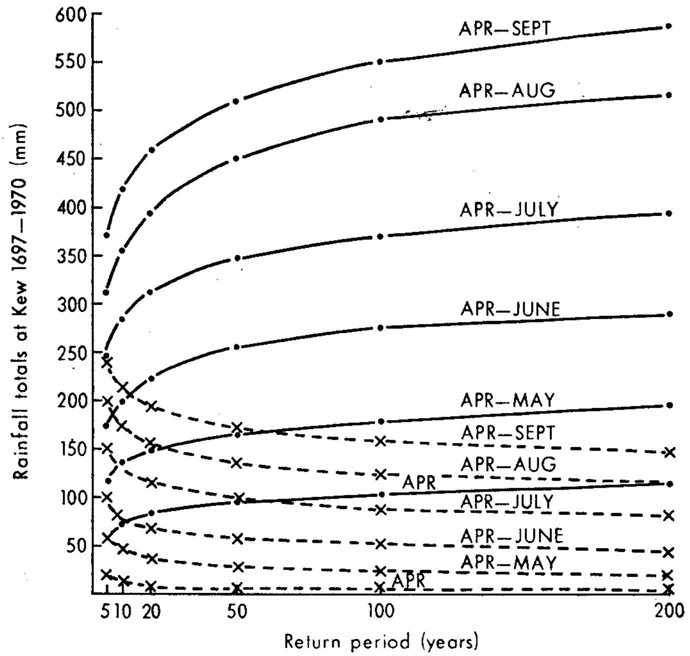

FIGURE 4—AMOUNTS OF RAINFALL AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

•——• Likely to occur or to be exceeded. x – – x Likely not to be exceeded.

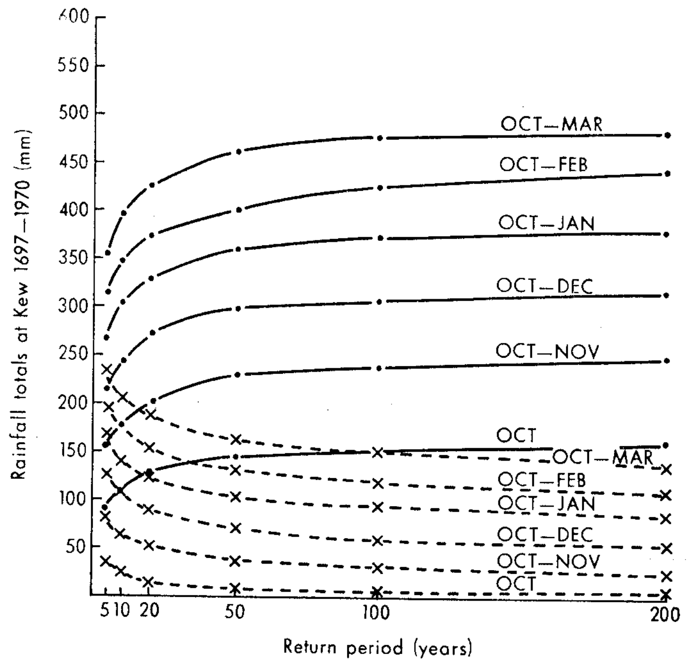

FIGURE 5—AMOUNTS OF RAINFALL AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

TABLE I—EXTRAPOLATION OF PROBABILITY DIAGRAMS TO PROVIDE ESTIMATES IN MILLIMETRES OF VALUES OF EXTREMELY RARE RAINFALL AT KEW

Probable extreme values

WET

	Return periods 500 years	Return periods 1000 years
Jan.	137·2	142·2
Feb.	127·0	132·1
Mar.	121·9	127·0
Apr.	124·5	129·5
May	134·6	142·2
June	172·7	188·0
July	185·4	190·5
Aug.	162·6	175·3
Sept.	152·4	160·0
Oct.	167·6	175·3
Nov.	190·5	200·7
Dec.	172·7	175·3
Year	980·4	1021·1
Apr.–May	205·7	213·4
Apr.–June	307·3	322·6
Apr.–July	424·2	436·9
Apr.–Aug.	533·4	546·1
Apr.–Sept.	612·1	629·9
Oct.–Nov.	254·0	261·6
Oct.–Dec.	322·6	330·2
Oct.–Jan.	388·6	398·8
Oct.–Feb.	447·0	452·1
Oct.–Mar.	487·7	492·8
Mar.–Apr.	177·8	182·9
May–Aug.	485·1	515·6
Sept.–Oct.	266·7	274·3
Nov.–Feb.	429·3	457·2

DRY

	Return periods 500 years	Return periods 1000 years
Year	292·1	279·4
Apr.–May	17·0	15·7
Apr.–June	42·7	40·6
Apr.–July	72·4	67·3
Apr.–Aug.	104·1	96·5
Apr.–Sept.	134·6	127·0
Oct.–Nov.	20·3	17·8
Oct.–Dec.	45·7	41·9
Oct.–Jan.	73·7	67·3
Oct.–Feb.	96·5	90·2
Oct.–Mar.	124·5	115·6
Mar.–Apr.	7·6	6·3
May–Aug.	83·8	76·2
Sept.–Oct.	22·9	17·8
Nov.–Feb.	73·7	68·6

TABLE II—RAINFALL AMOUNTS IN MILLIMETRES FOR THE SIX WETTEST AND SIX DRIEST MONTHS AT KEW, 1697–1970

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						Wettest					
136·7	126·5	118·4	121·9	140·7	183·1	177·8	165·6	145·0	169·9	189·0	169·4
1749	1951	1947	1829	1777	1903	1828	1878	1918	1744	1755	1747
127·5	120·4	102·9	111·8	116·8	147·3	174·5	149·6	139·5	151·1	171·7	166·6
1877	1763	1851	1744	1817	1860	1782	1941	1775	1841	1940	1914
120·1	104·4	100·3	98·3	115·6	135·6	165·1	134·4	136·1	151·1	157·0	146·6
1943	1879	1916	1878	1703	1797	1779	1912	1896	1880	1970	1876
117·6	102·9	100·1	97·5	111·0	129·5	157·2	132·6	135·4	150·6	154·4	136·9
1764	1937	1914	1756	1865	1838	1806	1737	1768	1891	1810	1915
109·5	102·4	99·1	95·5	106·7	117·1	150·6	128·3	130·6	149·9	152·4	135·1
1939	1866	1821	1809	1824	1728	1956	1879	1797	1865	1852	1779
109·2	94·0	96·5	93·0	105·9	116·8	139·2	123·2	127·0	147·1	134·4	132·1
1828	1812	1818	1800	1734	1852	1853	1931	1839	1882	1951	1821
						Driest					
3·1	0·0	0·8	2·3	4·8	1·0	0·0	0·5	0·0	2·0	6·9	0·0
1766	1821	1929	1938	1896	1925	1800	1750	1804	1788	1749	1788
3·3	2·3	1·3	2·3	5·1	5·1	2·5	1·8	1·8	3·8	7·4	2·5
1731	1959	1731	1855	1833	1921	1825	1727	1754	1947	1945	1829
4·8	2·3	2·0	2·3	5·6	6·3	3·8	2·0	2·5	4·1	9·9	2·8
1802	1891	1781	1840	1956	1923	1921	1726	1959	1969	1956	1762
6·1	2·5	2·3	2·5	7·4	6·3	6·9	2·3	2·5	4·6	10·2	6·1
1705	1725	1944	1893	1880	1757	1864	1940	1795	1809	1727	1926
6·3	3·3	2·3	2·5	7·6	6·6	7·6	2·5	2·8	6·3	10·7	8·1
1779	1895	1796	1817	1844	1932	1835	1818	1969	1708	1867	1933
6·6	4·3	2·5	3·8	8·4	7·1	10·2	2·5	3·3	8·1	10·9	9·1
1810	1932	1768	1912	1895	1962	1955	1742	1743	1781	1699	1844

TABLE III—SIX WETTEST AND SIX DRIEST OF SETS OF 1 TO 6 CONSECUTIVE MONTHS STARTING IN OCTOBER AND APRIL AT KEW, 1697–1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

Oct.	Oct.–Nov.	Oct.–Dec.	Oct.–Jan.	Oct.–Feb.	Oct.–Mar.	Apr.	Apr.–May	Apr.–June	Apr.–July	Apr.–Aug.	Apr.–Sept.
					Wettest						
169·9	247·7	317·5	379·5	463·0	483·4	121·9	202·4	312·9	421·4	521·2	603·3
1744	1852	1821	1876	1914	1914	1829	1878	1903	1903	1903	1903
151·1	245·1	308·9	379·0	428·5	479·8	111·8	185·2	273·6	384·6	512·8	579·6
1841	1841	1755	1914	1865	1876	1744	1703	1879	1879	1879	1879
151·1	237·2	306·1	373·4	423·9	476·8	98·3	177·3	272·3	363·5	497·6	527·8
1880	1939	1841	1929	1876	1755	1878	1879	1878	1728	1878	1782
150·6	232·9	304·5	365·0	412·5	469·9	97·5	167·9	271·8	357·4	469·9	522·5
1891	1940	1929	1755	1755	1865	1756	1777	1860	1782	1782	1878
149·9	229·1	303·5	363·5	400·8	466·9	95·5	162·8	266·2	349·3	444·5	517·4
1865	1755	1852	1911	1882	1911	1809	1782	1703	1703	1828	1768
147·1	228·6	290·1	357·1	397·8	455·9	93·0	162·6	256·5	342·9	436·4	515·1
1882	1960	1779	1852	1911	1915	1800	1819	1824	1860	1860	1860
					Driest						
2·0	17·8	17·8	74·7	104·7	127·8	2·3	16·5	29·0	60·7	85·9	130·6
1788	1788	1788	1879	1933	1724	1938	1844	1870	1921	1921	1921
3·8	30·2	63·5	79·0	108·2	147·8	2 3	19·1	44·2	70·1	131·3	151·6
1947	1708	1879	1788	1714	1879	1855	1870	1938	1938	1870	1959
4·1	31·0	66·8	88·9	118·1	155·7	2·3	19·3	56·1	80·0	133·9	161·0
1969	1947	1714	1834	1724	1890	1840	1762	1844	1870	1896	1705
4·6	36·3	68·6	90·9	122·2	158·5	2·5	19·6	56·9	82·5	135·1	172·7
1809	1733	1933	1714	1890	1933	1893	1896	1921	1762	1864	1870
6·3	37·3	71·1	99·1	129·8	162·6	2·5	24·9	57·4	86·6	138·7	172·7
1708	1897	1834	1933	1931	1931	1817	1795	1806	1781	1938	1714
8·1	39·6	73·7	112·8	130·3	165·9	3·8	29·2	58·2	89·4	141·2	174·5
1781	1809	1871	1858	1879	1730	1912	1785	1895	1705	1714	1893

TABLE IV—SIX WETTEST AND SIX DRIEST SEASONS AND YEARS AT KEW, 1697–1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

Spring (Mar.–Apr.)	Summer (May–Aug.)	Autumn (Sept.–Oct.)	Winter (Nov.–Feb.)	Year
		Wettest		
180·3	476·5	263·7	432·8	969·5
1818	1903	1880	1914–15	1903
166·1	435·4	256·8	385·8	922·0
1848	1879	1744	1876–77	1824
163·8	412·0	251·5	372·4	876·3
1964	1782	1841	1755–56	1821
161·8	411·0	224·3	348·2	863·9
1756	1860	1808	1950–51	1852
161·5	399·3	221·5	341·9	844·8
1862	1878	1903	1763–64	1841
161·3	383·5	219·5	321·6	841·0
1851	1828	1960	1911–12	1879
		Driest		
8·6	58·9	6·9	68·1	308·4
1840	1921	1969	1933–34	1921
8·9	97·3	28·2	82·5	311·7
1938	1959	1941	1714–15	1714
11·9	99·1	33·0	84·3	345·7
1796	1780	1834	1744–45	1731
13·2	105·2	33·5	87·1	370·8
1893	1899	1947	1703–04	1723
13·5	109·2	41·1	87·6	416·1
1781	1818	1890	1724–25	1864
16·8	109·7	41·1	96·0	417·3
1852	1714	1964	1890–91	1840

TABLE V—SIX WETTEST AND SIX DRIEST SEASONS AT KEW, 1871–1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

Spring (Mar.–Apr.)	Summer (May–Aug.)	Autumn (Sept.–Oct.)	Winter (Nov.–Feb.)
		Wettest	
163·8 1964 (3)	476·5 1903 (1)	263·7 1880 (1)	432·8 1914–15 (1)
161·0 1947	366·5 1917	221·5 1903 (5)	385·8 1876–77 (2)
137·2 1919	349·3 1941	219·5 1960 (6)	348·2 1950–51 (4)
133·9 1888	332·7 1946	208·0 1885	321·6 1911–12 (6)
131·3 1951	312·4 1958	207·0 1882	318·8 1929–30
127·0 1940	307·9 1924	196·9 1896	311·7 1940–41
		Driest	
8·9 1938 (2)	58·9 1921 (1)	6·9 1969 (1)	68·1 1933–34 (1)
13·2 1893	97·3 1959 (2)	28·2 1941 (2)	96·0 1890–91
27·2 1943	105·2 1899 (4)	33·5 1947 (4)	96·8 1908–09
27·9 1929	119·1 1896	41·1 1964 1890 (5) (6)	105·7 1879–80
31·2 1955	131·3 1911	50·0 1959	112·3 1873–74
34·5 1957	132·1 1940	51·3 1919	113·3 1931–32

Numbers in brackets show the ranks of events in the whole 274-year series.

Extreme-value plotting positions were calculated, using the formula shown in equation (1) with $n = 100$ years and with m taking values from 100 to 95. The six wettest and six driest values for each 'season' (1871–1970) were plotted on the same sheets of extreme-value probability paper as had been used to plot data from the whole 274-year period. Differences between 100-year and 274-year curves may be summarized as follows :

Changes introduced by using 1871–1970 data only

Spring	Wet :	Reduce thresholds (Figure 6) as follows : 20-yr by 13 mm; 50-yr by 10 mm; 100-yr by 5 mm
	Dry :	No change
Summer	Wet :	Reduce thresholds 20-yr by 31 mm; 50- and 100-yr by 23 mm; 200-yr by 20 mm
	Dry :	Reduce thresholds 50-yr by 8 mm; 100-yr by 13 mm; 200-yr by 15 mm

Autumn	Wet :	No change
	Dry :	Reduce thresholds 20-yr by 5 mm; 50-yr by 13 mm; 100-yr by 15 mm; 200-yr by 18 mm
Winter	Wet :	No change
	Dry :	No change

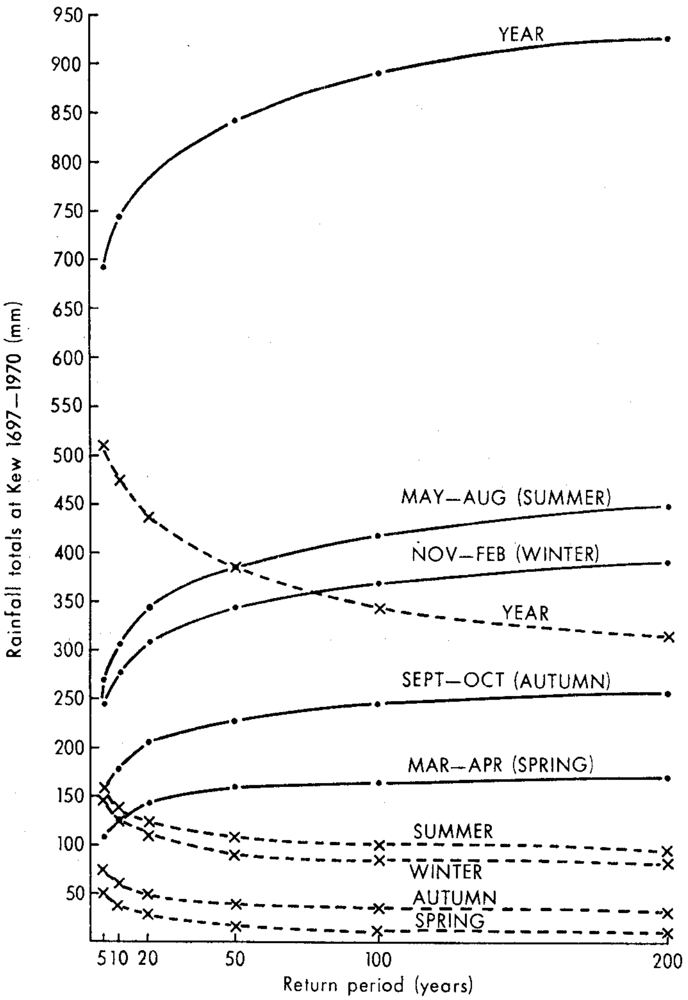

FIGURE 6—AMOUNTS OF RAINFALL AT KEW IN A YEAR OR IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

• —— • Likely to occur or to be exceeded. x – – x Likely not to be exceeded.

Another comparison can be made by considering the apparent status of the extreme values for 'seasons' from the whole 274-year series judged by the 274- and 100-year curves.

Year dates and return periods

		Spring	Summer	Autumn	Winter
Wet		1818	1903	1880	1914–15
	274-yr	400 years	400 years	400 years	500 years
	100-yr	400 years	> 500 years	400 years	400 years
Dry		1840	1921	1969	1933–34
	274-yr	400 years	5000 years?	5000 years?	1000 years?
	100-yr	400 years	> 1000 years	> 400 years	1000 years?

The recent 'summer' (1972) with only 74·8 mm of rainfall, would rank as a 200–300-year event judged by 1871–1970 data and could even be ranked as a 1000-year event in the whole 274-year series.

Trends in the series. The monthly totals of the whole series, added together for the seasons suggested by A. Bleasdale, are plotted as diagrams (Figures 7 to 10). The 'second extremes' in each decade are joined up by straight lines, the decadal extremes being shown as unconnected points. This has been done because extreme cases are often out of step with general trends; 10-year averages are shown as broken lines. The distances between the average points and the 'second extremes' show, roughly, how nearly the averages approximate to median values or, in other words, roughly how the individual year points are distributed for any season and decade.

As can be seen in Figure 11, decadal averages of annual totals rose from relatively low values at the beginning of the eighteenth century to a peak in the early nineteenth century, followed by several long-period undulations about an average value somewhat higher than that of the first half of the eighteenth century.

The decadal extremes show the same long-period trend with a steady rise to higher maxima and minima from the beginning of the record to the early nineteenth century. Since 1903, maxima have returned to the levels characteristic of the eighteenth century and the extreme dry year of the whole record (1921 with 308·4 mm) was the first year with rainfall less than 400 mm since 1731.

Summers (Figure 8), although erratic, show the same general trends very well. In the central 13 decades there have been 15 summers with $\geqslant$12 inches (304·8 mm) and only 9 in the outer 14 decades. For $\geqslant$15 inches (381·0 mm) the numbers are 5 and 1 respectively. Turning from wet summers to dry winters, we find only 10 winters with $\leqslant$5 inches (127·0 mm) in the central 13 decades but 18 in the outer 14 decades. For $\leqslant$4 inches (101·6 mm) the numbers are 2 and 6 respectively. Thus in the central period there were more very wet summers and fewer very dry winters and in the outer decades fewer very wet summers and more very dry winters.

'Autumn' (Figure 9) shows up as a remarkably reliable period, for rainfall, since the early nineteenth century, but with a slow downward trend, so that decadal averages in the twentieth century have almost returned to the values characteristic of the early eighteenth century.

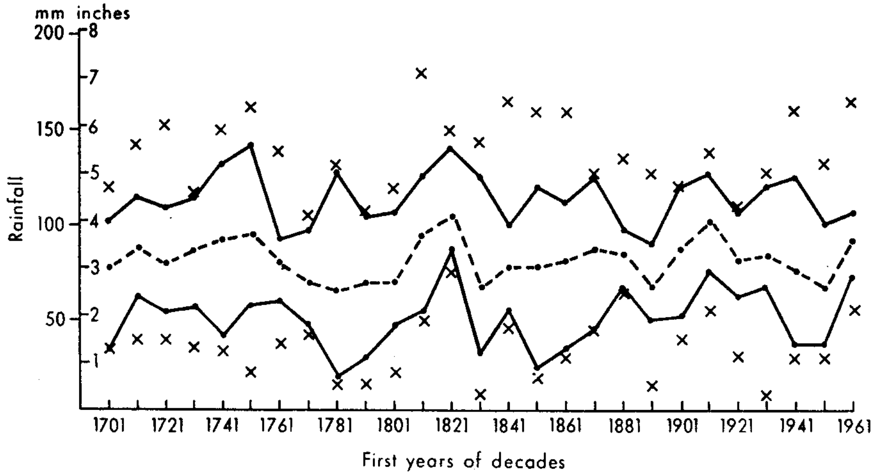

FIGURE 7—SPRING RAINFALL REPRESENTATIVE OF KEW

Uppermost curve : second wettest in each decade. Lowest curve : second driest in each decade. Middle curve (broken) : decadal average. x : wettest or driest in each decade.

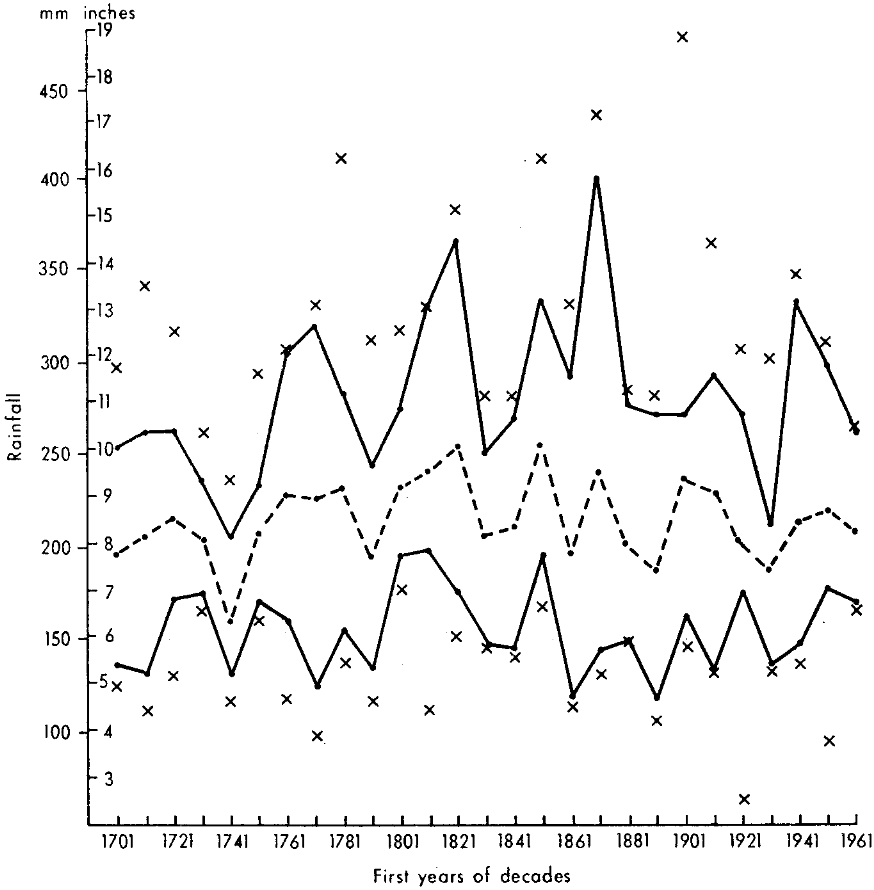

FIGURE 8—SUMMER RAINFALL REPRESENTATIVE OF KEW

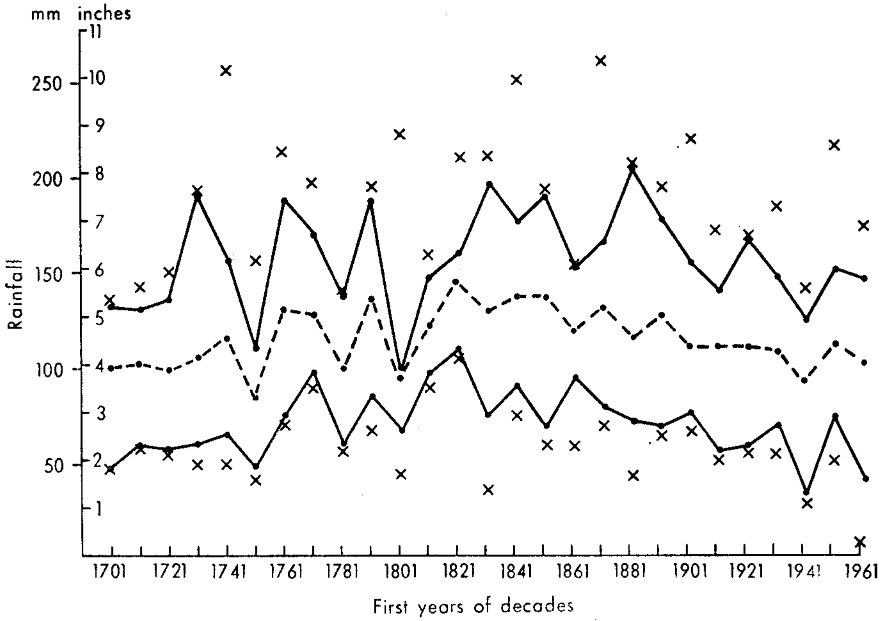

FIGURE 9—AUTUMN RAINFALL REPRESENTATIVE OF KEW

Uppermost curve : second wettest in each decade. Lowest curve : second driest in each decade. Middle curve (broken) : decadal average. x : wettest or driest in each decade.

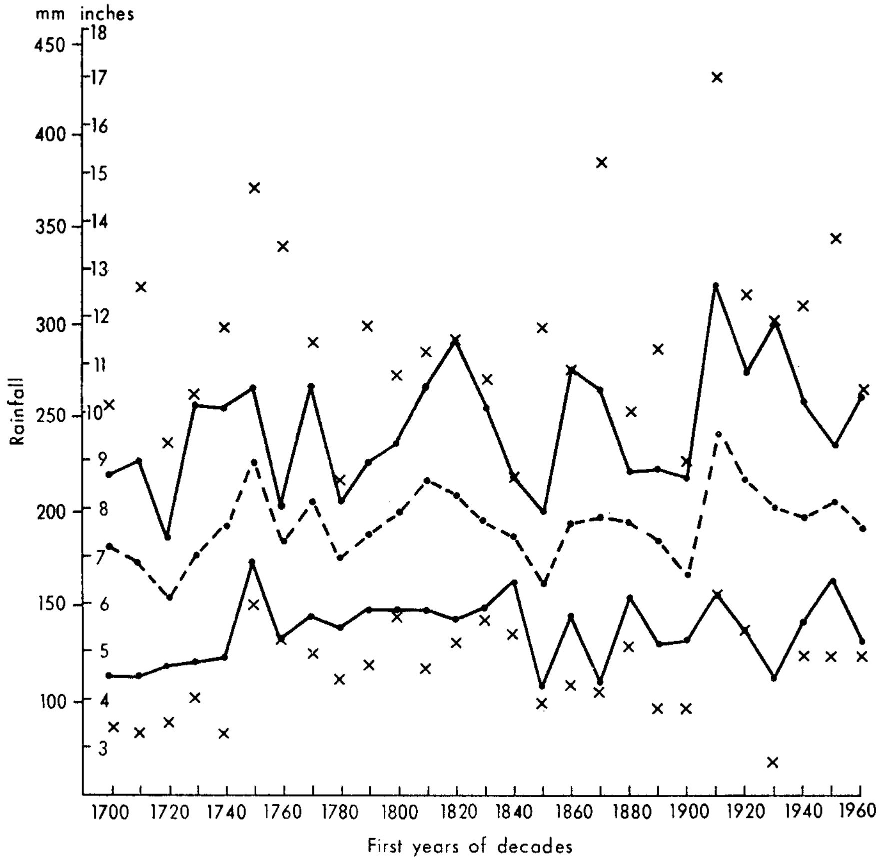

FIGURE 10—WINTER RAINFALL REPRESENTATIVE OF KEW

Uppermost curve : second wettest in each decade. Lowest curve : second driest in each decade. Middle curve (broken) : decadal average. x : wettest or driest in each decade.

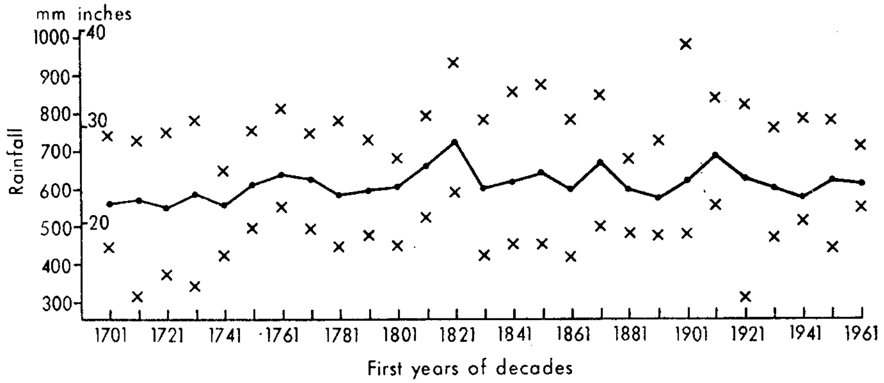

FIGURE 11—ANNUAL RAINFALL REPRESENTATIVE OF KEW

•——• Decadal average. x Wettest or driest in each decade.

Acknowledgements. In addition to the invaluable assistance of the computer programmers already mentioned the writer would like to thank Messrs A. Bleasdale, M. C. Jackson and A. F. Jenkinson for helpful advice and for comments on the draft of this article.

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551.593.653

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1972

By J. PATON

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Observations of the night sky during the period from 26–27 May until 6–7 August when noctilucent clouds (NLC) may be observed in latitudes south of about 60°N are contained in Table I. On nights when noctilucent clouds were reported, the period of time during which the clouds were observed appears in the second column. Observations of the characteristics of the observed NLC are entered in the third column. The remaining columns contain observations from selected stations, the latitude and longitude of which are given to the nearest half degree. The maximum elevation and limiting azimuths of the observed cloud field at the stated times in Universal Time (UT) appear in the last two columns. On nights when skies are sufficiently clear of tropospheric clouds to permit the decision that NLC are absent, 'No NLC' is entered in the third column. When the prevalence of tropospheric clouds makes it impossible to decide whether or not NLC are present, 'Cloudy' appears in the third column.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1972

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. *degrees*	Limiting azimuths *degrees*
26–27 May		Cloudy				
27–28		No NLC				
28–29		Cloudy				
29–30		No NLC				
30–31		Cloudy				
31 May–1 June		No NLC				
1–2 June		No NLC				
2–3		No NLC				
3–4		No NLC				
4–5		No NLC				
5–6		No NLC				
6–7		No NLC				
7–8		No NLC				
8–9		No NLC				
9–10		Cloudy				
10–11		No NLC				
11–12		No NLC				

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
					degrees	
12–13 June		No NLC				
13–14		No NLC				
14–15		Cloudy				
15–16		No NLC				
16–17		No NLC				
17–18		Cloudy				
18–19		No NLC				
19–20	2310–0130	Faint to moderately bright display, of limited extent, consisting of veil and bluish-white bands and billows.	57°N 2°W	2400	10	053
				0100	60	360–045
			55·5°N 3°W	0045	20	020–030
			55°N 3°W	0001	11	360–010
				0115	30	340–020
			54°N 0·5°W	0044	9	340–025
			54°N 1·5°W	2350	7	360–010
			53°N 0°	0015	5	015–032
				0115	7	360–016
			53°N 4°W	0001	5	340–020
			53°N 0·5W	0015	6	350
20–21		Cloudy				
21–22		No NLC				
22–23		No NLC				
23–24		Cloudy				
24–25	2345–0045	Wisps of NLC seen through low cloud.	55·5°N 1·5°W	2345	10	020–053
25–26	2145–0150	Veils, bands, billows and whirls seen through gaps in low cloud over the British Isles, and more clearly over Denmark.	57·5°N 7·5°W	0148		060–100
			57°N 2°W	0130	60	340–040
			55·5°N 12·5°E	2145	40	310–325
			53°N 0·5°E	2245	5	360
				0140	12	360–045
			53°N 0·5°W	2150	20	290–010
				2310	7	310–350
26–27	2330–0150	Widespread bands and whirls seen in poor observing conditions due to extensive cirrus. Seen from Aberdeen (57°N 2°W) to extend 'at morning twilight over entire northern half of sky up to and past zenith'.	58·5°N 3°W	2345	30	
			55·5°N 1·5°W	2345	25	340–050
27–28		No NLC				
28–29	2245–0050	Faint veil and bands	55·5°N 1·5°W	2245	8	330–030
				0050	5	350–045
29–30		No NLC				
30 June–1 July		No NLC				
1–2 July		No NLC				
2–3	2300–0130	Bright veil and bands visible through extensive cirrus	56·5°N 3°W	2330	8	025
			55·5°N 1·5°W	2300	15	330–020
				2400	10	360–040
			55·5°N 3°W	0130	15	020
3–4	2220–2400	Cloudy over British Isles. Greenish band and whirls observed from Denmark.	56°N 10°E	2258	12	320–060
4–5		No NLC				
5–6		Cloudy				
6–7	2100–2315	Overcast over most of British Isles except the extreme south. Extensive display of veil, bands, billows and possibly also whirls observed from Dover. Reports also from Denmark.	56°N 10°E	2100	15	340
				2230	20	340–020
			51°N 1·5°E	2127	95	
				2145	90	350
7–8	2240–0150	Brilliant display of greenish-white veil, bands, billows and whirls seen in gaps in extensive stratocumulus. The prevailing low cloud limited and made uncertain the measurements of elevations and azimuths.	57°N 2°W	2315	14	330–360
			56·5°N 3°W	2345	10	350–035
			55·5°N 1·5°W	2400	8	350–010
			55·5°N 3°W	2304	15	360–025
			55·5°N 5°W	2335	7	020–040
			54°N 4·5°W	0020	20	350
			52°N 6·5°W	0030	7	
8–		No NLC				
9–10		No NLC				

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths
					degrees	
10–11 July	2200–0210	Moderately bright display of veil and bands, 'with structure appearing almost to the zenith' at Oslofiord, Norway (59°N 10°E), between 2345 UT and 0045 UT.	60°N 1°W	2323	64	310–005
			57·5°N 7·5°W	0050	13	330–360
				0210	20	330–010
			56·5°N 7°W	2340	11	340–020
				0145	13	360–010
			56°N 10°E	2200	20	290–045
				0040	20	315–045
11–12	2245–0230	Compacted bands, generally faint but occasionally bright in parts.	57°N 2°W	2300	23	340–020
			56·5°N 3°W	2330	15	315–045
			55·5°N 1·5°W	2250	15	
			55°N 1·5°W	2250	20	320–340
				2345	5	320–010
			54°N 0·5°W	2250	7	004
			53°N 0·5°E	0145	7	360
				0230	15	340
12–13	2105–0230	Moderately bright display of veil, bands and billows.	56·5°N 3°W	0112	10	345–070
				0133	17	
			56°N 10°E	2105	10	045
				2200	23	315–045
			55·5°N 7·5°W	0210	6·5	030
			54·5°N 1·5°W	2300	2	350–010
				0051	4·5	350–045
				0200	6	340–020
			54°N 1·5°W	0030	4·5	330–040
				0130	5	330–040
13–14		No NLC				
14–15	2210–0200	Faint bands seen through occasional gaps in extensive stratocumulus cloud. No measurements of maximum elevation possible.	56·5°N 3°W	2245		345–360
				0045		010–020
			55·5°N 4·5°W	0200		010–020
15–16	2100–2300	Veil and bands visible from Denmark, brightest at 2140 UT. Cloudy over British Isles.	56°N 10°E	2100	40	315
				2200	20	
				2300	10	360
16–17	2230–2320	Bright veil and compacted bands.	56°N 10°E	2230	7	360–045
			54°N 4·5°W	2240	25	335–350
17–18	2230–2250	Short-lived display of weak bands.	56·5°N 3°W	2230	5	360–020
18–19	2210–0230	Moderately bright bands.	56·5°N 7°W	0130	13	340–020
19–20	2215	Greenish bands visible from Denmark close to northern horizon for about 20 minutes.	55·5°N 12·5°E	2215	10	
20–21		No NLC				
21–22	2100–0230	Bright display of veil and bands.	58·5°N 3°W	2400	20	315–360
			56°N 10°E	2100	10	360–045
				2320	7	315–045
22–23		Cloudy				
23–24		Cloudy				
24–25	0245–0310	Bands seen through temporary clearance in extensive low cloud.	54°N 4·5°W	0245	10	360–055
25–26	2225–0300	Bright bands and billows.	57·5°N 6°W	2400	3	010–020
				0100	7	360–020
				0200	15	340–030
				0300	25	355–030
			56·5°N 7°W	2225	10	340–030
				2340	5	340–020
				0150	8	340–040
				0250	8	350–040
26–27		No NLC				
27–28		No NLC				
28–29		No NLC				
29–30		Cloudy				
30–31		Cloudy				
31 July–1 Aug.		Cloudy				
1–2 Aug.		Cloudy				
2–3		No NLC				
3–4		Cloudy				
4–5	2245–0250	Veil, bands, billows and whirls, accompanied by aurora.	60°N 1°W	2245	15	320–030
				0200	15	340–040
			58·5°N 3°W	0120	12	340–040
5–6		Cloudy				
6–7		No NLC				

The number of nights during which NLC were observed in 1972 was 22. An adjustment to this figure to account for unobserved occurrences on cloudy nights (17) may be made by assuming that NLC would be present on the same fraction of these nights as of clear nights (22 in 56) during the NLC season, 26–27 May to 6–7 August. This gives a frequency of 29 nights for 1972. Making the same adjustment, the frequencies for the years for which data are available (1967–71) are found to be 44, 39, 30, 20 and 22 respectively.

The first appearance of the clouds was later than normal by over a fortnight. If the NLC consist of ice crystals, as has been indicated by rocket experiments, then one may assume that either the attainment of the summer minimum of temperature at the mesopause or the flow of water vapour up through the mesosphere was delayed during the summer of 1972.

Four displays, on the nights of 19–20 and 25–26 June and 6–7 and 10–11 July, extended farther south than is normal; the display of 6–7 July extended so far southwards that it was observed south of the zenith at Dover.

The clouds receded northwards at the usual time of early August. They were last seen from Stornoway, Wick and Lerwick on the night of 4–5 August when they occurred simultaneously with aurora. Well-marked whirls became more prominent as this display progressed, an event which has been observed on several occasions[1,2] when these two phenomena have occurred together.

The assistance of the many observers who, by providing visual observations, photographs and sketches, have made this analysis possible is gratefully acknowledged. These synoptic studies continue and new observers are invited to send their observations to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh EH8 9UA, Scotland. Notes on the recording of observations will be supplied from the laboratory.

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551.586:631

THE 'GROWING SEASON' AT ESKDALEMUIR OBSERVATORY, DUMFRIESSHIRE

By R. W. GLOYNE

Summary. The dates of the commencement and end of the 'growing season' and its length for the years 1914 to date, were examined for Eskdalemuir, a station in the Southern Uplands of Scotland. The commencing date in spring showed a greater degree of variability (a standard deviation of 13–16 days according to period) than did that of cessation (8–11 days). Mean values of the length of the season were higher for the decades 1941–50 and 1951–60 than either before or since; however the successively increasing length for each of the years 1970–72 should be noted. The commencing date in most years was found to be closely related to the mean temperature for the month of April.

Introduction. In temperate climates it is a conventional practice to define a 'growing season' as that period of the year when mean temperature (sometimes relating to shallow depths in the soil, but more generally in the air at the standard height of 1·25 m from the ground, exceeds 5·6°C (42°F).

Although the growth of a wide range of indigenous species cannot be too closely linked with a particular level of mean temperature, experience shows that the 'growing season' so defined is a useful crude parameter for evaluating the impact of climate on many phases of agricultural production.

The increasing interest in the agricultural potential of the hill areas and the possibility of climatic variations on a scale of decades of years having significant impact upon agriculture, renders an analysis of the 'growing season' a matter of some interest. For this exercise data from Eskdalemuir Observatory (55° 19′N, 03° 12′W, 242 m above MSL) for the period 1914–72 were examined.

Data and procedures. From the readily available week-by-week averages of mean daily air temperature, the day of the year (D_1) on which the level of mean temperature rose above 42°F and that (D_2) on which it fell below 42°F were estimated from a smooth curve drawn through the weekly values. In some years values oscillated about 42°F before being sustained above (or below) this threshold; in such cases an estimate, subjectively derived from the run of the curve, was adopted. Transient excursions of the temperature above 42°F occurring either very early or very late in the year were ignored when defining the passage of the curve through the threshold value.

The sequences of values of D_1 and D_2 are plotted in Figure 1, values of L (the length of the 'season') in Figure 2, and in Figure 3 the associated length (L') of the 'non-growing season'. In Figure 4 is given a scatter diagram showing the relationship between D_1 and the mean temperature for the month of April. Statistical parameters for D_1, D_2 and L, for 1914–20 and the subsequent decades 1921–30, etc. to 1961–70 are set out in Table I.

TABLE I—'GROWING SEASON' AT ESKDALEMUIR 1914–70, DECADAL AND PERIOD VALUES

	D_1			D_2			L		
	Mean value	Range	S.D.	Mean value	Range	S.D.	Mean value	Range	S.D.
			days			*days*		*days*	
1914–20	19/4	8/4–4/5	7	4/11	20/10–22/11	13	199	184–217	12
1921–30	21/4	3/4–4/5	10	30/10	17/10–15/11	8	192	173–217	12
1931–40	11/4	3/3–27/4	16	3/11	19/10–22/11	11	206	175–264	25
1941–50	6/4	11/3–29/4	15	4/11	23/10–17/11	8	213	184–243	19
1951–60	8/4	16/3–30/4	18	9/11	19/10–19/11	9	215	187–248	19
1961–70	10/4	1/3–24/4	15	4/11	27/10–14/11	6	209	195–250	17
1914–40	17/4	3/3–4/5	13	2/11	17/10–22/11	11	199	173–264	19
1941–70	8/4	1/3–30/4	16	6/11	19/10–19/11	8	212	184–250	19

D_1 = Mean date of beginning of season; D_2 = Mean date of end of season; L = Length of season; S.D. = Standard deviation.

Discussion. (a) From 1914 to about 1930 and from 1962 to 1971, the date of the beginning of the 'season' (D_1 of Figure 1) varied between about 10 April (day 100) and 30 April (day 120); in the intervening period it fluctuated widely, and in 10 of the years (most markedly in 1938, 1945, 1948,

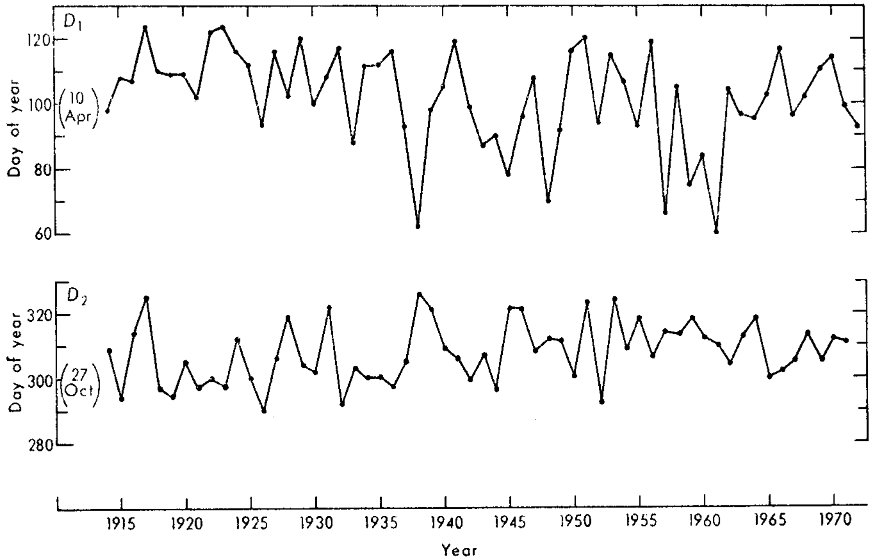

FIGURE 1—DATES OF THE BEGINNING (D_1) AND END (D_2) OF THE 'GROWING SEASON' AT ESKDALEMUIR

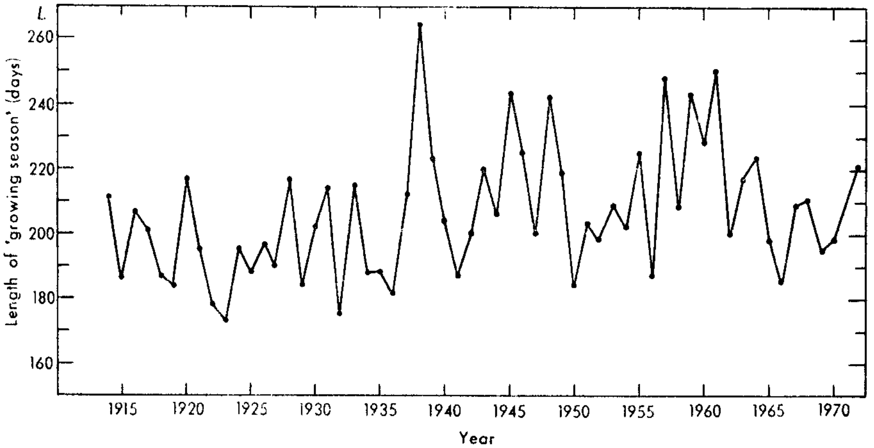

FIGURE 2—LENGTH (L) OF THE 'GROWING SEASON' AT ESKDALEMUIR

1957, 1959 and 1961) it occurred in the month of March. These dates are shown as anomalies in Figure 4; further examination of these cases revealed that all occurred with a monthly mean March temperature equal to or greater than 4·7°C (40·5°F).

The need for caution in projecting any short-period trend is well indicated by the behaviour of D_1 from 1966 to date.

Decadal means of D_1 are set out in Table I. The fortuitous effect of selecting any particular period for averaging is well illustrated by the contrast between the mean value for 1961–70 and that given by a 10-year period 1962–71 (mean D_1 being 10 April and 14 April respectively).

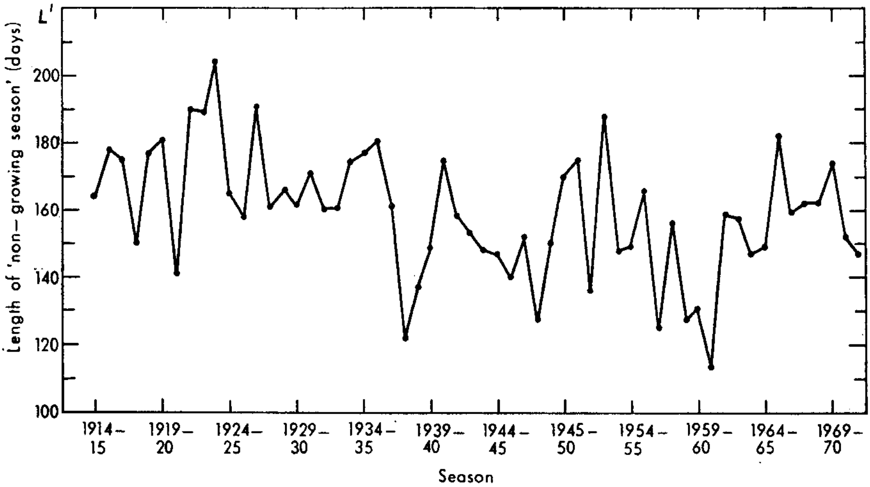

FIGURE 3—LENGTH (L') OF THE 'NON-GROWING SEASON' AT ESKDALEMUIR

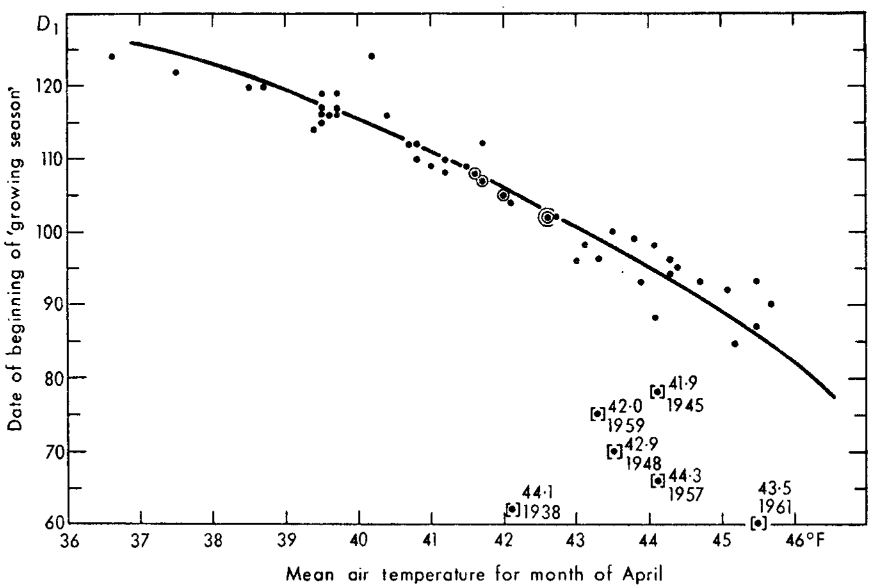

FIGURE 4—PLOT OF DATE (DAY OF YEAR) D_1 OF BEGINNING OF 'GROWING SEASON' AGAINST MEAN MONTHLY TEMPERATURE FOR APRIL — AND FOR SOME YEARS MARCH — AT ESKDALEMUIR (1914–70)

Encircled dots indicate repeated observations. Figures adjacent to plots in square brackets indicate mean temperature for *March* and year of occurrence.

(b) The date of the end of the season (D_2 of Figure 1) has fluctuated far less widely than has D_1; in most seasons this occurs between 24 October (day 297) and 16 November (day 320).

(c) The length (L) of the season (Figure 2) reveals the wide fluctuations in the 1936–61 period compared with the steadier behaviour prior to and subsequent to these years; furthermore the experience of long seasons (240 days or more) from the late 1930s to the early 1960s should not necessarily be regarded as typical on a long-term basis. It should also be noted that during this last-mentioned period, years occurred when the commencing date was as late, and the season as short, as was experienced more frequently during the preceding and the following periods. The effect of a very anomalous year 1938 on the value of the standard deviation of L for the 1931–40 decade (see Table I) underlines the need for caution when using this parameter for statistical estimation.

(d) In Figure 3 the data have been set out in terms of the length of the non-growing season. The 160(+) days prior to 1935–36, the more frequent shorter non-growing seasons from that date to 1960–61 and the more recent run of rather longer ones are evident.

(e) The arithmetic process of deriving a date such as D_1 or D_2 from the run of a mean temperature (T_m) necessarily implies a close association between the date and the value of T_m. However D_1 derived from the run of *weekly* means and the relationship between D_1 and a *monthly* mean is of some interest. A plot of D_1 against mean monthly temperatures for April is given in Figure 4 together with a free-hand 'best-fitting' curve.

There is a fairly satisfactory relationship between the date of D_1 (spanning the period 25 March to 5 May) and the mean temperature for April, unless the mean monthly March temperature was equal to or greater than 4·7°C (40·5°F); in all such cases and only in such cases the beginning of the season will occur in March and a March mean of 6·4°C (43·5°F) or more appears to be associated with a 'growing season' beginning in early March.

(f) To what extent the indications of the Eskdalemuir results can be regarded as representative for a substantial area of Scotland requires further investigation. However it is a matter of experience that maps of the 'temperature anomalies' (based upon mean monthly values) show a broad-scale coherent pattern over substantial areas, hence the year-to-year fluctuations in D_1 shown in Figure 4 (also those for D_2 and L) may be expected to be indicative of the experience over a wide area.

Secondly, a current parallel examination of the 'growing season' in south Norway from 1943 to date reveals the same contrast noted in Figure 1 between pre- and post-1961 behaviour.

Conclusions. Some tentative conclusions are :

(a) The date of the commencement of the 'growing season' at Eskdalemuir is considerably more variable than that of the end of the season.

(b) The frequent early dates of the beginning of the 'season' experienced in the 1936–61 period, and the associated prolonged seasons, are not typical of the pre-1936 or of the post-1961 eras. Alternatively expressed, the 'non-growing' ('winter') seasons prior to 1936 and since 1961–62 have tended to be longer than in the intervening years.

(c) The date of commencement of the 'growing season' is closely related to the mean temperature in the month of April, except when, and only when, the mean March temperature exceeds about 4·7°C (40·5°F), and in this case the season commences in March and possibly in early March.

551·509.323:551.525

EMBEDDED THERMOMETERS AND FORECASTS OF NIGHT MINIMUM TEMPERATURES AT WYTON

By W. G. RITCHIE and S. E. VIRGO, O.B.E.

Summary. This paper reports attempts to use temperatures obtained from thermometers embedded in soil and concrete to improve the accuracy of forecasts of night minimum air and concrete surface temperatures at Wyton.

Purpose of the experiment. Present methods of forecasting night minimum air temperatures use the properties of the air alone, but it has been suggested from time to time that better forecasts could be made if a method could be devised which incorporated the properties of the underlying soil; for example, Saunders[1] proposed the use of soil thermometers in 1952 and more recently Zdunkowski and Trask[2] have written a computer program which incorporates the properties of the soil. It might also be expected that temperatures measured inside the concrete of a road could be used to produce better forecasts of night minimum temperatures at the surface of the road. These conjectures led to the experiment with embedded thermometers described below.

Experimental arrangements. Thermometers were embedded with their bulbs at depths of 4 inches and 8 inches (10 cm and 20 cm) in an unused circle of mature concrete 25 yards (23 metres) in diameter and between 8 inches and 1 foot (20 cm–30 cm) thick in an open site on the airfield and at the same depths in the adjoining soil. A minimum thermometer, slightly tilted so that the bulb rested on the surface, was exposed near the thermometers embedded in the concrete, and the reading of this thermometer was taken to be the minimum surface temperature. In the rest of this paper this temperature will be called the minimum road surface temperature M_R (although the site was not actually a road) to accord with the nomenclature of previous papers.[3,4,5] To prevent accidental damage without appreciably affecting the exposure of the surfaces to the sky, a light frame was placed over the concrete thermometers and a similar frame over the soil thermometers. The frames were of angle-strip aluminium, 1/10-inch ($\frac{1}{4}$-cm) thick and $\frac{1}{2}$-inch ($1\frac{1}{4}$-cm) wide, in the form of an open 2-foot (60-cm) square with a 1-foot (30-cm) leg at each corner. The base of each leg was inserted into a piece of lead piping about 2-inches (5-cm) long to prevent movement by wind. All four embedded thermometers were read at 13 GMT daily, this being the time when night minimum temperature forecasts are made at Wyton.

Results.

1. *Forecasting night minimum air temperature.* The authors failed to find a method of using readings of the soil thermometers to improve forecasts of night minimum air temperature.

2. *Forecasting night minimum road surface temperature.* From data for the period October 1969 to September 1970, correlation coefficients were computed between the night minimum road surface temperature M_R and the previous day's 13 GMT temperatures at 4 inches (10 cm) and 8 inches (20 cm) in concrete and soil and air temperature and dew-point in the screen. All the

correlations were better for the winter than for the summer; this was fortunate as the aim was to improve frost forecasting. The three highest correlation coefficients were

between M_R and dew-point (screen)	0·71
between M_R and air temperature (screen)	0·69
between M_R and 4-inch concrete temperature	0·66.

It had been established previously that a regression equation set up for Watnall, giving M_R in terms of air temperature and dew-point at 12 GMT the previous day, was also valid for Wyton.[5] To determine whether air temperature or 4-inch concrete temperature would be a better starting point for forecasting M_R, a new regression equation was set up giving M_R in terms of 4-inch concrete temperature and screen dew-point at 13 GMT the previous day. Data for October 1969 were excluded because it was an unusually warm October. The equation was

$$M_R = 0{\cdot}40R_{13} + 0{\cdot}54D_{13} - 3{\cdot}1,$$

where R_{13} is the 4-inch concrete temperature at 13 GMT the previous day and D_{13} is the dew-point at the same time. Temperatures are in degrees Celsius.

For the nights during the periods October 1969 to April 1970 and October 1970 to April 1971 when no fronts passed between 12 GMT and 06 GMT, M_R was now forecast by three methods :

1. The indirect method. The first step was to forecast minimum air temperature by one of the recognized methods (McKenzie's method was used as it is convenient and as accurate as any other method[6]). The second step was to subtract a quantity which is a function of date alone and can be found from Ritchie's curve[3] or Parrey's equation[4] (these are essentially the same and give the same result).
2. Direct regression from air temperature and dew-point at 12 GMT the previous day.
3. Direct regression from 4-inch concrete temperature and dew-point at 13 GMT the previous day.

The forecasts were actually made after the event in order that mean wind speed and cloud amount could be estimated from observations in the Daily Register so as to eliminate any errors which might arise from inaccuracies in forecasts of these quantities.

The results obtained by the three methods are given in Table I. The error is reckoned as forecast value minus observed value in conformity with previous practice.[5,7] Distributions of errors are normal. The table shows remarkable agreement between values obtained for the season October 1969 to April 1970 — the season used for calculating the regression equation in the third method — and those obtained from independent data for the season October 1970 to April 1971.

Conclusion and discussion. Although no method was found of improving the forecasting of night minimum air temperature by means of readings taken at 13 GMT of thermometers embedded in soil and concrete, readings of a thermometer embedded at a depth of 4 inches in concrete could be used in a regression equation to improve the accuracy of forecasts of night minimum road surface temperature, but the improvement relative to the indirect method was only slight.

TABLE I—MEAN ERRORS AND STANDARD DEVIATIONS OF ERRORS IN FORECASTS OF ROAD SURFACE MINIMUM TEMPERATURE M_R BY THREE METHODS

	Oct. 1969–Apr. 1970 Mean	S.D.	Oct. 1970–Apr. 1971 Mean	S.D.
	degrees Celsius			
Indirect method	0·1	1·9	0·4	1·8
Regression from air temperature and dew-point	1·1	2·4	1·1	2·4
Regression from 4-inch concrete temperature and dew-point	−0·1	1·5	−0·1	1·6
Number of occasions	157		165	

S.D. = standard deviation.

It is suggested that the reason might lie in the close correlation between the 13 GMT air temperature and the 13 GMT 4-inch soil temperature. For the seven months October 1969 to April 1970 the correlation coefficient was 0·88 — a very high value. This is strong evidence for arguing that air temperature and soil temperature are not independent variables, and taking soil temperature into account introduces no new information into the calculations.

Insolation warms the surface of the soil (the area of concrete is small and its effect on air and soil temperatures must be trivial by comparison), and heat is transported downwards in the soil to the 4-inch level and lower by conduction and upwards in the air to screen level and beyond by convection and turbulence. Presumably this mechanism is responsible for the close correlation between the 13 GMT air and 4-inch soil temperatures.

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REVIEWS

Understanding lightning, by Martin A. Uman. 220 mm × 140 mm, pp. 166, *illus.*, The Oak Tree Press Ltd, Warwick House, 116 Baker Street, London W1M 2BB, 1972. Price: £2·75.

Dr Uman has spent 10 years or more in laboratory investigations into long sparks and research into lightning discharge. Much of this research has been sponsored by the United States Office of Naval Research, and during this time he has written many technical treatises on lightning and allied physical topics. With the present volume though, he turns his pen to a popular exposition designed for the non-scientist.

Experience in lecturing to high-school students and various lay societies has convinced Dr Uman that the same questions are always asked about lightning. In consequence, these questions have been used as chapter headings and so we have 'Why did Benjamin Franklin fly his kite?', 'How does a lightning rod work?', 'Does lightning never strike twice?', etc. There are 18 short chapters which fall into three groups. The first six chapters largely describe the behaviour of lightning whilst the second group of chapters attempts a physical explanation in simple terms of the processes occurring in the atmosphere. Towards the end of the book the subject matter becomes more speculative, answering questions such as 'Are UFO's and ball lightning related?' or 'Has lightning any practical use?'. The book is illustrated with some excellent photographs of lightning.

Almost inevitably the popular style leads to some looseness of phrase here and there, but on the whole the book provides an accurate description of lightning phenomena in accord with modern ideas. It is wellprinted and easy to read, so that the reader is encouraged to delve further. There are references at the end of each chapter to works which would enable the interested reader to establish his ideas on a more formal basis. Some of these books such as *Clouds, rain and rainmaking* by B. J. Mason or *The flight of thunderbolts* by B. F. J. Schonland are widely available, but other papers are in technical journals to which the lay reader is unlikely to have access. Probably the weakest aspect of the book is the way quantities are described, e.g. page 93 '. . . a few billionths of a second' or page 110 '. . . 1 000 000 watt-seconds per yard of channel length'. These units do not seem to be part of a scientific system nor are they likely to be readily appreciated by the non-scientist to whom the book is addressed.

It is difficult to imagine that anyone with some formal training in meteorology would prefer this book to other works which are available. It might well appeal to an uninformed member of the general public though, and be of value to teachers of elementary science in schools.

P. D. BORRETT

Clouds of the world, by Richard Scorer. 330 mm × 235 mm, pp. 176, *illus.,* David & Charles (Holdings) Ltd, South Devon House, Newton Abbot, Devon, 1972. Price: £12·60.

The book opens with the author's preface wherein he points out that the changing skies, although endowed through the ages with a spiritual existence, are mere physical and mechnical systems. It is his object to provide a simplified explanation in everyday terms of these systems, and this he does.

Professor Ludlam, another appreciative observer of clouds, gives a short history of cloud classification and suggests that current research into cloud physics supports a classification of clouds according to their genetic origin rather than to their form and shape.

The book is divided into 14 sections, each section dealing with a particular type of cloud. The sections are further subdivided to classify the clouds according to the processes which have caused their formation or affected their particular shape or location. Each section is prefaced by a concise text, well set out and clearly expressed, explaining the physical processes which caused the cloud to form or to take on a particular shape. The text is illustrated by simple well-drawn diagrams. Subsections have further brief notes and in some cases diagrams drawing attention to a particular feature of interest and explaining the air motions which gave rise to it.

Every subsection is then profusely illustrated by numerous coloured and, in some cases, black and white photographs, each with an appropriate text setting out the point of interest. Where stereoscopic pictures help to illustrate a special feature, the author has thoughtfully provided a selection of such pictures, adding a note on how these can be viewed without any special apparatus.

There is a short appendix on photogrammetry and stereo-photography with two examples of the accurate analysis of clouds in three dimensions, using stereoscopic photographs. A useful note is given on the method of taking stereo pictures from the air or from the ground using an ordinary single-lens camera. A brief bibliography is followed finally by a comprehensive index. The latter enables the reader to refer to the text and photographs concerning the phenomenon in which he is interested.

The numerous photographs have been carefully selected to bring out the features the author wishes to emphasize. They have been very well printed and the colour reproduction is excellent. Only about half a dozen of the many colour pictures have not really reproduced sufficiently well. The black and white pictures are as great a credit to the printer as to the original photographer. The author is to be congratulated on his selection and the printer on his high standard of reproduction.

Richard Scorer does not give long and involved proofs for his statements of the physical processes of cloud formation but he has convincingly produced visual evidence, capable of being understood by the intelligent reader with only a slight knowledge of physics and dynamics. He has achieved his object of providing a reference book for the meteorologist and the undergraduate, setting out in readable terms the physical and mechanical processes of the clouds, a subject much neglected by standard textbooks.

This book should most certainly appear in all university and senior school libraries and in the larger public reference libraries. Its pictures alone would fascinate many, so it is a pity that its price, a penalty for such an extensive use of colour, will place it beyond the pocket of the man in the street.

R. K. PILSBURY

The application of micrometeorology to agricultural problems, WMO Technical Note No. 119, edited by L. P. Smith. 275 mm × 213 mm, pp. vi + 74, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972. Price: Sw. fr. 10.

This publication, dealing with the planning and exploitation of fundamental research, further extends the range of topics dealt with in this very valuable series. As stressed (page xiii) the authors are concerned with the 'detailed examination on a micro-scale of the physical and meteorological processes taking place principally within the boundary layers between the top of a plant, tree or animal and the bottom of the roots in the soil'. Specifically they are not concerned with practical mesoscale phenomena such as, for example, 'frost hollows' — often incorrectly included under *micro*-meteorology; indeed they suggest (page 53) that 'micro-meteorology has little to offer at present in a direct manner to the land-worker or practitioner; ... and [results] have to be processed and modified before they can be used in practice'. The vocabulary and level of sophistication are those of, say, Sutton's *Micrometeorology*. The work is in three parts.

In Part I (pages 1–24) the inputs into the biological systems of six physical processes are examined, viz. radiation, momentum transport, heat and heat-transfer processes, water transport, carbon dioxide and transfer of matter other than carbon dioxide, each being further considered in the context of four disciplines, viz. soil sciences, atmospheric sciences, plant sciences and animal sciences. Research priorities are suggested, e.g. under 'radiation' the topic of first importance is considered to be the surface temperature of vegetation.

Part II (pages 25–49) lists practical agricultural problems under five heads, viz., improvement to production, dangers to production, physiology and growth, strategy (e.g. land-use planning) and tactics (e.g. choice of crop variety); the physical processes involved are identified and the scientific disciplines in which these are to be studied. These latter relationships are further summarized (pages 41–49) and priority problems in the several disciplines suggested.

Part III (pages 51–53) briefly examines the administrative and organizational means required for progress — the questions of information storage, retrieval and exchange underly many of the topics mentioned. Some pertinent assistance is given in Appendix I (an unavoidably incomplete list of 'Organizations at which micrometeorological research was taking place in 1968–69'); and in Appendix II a limited bibliography is provided of some 60 items selected both for their intrinsic interest and for the useful literature references.

Meteorologists of all specialisms will benefit from even a cursory reading of this publication. Agricultural meteorologists and allied workers in the 'developed' regions will find many familiar topics assessed and placed in a novel context. Those in the 'developing' regions, and others involved in the planning, administration and implementation of projects in agriculture and allied industries, might well find an approach through Part II (pages 25 and 41–49) and Part III the most profitable. A similar analysis of the interactions between agriculture and meso-climatology (with emphasis upon practical application) might arguably be an extremely worth-while enterprise to set alongside this current publication.

R. W. GLOYNE

CORRECTION

Meteorological Magazine, March 1973, page 66: Equation (4) should read

$$\frac{dT_m}{dt} = \frac{1}{hc_p\rho} \cdot \frac{dQ}{dt} = \frac{dT}{dt}. \qquad \ldots (4)$$

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THE PROBABILITY OF ENCOUNTERING RADAR WEATHER-ECHO NEAR GAN

By J. G. MOORE and R. P. W. LEWIS

Summary. A large number of photographs of the plan position indicator (PPI) display of a 10-cm radar located at Gan have been analysed in a way which provides assessments of the probability of encountering significant weather-echo at heights of 1 km and 5 km along tracks with lengths of from 25 nautical miles to 50 nautical miles; it is found that the probabilities follow a Modified Poisson, or negative binomial, law.

Regular measurements of the tops of weather-echo are used in conjunction with the photographic analysis in order to extend the range of applicability of the results and to investigate connections with routine climatological variables such as rainfall.

Introduction. A radar research project was set up on the island of Gan (00° 41′S, 73° 09′E) during 1968 for the study of the structure of weather systems over the tropical oceans and the production of statistics of weather-echo; observations were made from August 1968 until July 1969. The observations described in the next section — only a small part of the whole — have been analysed to obtain frequencies of radar-echo occurrence along specified tracks, and these frequencies have then been compared with those derived from a simple Poisson distribution and a Modified Poisson distribution. Chi-square tests showed that the simple Poisson distribution did not give good agreement with the observations whereas the Modified Poisson produced a good fit. The Modified Poisson distribution was then used to derive estimates of the probability of an aircraft encountering significant weather-echo on tracks of specified lengths and heights near Gan. As the presence of radar-echo near the equator is a good indication of severe weather and of turbulence, the results may be of value for planning operations involving supersonic transport aircraft.

Some technical details of the radar used are given in Appendix I, and the formulae and mathematics used in the statistical arguments are collected together in Appendix II.

Data used. Photographs of the plan position indicator (PPI) display were taken at various elevations with a range setting of 60 nautical miles (n. mile) on occasions that were thought by the operator to be 'interesting'. Of these occasions 74 were selected with photographs at elevations of 12° which gave a fairly even coverage of the whole year and of various times of day, not more than one occasion being chosen on any one day. A larger sample of 190 occasions was chosen with photographs at elevations of 0°.

Some photographs taken at an elevation of 2° were also used. Additionally, the heights and positions of the highest echo-tops (up to a maximum of 10) within 60 n. mile were noted at hourly intervals by the observers at Gan during all shifts of a roster system designed to give adequate coverage of all seasons and times of day. The method used was to select likely echoes by visual examination of the PPI display and then to follow them up through the atmosphere by increasing the elevation angle of the aerial until they just disappeared; the heights of the tops were then read off from previously calculated tables which allowed for the curvature of the surface of the earth and the variation of refractive index with height. Observations at a total of 1466 separate hours were used, and these form a much more extensive and representative sample of data than do the PPI photographs. Virtually synchronous measurements of tops were available for all the 74 photographs at 12° elevation, and for 157 out of the 190 photographs at 0° elevation. These observations of echo-tops allowed extension of results obtained from photographs of 'interesting' occasions to the general statistical population of occasions of all types. Use was also made of the routine rainfall measurements.

Methods of analysis and measurement. The PPI photographs taken at an elevation of 12° were projected on a diagram containing 8 circles of circumference 25 n. mile and 4 straight lines of length 25 n. mile in positions corresponding to a height of about 5 km (see Figure 1); the circles were chosen to represent a plausible path for an aeroplane circling an airfield.

The photographs taken at 0° elevation were projected on another diagram (see Figure 2) containing 24 equally spaced radii with tracks of length 25 n. mile and 50 n. mile marked on them; the heights of the 25-n. mile tracks varied between 0·8 and 1·7 km, and of the 50-n. mile tracks between 0·2 and 1·7 km.

For all occasions chosen for analysis, the numbers of echoes intercepted by the various straight and circular tracks were counted. Additionally, results for diametrically opposite 50-n. mile tracks at 0° elevation were combined to give figures for tracks of length 100 n. mile.

Comparison of observations with Poisson and Modified Poisson distributions. The frequency distributions of numbers of echo-encounters made by straight tracks of lengths 25, 50 and 100 n. mile at about 1-km elevation, and by the straight and circular tracks of length 25 n. mile at about 5 km, are shown in Table I, which also shows the expected frequencies derived by fitting both Modified Poisson and simple Poisson distributions. The '*d*' parameter for the Modified Poisson distribution is estimated from the sample variance (see Appendix II) and is a measure of the departure of the Modified Poisson from the simple Poisson distribution, being related to the correlation between numbers of encounters occurring simultaneously on two tracks of the same length. Now if the probability of encountering echo were always the same, i.e. if the weather situation and overall amount of convective activity near Gan never varied, one would expect the measured frequency distributions to conform to the simple Poisson form; however, as the overall activity does vary substantially from one day to another, the frequency distribution will be more complicated, and for reasons given in Appendix II will probably conform to the negative binomial, or Modified

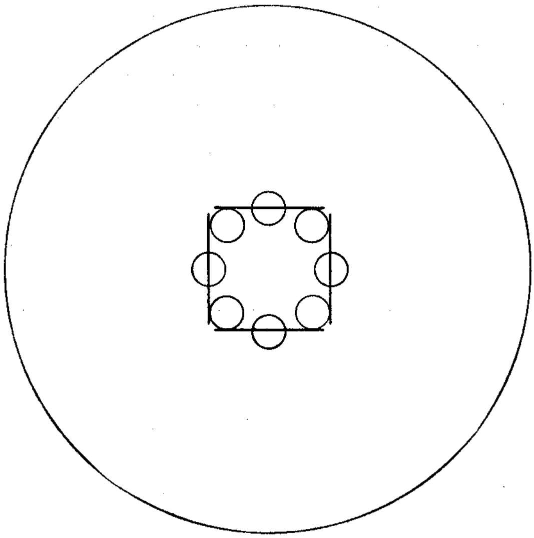

FIGURE 1—DIAGRAM OF TRACKS OF LENGTH 25 NAUTICAL MILES USED FOR MEASUREMENT ON PPI PHOTOGRAPHS AT AERIAL ELEVATION 12 DEGREES

Centres of small circles are 14 n. mile from centre of field; radius of large circle is 60 n. mile.

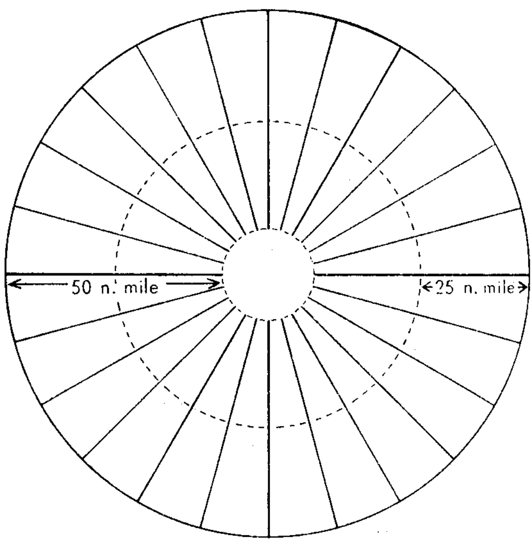

FIGURE 2—DIAGRAM OF TRACKS OF LENGTH 25 NAUTICAL MILES AND 50 NAUTICAL MILES USED FOR MEASUREMENT ON PPI PHOTOGRAPHS AT AERIAL ELEVATION ZERO DEGREES

Poisson, distribution. These theoretical expectations are confirmed by the figures of Table I: it is clear that the fit of observed and expected frequencies for the simple Poisson is bad, but that for the Modified Poisson the fit is reasonable except perhaps for the 100-n. mile tracks. Values of χ^2 for the fit of observed frequencies to those expected from the Modified Poisson distribution are, for the three lengths of track: 0·115 with two degrees of freedom (d.f.), 5·758 with four d.f., and 14·010 with five d.f.; these values of χ^2 have probabilities of being exceeded of 0·944, 0·218, and 0·016 respectively, which implies that the fit between observed and expected frequencies is likely to be as bad or worse on 94·4, 21·8, and 1·6 per cent of occasions and thus that the distribution fits the observed frequencies almost too well for the 25-n. mile tracks, well for the 50-n. mile, but very poorly for the 100-n. mile tracks.

A plot of m (mean number of encounters) and d against track-length for the tracks at about 1-km height (from photographs at 0° elevation) is shown in Figure 3; it is clear that the value of d for 100 n. mile is much smaller than would be expected from the theory of Appendix II, where it is shown

TABLE I(a)—FREQUENCY DISTRIBUTION OF NUMBERS OF ENCOUNTERS WITH RADAR-ECHO ON STRAIGHT TRACKS OF VARIOUS LENGTHS AT HEIGHTS OF ABOUT 1 KILOMETRE

Number of encounters	25-n. mile tracks O	P	MP	50-n. mile tracks O	P	MP	100-n. mile tracks O	P	MP
				frequencies					
0	3766	3703	3762	3297	3103	3275	1255	1056	1225
1	662	771	666	894	1194	931	572	813	622
2	111	80	109	275	230	254	262	313	264
3	18	6	17	69	29	68	131	80	105
4	3	0	3	22	3	18	41	15	40
5				2	0	5	15	2	15
6				1	0	1	1	0	6
7							3	0	2
8							0	0	1
	m = 0·208			m = 0·385			m = 0·770		
	σ^2 = 0·245			σ^2 = 0·521			σ^2 = 1·168		
	d = 0·177			d = 0·355			d = 0·517		

O is observed frequency; P is frequency from simple Poisson distribution; MP is frequency from Modified Poisson distribution.
m = mean number of echo-encounters; σ^2 = variance of the frequency distribution; d = second parameter of the Modified Poisson distribution.

TABLE I(b)—FREQUENCY DISTRIBUTION OF NUMBERS OF ENCOUNTERS WITH RADAR-ECHO ON STRAIGHT AND CIRCULAR TRACKS OF LENGTH 25 NAUTICAL MILES AT HEIGHTS OF ABOUT 5 KILOMETRES

Number of encounters	O	P	MP
		frequencies	
0	696	668	693
1	144	190	150
2	37	27	34
3	9	3	8
4	2	0	2

m = 0·285
σ^2 = 0·375
d = 0·316

Note : For explanation of symbols see foot of Table I(a).

that both m and d are proportional to the length of track; (values of m for 50 and 100 n. mile are constrained to lie on the same straight line through the origin by the method used for constructing the 100-n. mile data). The value of d for 100 n. mile estimated from the observed proportion of zeros is larger (0·63) than that estimated from the variance (0·52); it is still however appreciably less than twice the value of d for 50 n. mile.

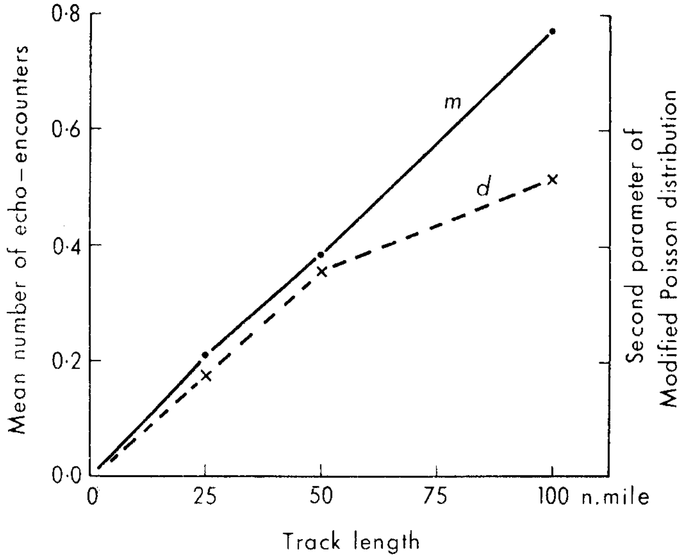

FIGURE 3—VARIATION WITH TRACK-LENGTH OF MEAN NUMBER OF ECHO-ENCOUNTERS (m) AND OF d (THE SECOND PARAMETER OF THE MODIFIED POISSON DISTRIBUTION)

The fact that the value of d for the 100-n. mile track is smaller than expected means that the total variance of the distribution is smaller than it would be if the distribution were of the Modified Poisson form. The total variance is composed of the variance of the parameters of the individual component distribution (i.e. var λ, also written $\sigma_\lambda{}^2$) plus the mean variance of the individual spatial distributions (equal to $\bar{\lambda}$ for individual Poisson distributions — see Appendix II), being the mean number of encounters over a large number of similar tracks at any one time. The most likely cause for the relative smallness of the total variance for the 100-n. mile tracks is a reduction of the mean variance of the individual spatial distributions below the Poisson value, and it may be argued that such a reduction is caused by, and is in fact indirect evidence of, negative correlation between the occurrences of radar-echo at distances of the order of the separation of the two halves of the 100-n. mile track, viz. 70 n. mile. (The correlation between the numbers of encounters on the two tracks as deduced from the present data is in fact positive, because these data are derived from a large number of occasions and thus extend over a spectrum of values of λ; the suggestion is, however, that this correlation is not as large as it would be if the component distributions were simple Poisson.) The presumed existence of such a negative correlation (the present data are inadequate to demonstrate it directly) is indicative of the mesoscale structure of systems producing weather-echo, and shows that such systems possibly have a characteristic size of from 50 to 100 n. mile, since the separation of the centres of the two component tracks is 70 n. mile. Other studies based on satellite observations[1] have shown that cloud-clusters in tropical regions tend to be of size 100 to 200 n. mile — figures in passable agreement with the present estimate, considering that the latter is indirect and that the former may be overestimates.[1]

Relationship of numbers of echo-encounters to numbers of echo-tops. One would expect that a simple relationship — probably linear — would exist between the number of echo-encounters along tracks at a certain height H in the atmosphere and the number of echo-tops extending up to or above that height. The results of the investigation support this expectation as can be seen from Table II which shows for $H = 1$ km and $H = 5$ km the mean number m of echo-encounters for four different classes defined by the number of echo-tops equalling or exceeding H, namely : 1, 2 or 3 tops; 4, 5 or 6 tops; 7, 8 or 9 tops; 10 or more tops.

TABLE II—MEAN NUMBER OF ECHO-ENCOUNTERS (m) ON STRAIGHT TRACKS OF LENGTH 25 NAUTICAL MILES AT HEIGHT H FOR DIFFERENT NUMBERS OF ECHO-TOPS ABOVE H

	$H = 1$ km	$H = 5$ km
Number of tops	*mean number of encounters*	
$\geqslant 10$	0·46	0·44
7, 8, or 9	0·27	0·34
4, 5, or 6	0·14	0·18
1, 2, or 3	0·09	0·10

Extension of results to the general population. The results obtained so far are not necessarily typical of the general 'population' of occasions of encountering weather-echo since they are based on a special sample of 'interesting' cases when echo is likely to be more widespread and dense than the average. If we compare the statistics of frequency of occurrence of different numbers of echo-tops in the special samples and in the complete record — intended and designed to be representative (Table III) we see that at a height of 5 km there are indeed considerable differences, though at 1 km the differences are trivial.

TABLE III—PERCENTAGE FREQUENCIES OF DIFFERENT NUMBERS OF ECHO-TOPS AT HEIGHTS EQUAL TO OR EXCEEDING H IN SPECIAL SAMPLE AND OVER WHOLE YEAR

	$H = 1$ km		$H = 5$ km	
	Sample	Whole year	Sample	Whole year
Number of tops		*percentage frequencies*		
$\geqslant 10$	22	22	38	12
7, 8, or 9	19	19	16	18
4, 5, or 6	32	28	12	27
1, 2, or 3	27	31	34	43

It is possible to estimate values of the parameters of the Modified Poisson distribution appropriate to the general population by using relationships with echo-top data such as those described above.

The value of m (mean number of echo-encounters on a track) appropriate to the population, or m_p, is easily formed by weighting the class-values of m by the relative frequencies of occurrence of the various classes. ('Class' is defined with reference to the number of echo-tops occurring at or above the relevant height.) The class-values of m are taken from the column of Table II appropriate to height $H = 1$ km even when encounters at 5 km are being considered; this is because the two columns of Table II show no evidence of significant variation of class-values with height, and the figures for $H = 1$ km are based on a very much larger sample of data (3768 cases) than those for 5 km (74 cases) and are thus considered to be more reliable.

It is more difficult to estimate the population value of d, or d_p. In the notation of Appendix II, if the total variance of the observations of numbers of echo-encounters in a sample is σ^2, then

$$\sigma^2 = \lambda^2 + \sigma_\lambda{}^2.$$

$\sigma_\lambda{}^2$ is the variance of λ over all component simple Poisson distributions and may be regarded as the variance of the class-means of λ (or $\sigma_{\lambda c}{}^2$) plus the mean variance of λ within classes (or $\overline{\Delta^2}$); that is

$$\sigma_\lambda{}^2 = \sigma_{\lambda c}{}^2 + \overline{\Delta^2}.$$

Since $d = \sigma_\lambda{}^2 / \bar{\lambda}$,

$$d\bar{\lambda} = \sigma_{\lambda c}{}^2 + \overline{\Delta^2}. \qquad \ldots (1)$$

$\sigma_{\lambda c}{}^2$ is easily derived either for the special sample or for the general population by use of the appropriate class-frequencies and the class-means of λ. $\overline{\Delta^2}$ must be assumed constant from special sample to general population, and can be estimated by inserting the sample values of $\bar{\lambda}$ (or m), d, and $\sigma_{\lambda c}{}^2$ in equation (1); d_p is then found by applying equation (1) a second time using population values of $\bar{\lambda}$ (i.e. m_p), $\sigma_{\lambda c}{}^2$ and the value of $\overline{\Delta^2}$ just derived.

The actual working for the parameters of the Modified Poisson distribution for numbers of echo-encounters on 25-n. mile tracks at 5 km is as follows :

(a) Special sample

Classification by number of tops	Frequency (f_c)	Class-value of m ($= \lambda$)
$\geqslant 10$	28	0·46
7, 8, 9	12	0·27
4, 5, 6	9	0·14
1, 2, 3	25	0·09
Total	74	

These figures give values of $m = 0{\cdot}265$ (to be compared with $m = 0{\cdot}285$ from the actual counts given in Table I(b) and $\sigma_{\lambda c}{}^2 = 0{\cdot}0266$.

Taking the values of m and d appropriate to all straight and circular tracks at 5 km as given in Table I(b), viz. $m = 0{\cdot}285$ and $d = 0{\cdot}316$, we find

$$\overline{\Delta^2} = (0{\cdot}285 \times 0{\cdot}316) - 0{\cdot}0266$$
$$= 0{\cdot}0635.$$

(b) Whole-year sample

Classification by number of tops	Frequency (f_c)	Class-value of m ($= \lambda$)
$\geqslant 10$	100	0·46
7, 8, 9	143	0·27
4, 5, 6	220	0·14
1, 2, 3	346	0·09
0	657	0·00
Total	1466	

These figures give $m_p = 0{\cdot}100$, $\sigma_{\lambda c}{}^2 = 0{\cdot}0164$

hence $d_p = (0{\cdot}0164 + 0{\cdot}0635)/(0{\cdot}100) = 0{\cdot}80$.

This calculation has assumed that $\overline{\Delta^2}$ is constant over *all* classes, including that of no echo-tops at or above 5 km. It is much more reasonable to assume however that only those classes with a non-zero number of echo-tops have any within-class variability, which means that $\overline{\Delta^2}$ for the general population should be multiplied by the ratio of the total frequency in non-zero classes to the total frequency in all classes or 809/1466.

This reduces the value of $\overline{\Delta^2}$ from 0·0635 to 0·0350 and hence

$$d_p = (0{\cdot}0164 + 0{\cdot}0350)/(0{\cdot}100) = 0{\cdot}51.$$

For the calculation of m_p and d_p for encounters on tracks at 1 km, the close similarity of the frequencies of occurrence of different numbers of echo-tops in the special sample and in the general population (see Table III) enables us to apply a different method which does not depend on an attempt to assign a value to $\overline{\Delta^2}$. Assume that the frequency distributions for both special sample and general population are identical except for the frequency of occasions of no echo-encounter, and use equation (9) of Appendix II to show that

$$m + d = m_p + d_p.$$

If m_p is determined from the frequencies of numbers of echo-tops above 1 km given in Table III the value of d_p follows at once.

The working is as follows :

(a) Special sample : $m = 0{\cdot}208$ $d = 0{\cdot}177$

(b) Whole-year sample

Classification by number of tops	Frequency (f_c)	Class-value of m ($= \lambda$)
$\geqslant 10$	217	0·46
7, 8, 9	190	0·27
4, 5, 6	272	0·14
1, 2, 3	307	0·09
0	480	0·00
Total	1466	

These figures give $m_p = 0{\cdot}148$, whence $d_p = 0{\cdot}237$.

It is of interest that application of this latter method to the 5-km data yields a value of d_p for 25-n. mile tracks of 0·50 — very close to the value of 0·51 found above, even though the frequency distributions of numbers of echo-tops are markedly different for special sample and general population; this close agreement between estimates produced by two different methods encourages one to think that the extension of special results to the general population may be more reliable than it at first appears.

Extension of results to other levels. We may use the results of the routine measurements of echo-tops to make a rough estimate of the probability of encountering echo at levels in the atmosphere other than 1 km or 5 km. From Appendix II the probability P_1 of making at least one echo-encounter on a track is $(1 - (1 + d)^{-m/d})$. Assume that for 25-n. mile tracks the relationship between m (the mean number of encounters on a track) and numbers of echo-tops is that used above and that d is constant with height and equal to 0·50. (A better value of d could only be obtained from information on the magnitude of $\overline{\Delta^2}$ — the within-class variance — which we do not possess; also, the value of P_1 is not very sensitive to variations of d, those in m being far more important.) Values of m and d for 50-n. mile tracks may be obtained by doubling those for the 25-n. mile tracks, but in view of the results described earlier it was decided not to continue the process as far as 100 n. mile.

Table IV gives frequencies over the whole year of different numbers of highest echo-tops occurring at or above various levels from 3 km upwards. From these data, values of P_1 for 25-n. mile and 50-n. mile tracks as a function of height are derived, as shown in Figure 4.

It is hardly necessary to emphasize that the derivation of Figure 4 is crude; nevertheless it should give some idea of the probability of encountering echo at various levels near Gan.

Relationship of echo-encounter measurements to other meteorological variables. It is obvious that if a high correlation could be established between the frequency of radar-echo encounter as measured during the special short-term investigation and other meteorological variables (such as rainfall) which have good, consistent, long-term records, then it ought to be possible to make useful deductions about the seasonal and year-to-year variations of echo-activity which the radar records themselves would be quite inadequate

TABLE IV—FREQUENCIES OF NUMBERS OF ECHO-TOPS AT OR ABOVE VARIOUS LEVELS WITHIN 60 NAUTICAL MILES OF GAN

	Levels (kilometres)														
Number of tops	⩾3	⩾4	⩾5	⩾6	⩾7	⩾8	⩾9	⩾10	⩾11	⩾12	⩾13	⩾14	⩾15	⩾16	⩾17
⩾10	198	157	100	33	6	1									
9	62	58	53	33	13	3	1								
8	48	54	46	30	15	9	3								
7	70	67	44	42	15	5	3	1							
6	74	75	66	51	38	10	6	3							
5	78	71	70	56	41	18	11	8	1						
4	97	85	84	66	35	29	10	12	8	1					
3	111	99	86	84	56	34	24	11	8	8	1				
2	89	101	109	106	77	57	52	27	26	11	5	3			
1	103	125	151	160	170	141	88	84	59	50	31	18	6	2	1
0	536	574	657	805	1000	1159	1268	1320	1364	1396	1429	1445	1460	1464	1465
	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466	1466

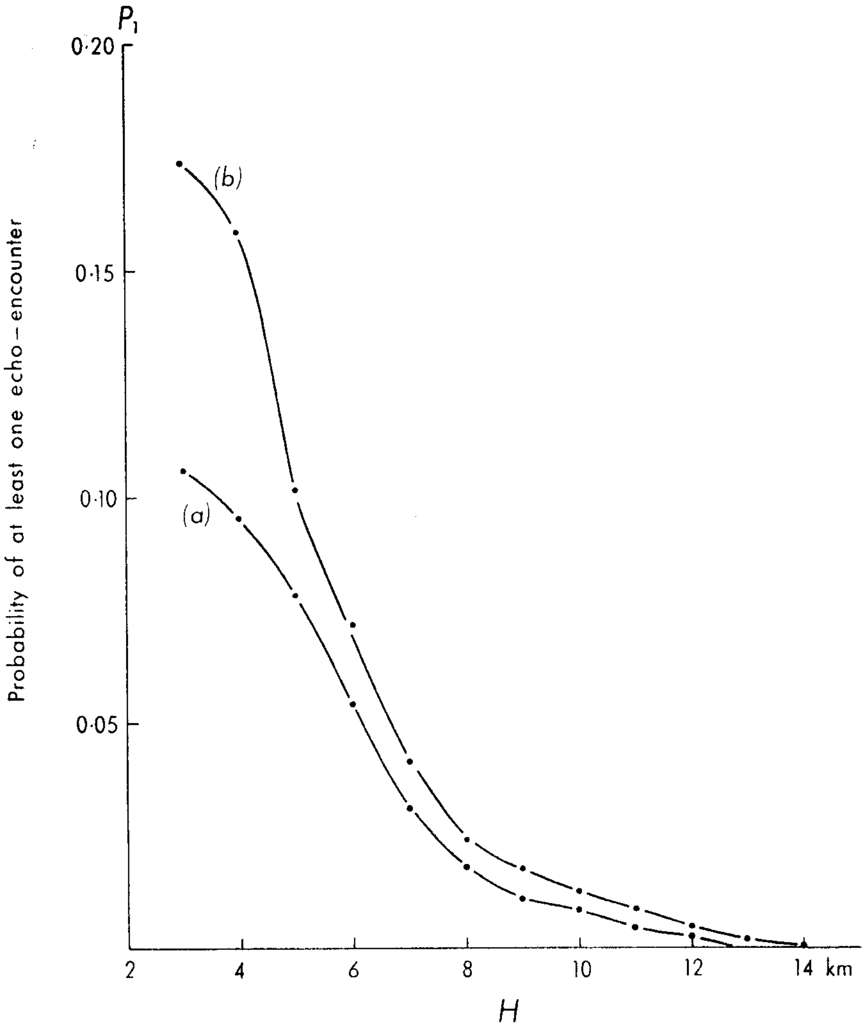

FIGURE 4—VARIATION WITH HEIGHT (H) OF THE PROBABILITY (P_1) OF AT LEAST ONE ECHO-ENCOUNTER ON TRACKS OF LENGTH 25 NAUTICAL MILES (a) AND 50 NAUTICAL MILES (b)

to reveal. Figure 5 shows the monthly rainfall amounts recorded at Gan from August 1968 to July 1969, and monthly values of the mean number m of echo-encounters expected on a 25-n. mile track at an altitude of 5 km; these values of m were calculated from the monthly frequencies of numbers of highest echo-tops at or above 5 km and the data of Table II. Values of both variables are plotted as time series and it is obvious that there is good agreement. The correlation coefficient between the two sets of figures is in fact 0·88 with 95 per cent confidence limits (assuming independence) of 0·62 and 0·97. The month with the greatest discrepancy between rainfall and m is November

1968; examination of the November data shows that during this month relatively more echoes were detected on the periphery of the scanned area than in the immediate vicinity of Gan.

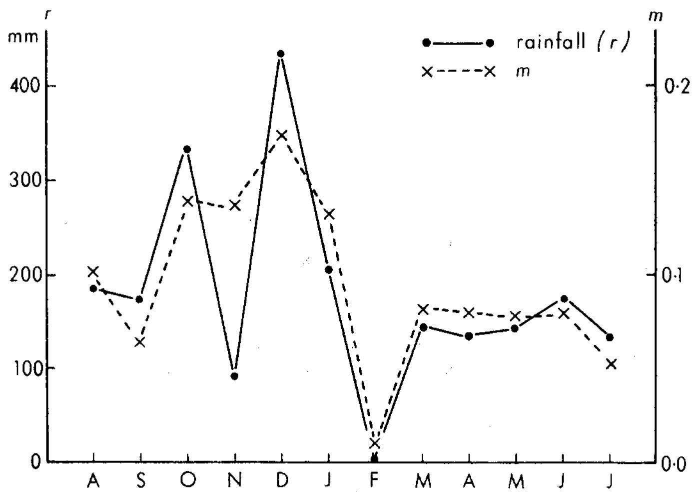

FIGURE 5—VARIATION FROM AUGUST 1968 TO JULY 1969 OF MONTHLY RAINFALL AT GAN (r) AND THE MEAN NUMBER OF ECHO-ENCOUNTERS (m) ON A TRACK OF LENGTH 25 NAUTICAL MILES AT A HEIGHT OF 5 KILOMETRES, ESTIMATED FROM ECHO-TOP DATA

Figure 6 shows a comparison of the monthly rainfall totals for the experimental period with those for the 11-year period 1961–71. Rainfall totals vary considerably from year to year and it would be difficult to describe many months of the experimental period as being particularly typical of the long-term pattern; there does appear, however, to be a tendency for smaller rainfall amounts to be recorded in February and March than in other months of the year.

Figure 7(a) shows expected frequencies of occurrence of one or more echo-encounters on 25-n. mile and 50-n. mile tracks at 5 km over the 12 months of the investigation calculated from the Modified Poisson distribution with $d = 0{\cdot}50$ and m estimated from the monthly frequencies of numbers of echo-tops at or above 5 km (Table V) taken in conjunction with the data of Table II. Figure 7(b) shows corresponding estimates of monthly mean and extreme values of frequency of occurrence of echo-encounters for the 11-year period 1961–71, m being estimated by means of a regression equation on monthly rainfall derived from the data of Figure 5. (Frequencies for the 50-n. mile tracks were derived by using values of m and d equal to twice those used for the 25-n. mile tracks.) It may be noted that the frequencies of echo-encounters on both 25-n. mile and 50-n. mile tracks in February 1969 (Figure 7(a)) are appreciably lower than the February extremes shown in Figure 7(b) for the period 1961–71; this inconsistency is due to the regression on monthly rainfall used in the derivation of the frequencies shown in Figure 7(b).

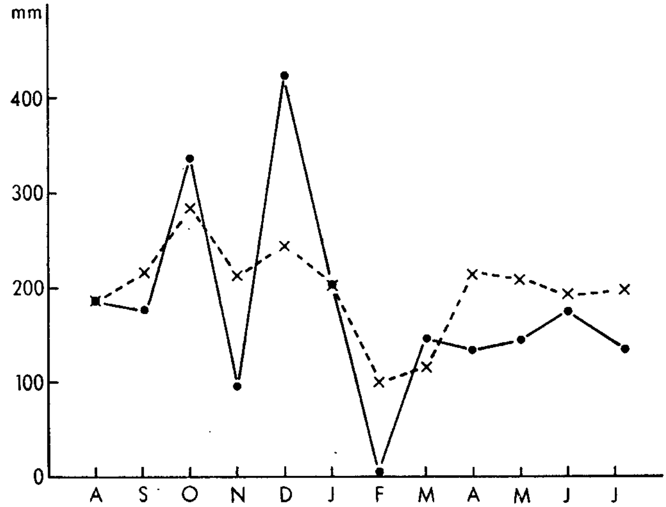

FIGURE 6—COMPARISON BETWEEN MONTHLY RAINFALL TOTALS AT GAN

·——· from August 1968 to July 1969
x – – – x 11-year averages (1961–71)

TABLE V—MONTHLY FREQUENCIES OF NUMBERS OF ECHO-TOPS AT OR ABOVE 5 KILOMETRES

Number of tops	Aug. 1968	Sept. 1968	Oct. 1968	Nov. 1968	Dec. 1968	Jan. 1969	Feb. 1969	Mar. 1969	Apr. 1969	May 1969	June 1969	July 1969	All months
							frequencies						
⩾10	7	2	17	12	27	14	1	1	6	7	5	1	100
9	0	1	13	6	12	9	0	1	4	1	4	2	53
8	2	1	5	5	13	7	0	2	4	1	4	2	46
7	1	1	4	12	9	6	0	2	0	2	5	2	44
6	4	4	9	4	12	8	0	4	3	6	5	7	66
5	4	11	9	9	3	9	0	4	6	10	4	1	70
4	5	7	6	12	13	9	0	5	4	9	9	5	84
3	5	2	8	12	6	7	0	12	8	8	8	10	86
2	6	11	7	11	14	6	0	13	15	12	9	5	109
1	4	4	7	16	14	7	1	19	30	14	13	22	151
0	34	55	52	38	41	53	64	30	63	73	72	83	657
	71	99	137	137	164	135	66	93	143	143	138	140	1466

The diagrams indicate that for most months a 25-n. mile track at 5 km will have at least one echo on about 8 per cent of occasions; in February the figure falls (on average) to about 5 per cent. Even in the wettest months the 25-n. mile tracks will have echo on no more than 14 to 15 per cent of occasions (8 to 9 per cent in February).

The other graphs in Figure 7 indicate that on average a 50-n. mile track at 5 km will have echo on about 14 per cent of occasions for most of the year, falling to about 9 per cent in February; the corresponding figures for the wettest years are 23 per cent and 14 per cent.

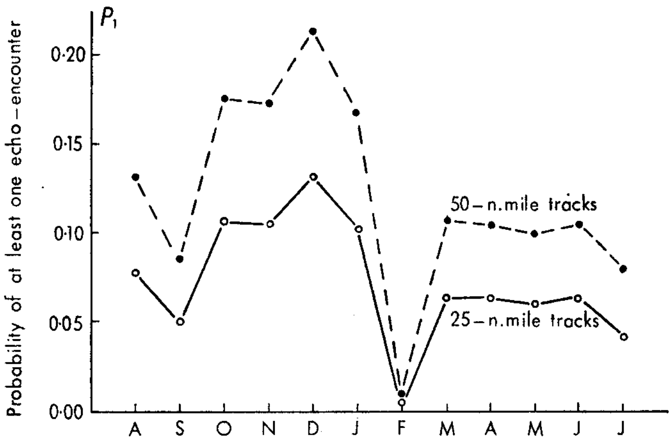

FIGURE 7(a)—VARIATION FROM AUGUST 1968 TO JULY 1969 OF PROBABILITY (P_1) OF OCCURRENCE OF AT LEAST ONE ECHO-ENCOUNTER ON TRACKS OF LENGTH 25 NAUTICAL MILES AND 50 NAUTICAL MILES AT A HEIGHT OF 5 KILOMETRES

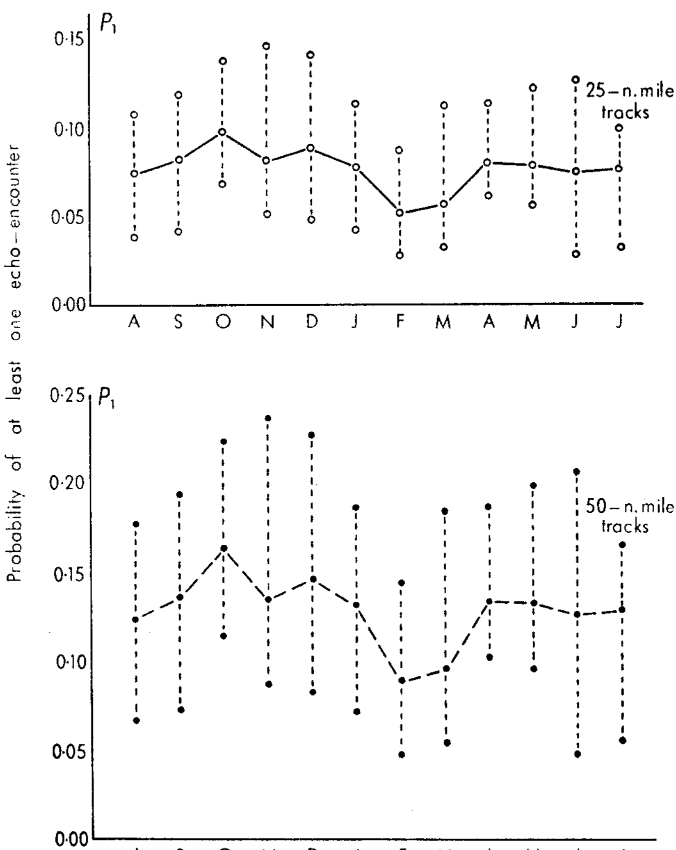

FIGURE 7(b)—CORRESPONDING MEAN AND EXTREME VALUES OF P_1 FOR THE PERIOD 1961–71 ESTIMATED FROM A REGRESSION ON MEAN AND EXTREME MONTHLY RAINFALL TOTALS

Length of echo intercepted by aircraft tracks. The frequency distribution of echo-lengths would be expected to be exponential in form if the echo-length were a non-negative random variable without memory.[2] The lengths of individual echoes intercepted by various tracks at 1 km and 5 km were measured, as were also the total lengths of echoes intercepted by the tracks. The resulting frequency distributions are illustrated in Figures 8 and 9 which show plots of the logarithm of the cumulative frequencies against length of echo. All points would lie on a straight line if the frequencies were exponential, but it is obvious that the frequencies of occurrence of large values are greater than would be expected on such an assumption; the obvious implication is that there is a considerable amount of 'memory' (or autocorrelation) involved in the radar-echo 'process' as would indeed be expected on physical and intuitive grounds.

The mean length of echo at 1 km is 3·6 n. mile and at 5 km, 3·2 n. mile.

It is interesting to apply the ideas contained in the discussion of the finite size of echo in Appendix II to the figures of Table I for the mean numbers of echo-encounters at 1 km on 25-n. mile and 50-n. mile tracks, each 25-n. mile track comprising one-half of a 50-n. mile track.

The total number of encounters on the 50-n. mile track is 1755. Using equation (11) of Appendix II we expect to have on the 25-n. mile track

$$\tfrac{1}{2} \times 1755\ (1 + 3{\cdot}6\ /\ (25{\cdot}0 + 3{\cdot}6)\ ) = 988 \text{ encounters.}$$

The number actually observed is 950; the discrepancy of 38 is within the range of normal statistical fluctuation. (If the effect of finite size of echo were ignored, one would expect only $\tfrac{1}{2} \times 1755$, or 877, encounters on the 25-n. mile track.)

Acknowledgements. The authors wish to acknowledge the hard and painstaking work of the meteorological and technical staff at Gan who made the observations upon which the present study has been based; they thank in particular Mr H. D. Westwood (the Meteorological Officer-in-charge) for his general support of the investigation, and Mr M. Morrish, who had local scientific control and who carried out the bulk of the photographic and other measurements.

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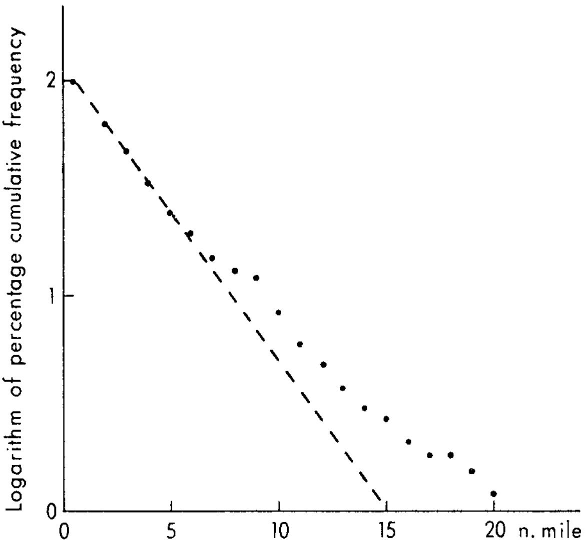

FIGURE 8(a)—LOGARITHM OF PERCENTAGE CUMULATIVE FREQUENCIES OF LENGTHS OF INDIVIDUAL ECHOES INTERCEPTED BY TRACKS OF LENGTH 25 NAUTICAL MILES AT A HEIGHT OF 1 KILOMETRE

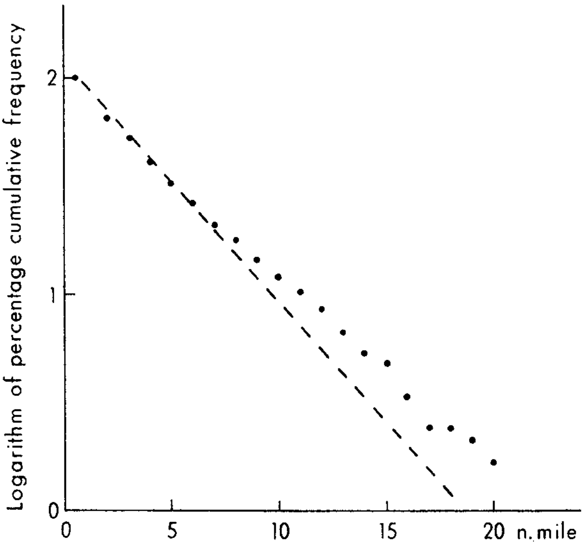

FIGURE 8(b)—LOGARITHM OF PERCENTAGE CUMULATIVE FREQUENCIES OF TOTAL LENGTH OF ECHO INTERCEPTED BY TRACKS OF LENGTH 25 NAUTICAL MILES AT A HEIGHT OF 1 KILOMETRE

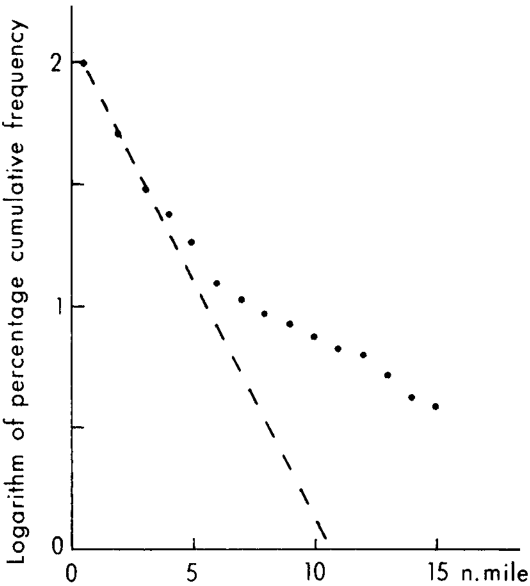

FIGURE 9(a)—LOGARITHM OF PERCENTAGE CUMULATIVE FREQUENCIES OF LENGTHS OF INDIVIDUAL ECHOES INTERCEPTED BY TRACKS OF LENGTH 25 NAUTICAL MILES AT A HEIGHT OF 5 KILOMETRES

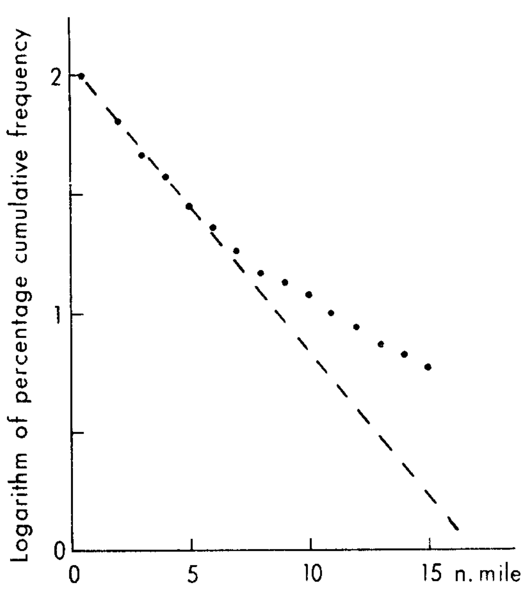

FIGURE 9(b)—LOGARITHM OF PERCENTAGE CUMULATIVE FREQUENCIES OF TOTAL LENGTH OF ECHO INTERCEPTED BY TRACKS OF LENGTH 25 NAUTICAL MILES AT A HEIGHT OF 5 KILOMETRES

APPENDIX I — CHARACTERISTICS OF THE RADAR

1. Make and type
Plessey Meteorological Radar, Type 43S

2. Aerial system
General : Parabolic dish, modified Cutler-type feed
Aperture : 12 ft (3·658 m) diameter
Polarization : Vertical
Gain : Not less than 37 dB with respect to an isotropic radiator
Beam width : $2° \pm 0{\cdot}25°$ at -3 dB points
Sidelobes : Within $\pm$ 10° — better than -27 dB
Outside $\pm$ 10° — better than -32 dB
Elevation limits : 0° to 35°
Modes of operation : (a) Manual setting
(b) Continuous rotation at 10 rev/min or 20 rev/min

3. Transmitter/receiver
Transmitter characteristics :
Frequency : 2700–2720 MHz
Peak power : 675 kW (nominal)
Pulse length : $2\mu s \pm 0{\cdot}2\mu s$ (at 50 per cent peak amplitude)
Mean power : 370 W (nominal)
Pulse repetition frequency : 275 pulses per second $\pm$ 10 per cent
Receiver characteristics :
Type : Linear/logarithmic
Intermediate frequency : 30 MHz
Video band width : 6 MHz (nominal)
Noise factor : Better than 6 dB
Characteristic of sensitivity :
Time control : Preset R^{-2} law to approx. 200 km

4. Calibrated intermediate-frequency attenuator
Fine settings : 6 steps of 2·3 dB each
Coarse settings : 3 steps of 16 dB each

APPENDIX II

The statistical distribution of the numbers of encounters with radar echo on tracks of various lengths

1. The simplest assumption to make about the distribution of significant radar-echo in space at any one time is that it is random in the following sense :

Consider an ensemble of lines, randomly distributed in space, all of the same length which is large compared to the dimensions of any single radar echo. The passage of the line through any radar echo is regarded as a single encounter regardless of the length of echo intercepted. The number of encounters on a line is then assumed to have a Poisson distribution such that the probability p_k of k encounters is given by

$$p_k = e^{-\lambda}\lambda^k/k!, \qquad \ldots (1)$$

where λ is the usual Poisson parameter and is equal to the mean number of encounters on a track. (λ is proportional to the length L of the track so that $\lambda = L\lambda_0$ where λ_0 is the mean number of encounters per unit length.) Also assume that λ is the same for all tracks of the same length whatever their shape, so that the statistical distribution of numbers of encounters will be identical for both straight and circular tracks.

Although λ is assumed constant in space at any one time, it is certain to vary with time over periods greater than a few hours, and will itself have a frequency distribution —$f(\lambda)$, say.

The probability of k encounters over the track for all times will thus become

$$p_k = \int (e^{-\lambda}\,\lambda^k/k!) f(\lambda)\; d\lambda. \qquad \ldots (2)$$

The expected number of encounters at one time — which is equivalent to the mean number of encounters over a large number of similar tracks — is equal to λ. It follows that the expected number of encounters for all times, or m, is equal to the mean values of λ (or $\bar{\lambda}$) derived from the assumed frequency distribution $f(\lambda)$.

The variance of the number of encounters over all times, or σ^2, is given by the sum of $\bar{\lambda}$ and the variance of λ, or $\sigma_\lambda{}^2$.

Hence

$$\left.\begin{aligned} m &= \bar{\lambda} \\ \sigma^2 &= \bar{\lambda} + \sigma_\lambda{}^2 \end{aligned}\right\}, \qquad \ldots (3)$$

and these equations hold whatever the exact form of $f(\lambda)$ may be.

Assume that $0 \leqslant \lambda \leqslant \infty$ and that $f(\lambda)$ is markedly skew. If $f(\lambda)$ is of the Gamma (or Pearson Type III) form, i.e. if

$$f(\lambda) = \frac{1}{d^t\,(t-1)!}\; e^{-\lambda/d}\lambda^{t-1} \qquad \ldots (4)$$

then

$$\left.\begin{aligned} m &= \bar{\lambda} = td \\ \sigma^2 &= \bar{\lambda} + \sigma_\lambda{}^2 = td + td^2 = m(1 + d) \end{aligned}\right\}, \qquad \ldots (5)$$

whence

$$\left.\begin{aligned} d &= (\sigma^2/m) - 1 = \sigma_\lambda{}^2/\bar{\lambda} \\ t &= m/d \end{aligned}\right\}, \qquad \ldots (6)$$

where d and t are parameters of the distribution. p_k is easily found as a negative binomial such that p_k for $k = 0, 1, 2, 3, \ldots$ is given by

$$\left(\frac{1}{1+d}\right)^{t}\left\{1, \frac{td}{1+d}, \frac{t(t+1)}{2!}\left(\frac{d}{1+d}\right)^{2}, \frac{t(t+1)(t+2)}{3!}\left(\frac{d}{1+d}\right)^{3}, \ldots\right\}$$

or

$$\left(\frac{1}{1+d}\right)^{m/d}\left\{1, \frac{m}{1+d}, \frac{m(m+d)}{2!(1+d)^{2}}, \frac{m(m+d)(m+2d)}{3!(1+d)^{3}}, \ldots\right\}. \qquad \ldots (7)$$

If the modal value of λ is λm,

$$\lambda m = (t-1)d = m - d. \qquad \ldots (8)$$

The parameter 'd' is a measure of the departure of the distribution of p_k from the simple Poisson; both m and d are proportional to the length of the track, i.e. they are linearly dependent on scale. The distribution (7) is referred to as the Modified Poisson.

Note that the expression $(m + d)$

$$\begin{aligned} &= m + (\sigma^2/m) - 1 = \{(m^2 + \sigma^2)/m\} - 1 \\ &= \{(\Sigma p_k k^2)/(\Sigma p_k k)\} - 1, \end{aligned} \qquad \ldots (9)$$

and is thus independent of p_0, i.e. is independent of the number of occasions when *no* encounters were observed.

2. Any frequency table derived from practical observations or measurements is usually regarded as a particular sample drawn from a hypothetical infinite population, and we wish to use the statistical information contained in the sample to the best advantage in order to derive the most probable description of the frequency distribution of the infinite population.

The course generally adopted is, firstly, to assume the functional form of the frequency distribution — Gaussian, Poisson, negative binomial, etc. — and secondly, to assume that the numerical values of the parameters of the functional form (e.g. mean and standard deviation for the Gaussian) are such as to maximize the chances of the values associated with the particular sample occurring in a random set of observations. (The second assumption is the Principle of Maximum Likelihood.)

The two parameters associated with the Modified Poisson, or negative binomial, distribution are 'm' and 'd'. The Principle of Maximum Likelihood gives a simple expression for m — it is in fact the sample mean — but d is obtained only by solving a very complicated transcendental equation and it is therefore normally necessary in practice to use simpler methods.[3]

The two most common are estimation from the sample variance and equation (6) above, and from the observed proportion of zeros which by equation (7) is equal to $(1 + d)^{-m/d}$.

The efficiency of these and other methods is discussed by Anscombe[3] but since in the present case there is no real reason to believe that the parent population is *exactly* described by the Modified Poisson, great refinement of argument would be spurious.

A further reason for not being too worried over the theoretical accuracy of the methods employed is that frequencies calculated from equation (7) are not very sensitive to small variations in d for constant m. This is illustrated by Table VI which shows, for values of m of 0·2, 0·5 and 1·0, frequencies of occurrences of these events for a considerable range of values of d.

TABLE VI—PERCENTAGE FREQUENCIES OF OCCURRENCE OF THREE EVENTS DERIVED FROM THE MODIFIED POISSON DISTRIBUTION FOR VARYING VALUES OF THE PARAMETERS m AND d

	d										
	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
m	*percentage frequencies*										
0·2	0·1	0·3	0·4	0·5	0·6	0·7	0·8	0·8	0·9	0·9	1·0
0·5	1·3	1·6	1·9	2·2	2·3	2·5	2·6	2·7	2·7	2·7	2·8
1·0	6·1	6·4	6·5	6·6	6·6	6·6	6·5	6·5	6·4	6·3	6·3

3. It was assumed above that the distribution of echo at any one time was purely random and hence describable by a Poisson formula. It is however quite likely on physical grounds that rather greater clustering takes place than would be expected on a purely random basis. Eggenberger and Pólya[4] have shown that in such circumstances the basic probability distribution of numbers of encounters on any one occasion (over an ensemble of tracks of equal length) is itself of the negative binomial form, so that the final form of the overall probability distribution p_k will depend upon a convolution of a negative binomial with the frequency distributions of its parameters. An approximate analysis of variance shows that if the 'd parameter' of the spatial distribution (d_s) is constant in time, and if the resultant distribution is also of the negative binomial form, then the resultant d parameter is measured by an amount d_s over what it would have been if the primary spatial distribution were Poisson (with $d_s = 0$).

4. If for a mixture of simple Poisson distributions we have on each occasion *two* samples (i.e. two samples with the same parameter λ) then the overall mean number of events for all occasions of two samples will be $m_2 = 2m$. The variance of the number of events in the two samples combined we call $\sigma_2{}^2$, so that

$$\sigma_2{}^2 = 2\sigma^2 (1 + \rho),$$

where ρ is the correlation between the numbers of events in the two samples. If the Modified Poisson distribution for the combined number of events in the two samples has parameter d_2, then we know that (because of the proportionality to scale) $d_2 = 2d$. Also,

$$d_2 = (\sigma_2{}^2/m_2) - 1,$$

whence

$$2d = \{2\sigma^2 (1 + \rho)/2m\} - 1,$$

giving

$$d = \rho/(1 - \rho) \,. \qquad \ldots (10)$$

This gives a further meaning to the parameter d. (For simultaneous coherent distributions, e.g. that of Eggenberger and Pólya, ρ is the correlation between numbers of events in the two halves of a straight track).

5. The discussion so far has ignored the effect of the finite size of echoes. Consider a straight track ABC made up of two halves AB and BC each of length. L. Consider an echo of length e, where $e \ll L$, occurring at random

anywhere on AC. The probability that the echo straddles the point of division B, so that it is recorded as occurring both in AB and BC, is $(2e/2(L + e))$ or $e/(L + e)$. If there are $n(e)$ echoes of length e, and N echoes altogether, then the number straddling B is

$$\Sigma n(e) \cdot e/(L + e) = N\overline{e/(L + e)}$$
$$\approx N \cdot \bar{e}/(L + \bar{e}) ,$$

where the overbar indicates a mean value.

Thus if N echoes are observed on a track of length $2L$, we may expect to observe, on average,

$$\tfrac{1}{2}\{N - N\bar{e}(L + \bar{e})^{-1}\} + N\bar{e}(L + \bar{e})^{-1}$$
$$= \tfrac{1}{2}N\{1 + \bar{e}(L + \bar{e})^{-1}\} \qquad \ldots (11)$$

echoes in either half of the track where $\bar{e}$ is the average length of echo.

551.507.362.1:551.524.7:551.557

A COMPARISON OF GEOSTROPHIC AND ROCKET WINDS AT STRATOSPHERIC LEVELS, MEASURED FROM A SMALL NETWORK OF ROCKET SOUNDING STATIONS

By G. C. BRIDGE

Summary. The temporary formation during January and February 1971, of a network of three stations over north-west Europe (West Geirinish and Aberporth in the United Kingdom, and Kiruna in Sweden) recording near-simultaneous observations of temperatures and winds at stratospheric levels, provided an opportunity to compare theoretical geostrophic winds, calculated from contour-height differences between these stations, and the actual winds measured during the descent stage of the SKUA rocket payload. Analysis of the results showed that provided changes of temperature and wind direction in the stratosphere were slow, values of geostrophic wind were calculated which compared favourably with the actual measured wind.

Introduction. During the latter part of January and early February 1971, the British Meteorological Office programme of SKUA rocketsonde observations of temperature and wind from West Geirinish in the Outer Hebrides was supplemented by similar observations from the European Space Research Organization (ESRO) rocket range (ESRANGE) at Kiruna, situated in the far north of Sweden (see Figure 1). These additional observations were obtained for a research project carried out by University College, London, in conjunction with ESRO, to clarify more fully the mechanism and structure of stratospheric warmings which occur over north-west Europe during the winter period.

The occasion was considered suitable for operating a third rocketsonde station in order to obtain sets of data suitable for synoptic interpretation. The only additional site available was at Aberporth, on the Cardiganshire coast, which had previously been found suitable for the firing of the short version of the SKUA rocket. However, as a result of the close proximity of populated land areas and somewhat restricted sea and air boundaries to the range, success of the firing programme was largely governed by the frequency of weather conditions giving generally light winds at most levels up to 100 mb.

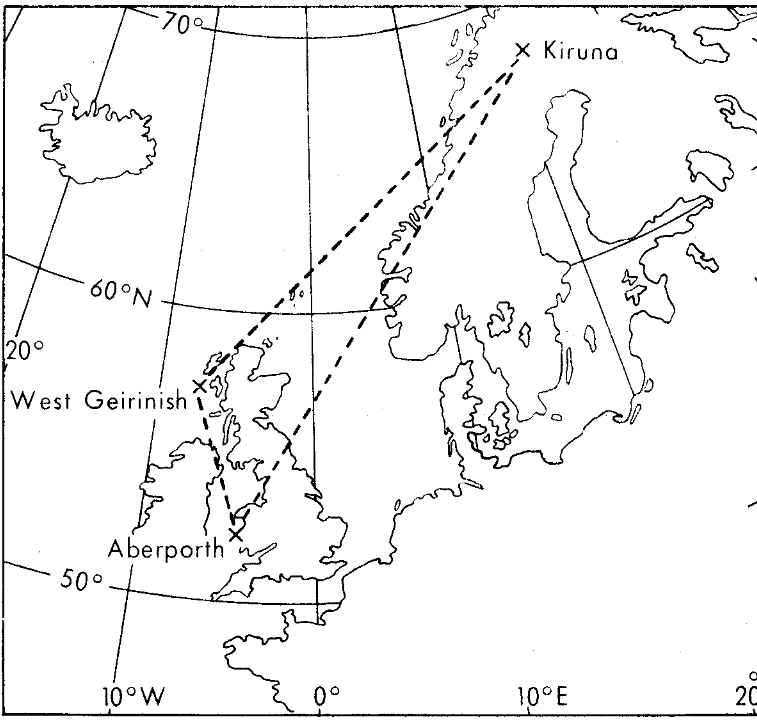

FIGURE 1—LOCATION OF THE THREE ROCKETSONDE STATIONS

It was intended to fire rockets from the three stations simultaneously; the extent to which inclement weather, unserviceability of equipment, etc. affected the success of the venture can be seen from Table I.

Contour height and wind calculation. As a first and necessary step towards the calculation of geostrophic wind, the geopotential heights of selected pressure surfaces were calculated. Firstly, integration of the equation

$$\mathrm{d} \log P = \frac{-g}{RT} \, \mathrm{d}z$$

gave the height z in geometric metres of the selected levels, where

P is the pressure in millibars,
T is the temperature in kelvins,
$g = 9{\cdot}8166 \{1 - (3{\cdot}143 \times 10^{-7}z)\}$ m s^{-2}
$R = 287{\cdot}05$ J/(kg K).

Since all rocketsonde descents terminated at around 20 km, 50 mb was taken as the standard lower boundary for the integration. Values of the contour height (converted to geometric metres) and temperature at this level were found by interpolation from 50-mb synoptic charts based on midnight radiosonde measurements. The mean difference between temperature measured by the rocketsonde at 50 mb and the chart value was found to

TABLE I—PROGRAMME OF ROCKET LAUNCHES FROM WEST GEIRINISH, ABERPORTH AND KIRUNA DURING THE PERIOD 19 JANUARY–11 FEBRUARY 1971

	West Geirinish (57° 21′N 7° 22′W)		Aberporth (52° 08′N 4° 34′W)		Kiruna (67° 49′N 22°00′E)	
	Rocket No.	Useful data range *km*	Rocket No.	Useful data range *km*	Rocket No.	Useful data range *km*
19 Jan.			M320A	nil	004	20–60
20 Jan.	M325	20–60				
21 Jan.			M322A	nil	005	20–58
22 Jan.	M327	20–60	M324A	20–60		
23 Jan.	M329	19–55			006	nil
24 Jan.						
25 Jan.	M331	20–60			007	20–58
26 Jan.			M326A	19–61		
27 Jan.					008	20–35
28 Jan.	M333	20–47	M328A	20–57		
29 Jan.					009	20–60
30 Jan.						
31 Jan.					010	20–37
1 Feb.	M335	19–58				
2 Feb.						
3 Feb.	M336	19–58			011	20–55
4 Feb.			M330A	19–62		
5 Feb.	M337	19–58				
6 Feb.						
7 Feb.						
8 Feb.			M332A	20–62	012	20–44
9 Feb.					013	20–50
10 Feb.	M338	19–60	M334A	19–62		
11 Feb.					014	20–55

Arrowed lines joining Aberporth to West Geirinish and Kiruna show how comparisons were made to arrive at data presented in Table II.

be about 1 degC, which led to an estimated mean difference of 20 metres in contour height. The only corrections applied to the sonde temperature determinations were those for dynamic heating (the fall-speeds at 60 km and 20 km being 120 m/s and 10 m/s respectively), and for cooling by infra-red radiation loss. Solar-radiation error was avoided by launching in darkness (usually soon after sunset at 75 km).

The integration was performed from the 50-mb level upwards by the use of interpolated temperature data over steps of one kilometre. The height values of the selected pressure levels for each of the three stations were obtained and converted to geopotential metres. In this exercise, 5, 2, 1, 0·5, 0·3 and 0·2 mb were selected and the relevant contour heights entered on the triangular grid ABC formed by the three launching sites (see Figure 2).

Low contour height prevailed over the region to the north and east of Norway, hence values at points C and A were always the smallest and the greatest respectively. A contour height equal in value to that at point B was always located somewhere along AC. Its position (labelled D in Figure 2) was calculated on the assumption that uniform contour gradients existed along each of the sides of ABC. BD was then drawn and its angle with a true-north direction through the centroid O of the grid triangle represented the direction of the wind, on the assumption that there was no ageostrophic motion over the area of the grid.

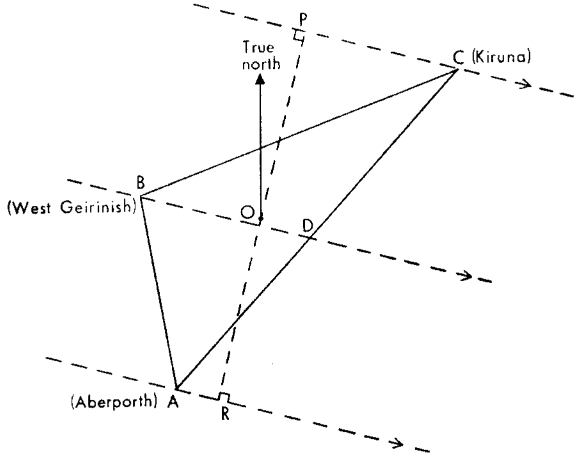

FIGURE 2—THREE-STATION GRID DIAGRAM AND CONSTRUCTION LINES

Geostrophic wind velocity V_g was then evaluated by means of the equation

$$V_g = \frac{g}{f} \times \frac{\mathrm{d}h}{\mathrm{d}n},$$

where g is the local acceleration due to gravity,
f is the Coriolis parameter, which varies with latitude, and
$\frac{\mathrm{d}h}{\mathrm{d}n}$ is the gradient of geopotential height.

One contour having already been constructed through BD, two others were then drawn parallel to it through points A and C respectively. Perpendiculars from these to point O were then drawn at R and P and this process yielded two values for dn. Contour-height differences A–B and B–C gave two values of dh; hence, by deducing values for f at the mid points of PO and RO, two values for V_g were calculated. The mean of these two values was assumed to be equal to the mean wind over the grid ABC.

Comparison between calculated and observed winds. The next step was to make the comparison between the theoretical winds thus computed and the rocketsonde wind observations from the three stations. Rocket winds were calculated by tracking the falling sonde-parachute by radar, the parachute being constructed with silvered reflecting panels. The parachute was assumed to take up the environmental wind at a height of about 0·1 mb or 65 km, hence, from a series of readings of azimuth, elevation and slant range, together with time elapsed, wind–height profiles could be plotted and the value of the wind be calculated at each kilometre level, meaned over a 2-kilometre layer centred on the level in question.

Since it was only possible to calculate a mean geostrophic wind over the grid, winds observed at points A, B and C had to be averaged before any comparison could be made. This was achieved by taking the means of the zonal and meridional components of the observed winds and converting the final result back to represent a grid rocketsonde wind. A limitation in the method employed is the assumption of the existence of a constant wind gradient along AB, BC and CA. In practice this would rarely occur, and deviations would be accentuated by the large distance of point C from both A and B. Reference to Table I shows how the data were assembled from the various comparisons available. The results of the comparisons are presented in Table II.

TABLE II—COMPARISON OF THE MEAN THEORETICAL GEOSTROPHIC WIND AND MEAN OBSERVED ROCKET WIND OVER THE THREE-STATION GRID AT VARIOUS PRESSURE LEVELS

Height	Wind type	22 Jan. 1971	25 Jan. 1971	28 Jan. 1971	03 Feb. 1971	10 Feb. 1971
0·2 mb	Rocket	280° 130 kt	265° 170 kt			
	Theory	255° 150 kt	255° 160 kt			
0·3 mb	Rocket	275° 130 kt	265° 150 kt		270° 175 kt	265° 200 kt
	Theory	245° 160 kt	260° 130 kt		255° 200 kt	240° 230 kt
0·5 mb	Rocket	280° 130 kt	260° 130 kt		265° 170 kt	270° 180 kt
	Theory	245° 160 kt	265° 110 kt		260° 200 kt	270° 200 kt
1·0 mb	Rocket	300° 75 kt	260° 70 kt	255° 95 kt	265° 110 kt	270° 140 kt
	Theory	240° 110 kt	275° 65 kt	240° 115 kt	260° 140 kt	255° 190 kt
2·0 mb	Rocket	335° 65 kt	290° 30 kt	280° 45 kt	275° 75 kt	265° 90 kt
	Theory	255° 55 kt	305° 40 kt	250° 55 kt	290° 65 kt	265° 120 kt
5·0 mb	Rocket	340° 80 kt	345° 40 kt	355° 40 kt	305° 45 kt	285° 50 kt
	Theory	290° 50 kt	335° 50 kt	345° 40 kt	305° 55 kt	285° 55 kt

Note : Wind direction is reported to the nearest 5°. Wind speed is reported to the nearest 5 kt up to 100 kt, and to the nearest 10 kt over 100 kt.

It was obvious that another limitation on the method was that on no occasion were three simultaneous observations obtained. Consequently data for the day preceding or following the date in question had to be used. At Kiruna, however, on three occasions the means of both were available to yield a more acceptable value. Since, as can be seen from Figure 3, no stratospheric warming occurred during the observational period, day-to-day changes at these high levels were considered to be gradual and quite small, and this inspired confidence in the use of data from adjacent dates.

A convenient method of expressing the overall error between the two sets of winds is to take the root-mean-square (r.m.s.) error derived from their component values. Thus

$$\text{r.m.s. wind error} = \sqrt{\left\{\frac{1}{n}\sum(u_g - u_r)^2 + \frac{1}{n}\sum(v_g - v_r)^2\right\}},$$

where u_g and v_g, u_r and v_r are the geostrophic and rocket wind components respectively, and n is the number of observations. The daily r.m.s. errors obtained by summing all heights are

Date	22 Jan.	25 Jan.	28 Jan.	3 Feb.	10 Feb.
r.m.s. wind error	79 kt	21 kt	25 kt	34 kt	50 kt.

Combination of all days, and tabulation against height levels gives

Height level	0·3 mb	0·5 mb	1·0 mb	2·0 mb	5·0 mb
r.m.s. wind error	70 kt	51 kt	55 kt	41 kt	29 kt.

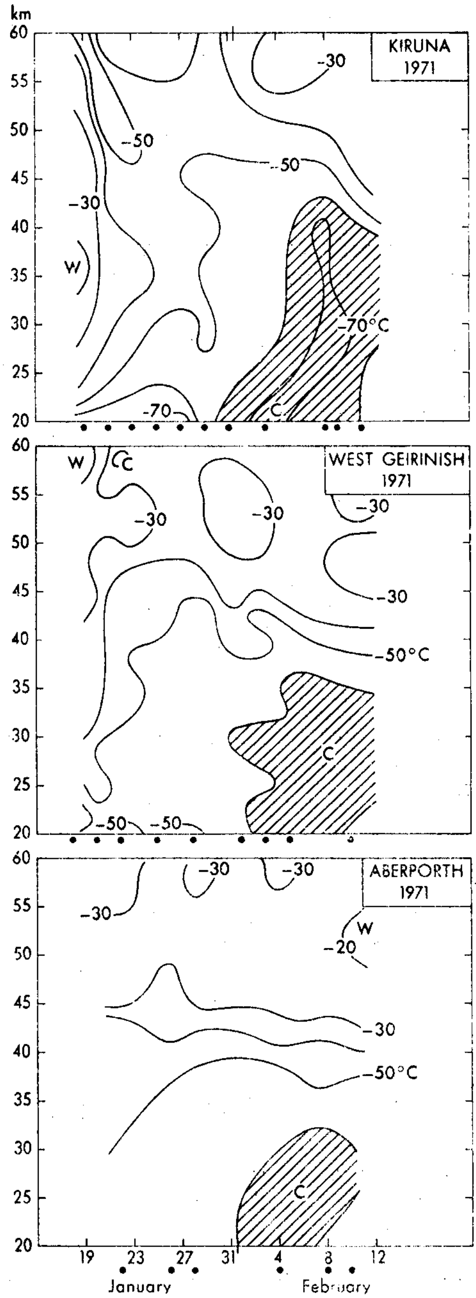

FIGURE 3—HEIGHT–TIME CROSS-SECTIONS OF TEMPERATURE DURING THE PERIOD OF DATA COMPARISON

C denotes cold; W denotes warm; ● indicates a rocket sounding; hatched areas represent temperature below −60°C (a small area has inadvertently been omitted from the top diagram).

However, at Kiruna and West Geirinish, fluctuations of the temperature field with time were present initially and may well account for the large wind-direction discrepancies which occurred on 22 January 1971. If data for this date are ignored, the following results are obtained :

Height level	0·3 mb	0·5 mb	1·0 mb	2·0 mb	5·0 mb
r.m.s. wind error	66 kt	27 kt	41 kt	24 kt	9 kt.

The apparent increase of error with height is most probably associated with the gradual increase in actual wind speed with height. If the ratio of the r.m.s. wind error to the scalar mean rocket wind speed is computed for the selected height levels, the following values are obtained :

Height level	0·3 mb	0·5 mb	1·0 mb	2·0 mb	5·0 mb
Ratio $\frac{\text{r.m.s. wind error}}{\text{scalar mean}}$	0·38	0·17	0·39	0·40	0·21.

Similarly, comparison of the mean vector difference between the observed rocket winds and the theoretical geostrophic winds with the scalar mean rocket wind speed yields

Height level	0·3 mb	0·5 mb	1·0 mb	2·0 mb	5·0 mb
Ratio $\frac{\text{mean vector error}}{\text{scalar mean}}$	0·33	0·16	0·36	0·38	0·20.

The absence of any gradual changes in magnitude of the error with height implied by these ratios would suggest that inaccuracies produced by the upward integration are small, once a stable temperature field has been established.

The results of Table II, and the subsequent tabulated values, imply that, bearing in mind the various assumptions made during the computations, it would seem that the determination of stratospheric geostrophic winds by contour-height comparison over a small grid yields fairly acceptable values. Much improvement would be realized by reducing the grid size or by using data from stations forming square or rectangular grids. A network of interconnecting grids is the next logical step, the analysis of data from which would give stratospheric winds at many levels over vast areas. Such a network made up from rocketsonde stations would however be quite impracticable for logistic and financial reasons. On the other hand satellites are producing radiance data from the stratosphere with coverage on a global scale. By using overlapping sets of radiance data from various levels over one position, a mean temperature profile up to stratospheric heights can be obtained. The contour data at say 50, 100 or even 200 mb having been established from radiosonde observations, and the temperature profile above being known, then contour heights at many levels over large areas could easily be computed and would yield sequences of stratospheric upper-air charts. Data produced at these levels would enable atmospheric models to include regions at present largely ignored, and would be of significant importance in the prediction of conditions likely to affect the performance of high-level supersonic transports.

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THE PERFORMANCE OF WET-BULB THERMOMETERS IN THE LARGE THERMOMETER SCREEN

By H. E. PAINTER

Summary. By comparing temperatures from a fully aspirated psychrometer with simultaneous readings of mercury-in-glass and platinum resistance thermometers in a Large Thermometer Screen it is shown that, by using the accepted psychrometric coefficients, the glass thermometer with a standard muslin cap gave wet-bulb depressions on the average about 7 per cent too small, while a platinum resistance thermometer with sleeving covering its entire length gave wet-bulb depressions about 2 per cent too great. There was also some variation with wind speed.

Introduction. From the beginning of 1969, a recording aspirated resistance psychrometer[1] became the official instrument at Kew for measuring dry-bulb and wet-bulb temperatures. It was considered desirable to have comparisons of these temperatures with temperatures recorded simultaneously in a Large Thermometer Screen. Two platinum resistance thermometers were therefore set up, in the screen, in addition to the standard mercury-in-glass thermometers. The temperatures from these resistance thermometers were recorded by the same recorder as was used for the aspirated psychrometer. In the course of checking the self-consistency of these adjacent glass and resistance thermometers, it was found that the temperature of the two wet-bulb thermometers in the screen deviated more and more as the wet-bulb depression increased. The same two thermometers when used as dry bulbs gave entirely consistent readings over a wide range of temperatures. The glass thermometer always gave a smaller wet-bulb depression than the resistance thermometer and this suggested that more heat was being conducted down its stem to the bulb. It is possible that the psychrometric coefficient used for the screen measurements had been selected to suit such a glass thermometer with muslin cap and that this coefficient was not necessarily applicable to readings from the resistance thermometer. To investigate this problem a series of simultaneous readings from the glass and resistance thermometers in the screen and from the aspirated psychrometer was taken.

Site and observations. The Large Thermometer Screen was situated 5 metres to the east of the aspirated psychrometer, and contained the standard four glass thermometers, thermograph and hygrograph. The wet-bulb thermometer was covered with a standard circular muslin cap.[2] Standard Mk 2 Meteorological Office platinum resistance thermometers were fixed horizontally in the screen so that the ends with the resistance elements were 5 millimetres from the corresponding glass thermometers. A close-fitting woven sleeve was fitted to the wet-bulb resistance thermometer and this sleeve extended 10 centimetres along its length; the other end of the sleeving passed into the water reservoir. The temperature recorder registered the temperatures of the resistance thermometers at 10-second intervals, the sequence being : aspirated dry-bulb, aspirated wet-bulb, screen dry-bulb and screen wet-bulb. The time between successive measurements from the same thermometer was two minutes. Each glass thermometer was read at exactly the same time as the recorder was registering the temperature of the associated screen resistance thermometer. The mean of six consecutive readings from each of the six thermometers provided the simultaneous data to be compared and any shorter-period variations of temperature were smoothed out. All index and recorder corrections were applied as necessary. From March to October 1970 about 140 sets of such observations were obtained.

Treatment of the data. In addition to the two wet-bulb temperatures obtained from the screen, another wet-bulb temperature, which has been used as a reference, was deduced from the dew-point derived from the aspirated psychrometer and the screen dry-bulb temperature. This procedure is considered to be justified since, under the conditions of the investigation, the dew-point is conservative, particularly with respect to radiation which affects dry-bulb and wet-bulb temperatures in a screen. The dew-points were derived from tables for aspirated psychrometers based on a psychrometric coefficient of $0{\cdot}667 \times 10^{-3}$ degC^{-1}; the reference wet-bulb temperatures were derived from tables for the screen instruments based on a psychrometric coefficient of $0{\cdot}799 \times 10^{-3}$ degC^{-1}. In both tables the atmospheric pressure is assumed to be 1000 mb. Differences of the temperature of each wet-bulb thermometer from the reference wet-bulb temperature have been plotted in Figure 1 against the depression of the latter below the screen dry-bulb temperature. Since the ventilation in the screen varies with wind speed, the differences have been plotted using three different symbols, depending upon the wind speed given by the Observatory pressure-tube anemometer. Although this was some considerable distance from the thermometers, and about 19 metres higher it has been assumed to give a measure of the ventilation in the screen. Subsequent measurements have shown that the wind speed at a height of 2 metres at a site near the thermometer screen is, in general, about one-half of that given by the pressure-tube anemometer, but it can be significantly different from this on occasions. The three ranges of wind speed into which the readings were divided were : 0–5 knots, 6–10 knots and 11 knots or more. The greatest wind speed during these observations was 19 knots. The best-fitting straight lines through the origin have been evaluated and drawn for each combination of thermometer and wind speed. It can be seen that the slopes of the lines vary according to the wind speed. It can also be seen that the difference between the mercury-in-glass wet-bulb temperature and that from the resistance thermometer is about 8–9 per cent of the wet-bulb depression irrespective of the wind speed. A mean of all readings shows that the glass thermometer gives wet-bulb depressions that are about 7 per cent too small whilst the resistance thermometer gives wet-bulb depressions about 2 per cent too large.

The suggested inadequate covering of the glass thermometer with the muslin cap was further investigated on four occasions by setting up a second wet-bulb thermometer which was covered with a woven sleeve extending 2 centimetres above its bulb and with threads tied above and below its bulb so that the sleeve fitted the bulb of the thermometer closely. Table I gives the results of simultaneous readings, meaned over a period of 10 minutes, from each of the glass wet-bulb thermometers and the resistance thermometer. The reference wet-bulb temperature and its depression below the screen dry-bulb temperature are also included together with the wind speed from the pressure-tube anemometer.

In the case of standard glass thermometers the difference in temperature with different coverings on the wet bulbs can be clearly seen in this table.

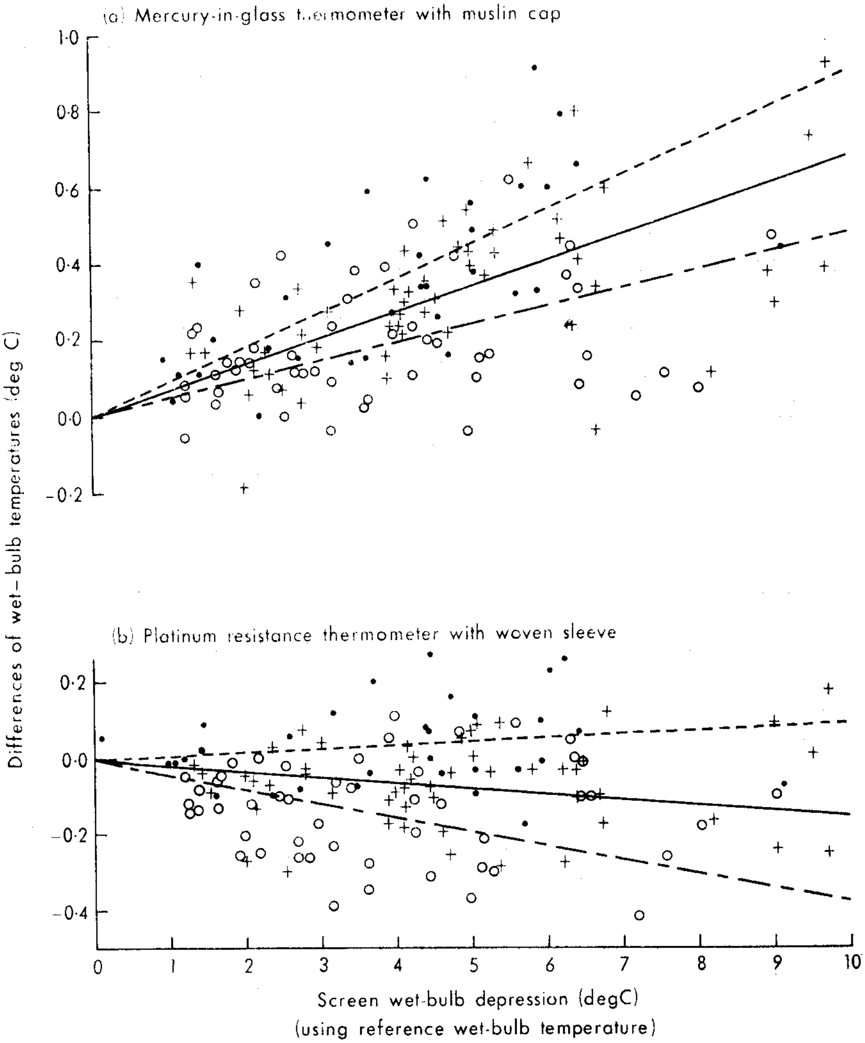

FIGURE 1—DIFFERENCES BETWEEN WET-BULB TEMPERATURES FROM THERMOMETERS EXPOSED IN A LARGE THERMOMETER SCREEN AND REFERENCE WET-BULB TEMPERATURES, PLOTTED AGAINST THE WET-BULB DEPRESSION

(a) for a standard mercury-in-glass thermometer with muslin cap.
(b) for a standard Mk 2 Meteorological Office platinum resistance thermometer with 10 cm of the sheath covered with sleeving.
● - - - - for anemograph wind speeds 0–5 knots
+ ——— for anemograph wind speeds 6–10 knots
o — — — for anemograph wind speeds ⩾11 knots

It can also be seen that the glass thermometer with a sleeve is in closer agreement with the reference and resistance wet-bulb readings than a glass thermometer with a muslin cap.

TABLE I—WET-BULB TEMPERATURES MEASURED IN A LARGE THERMOMETER SCREEN BY DIFFERENT THERMOMETERS WITH SPECIFIED WET-BULB COVERINGS

Glass thermometer with sleeve	Glass thermometer with muslin cap	Resistance thermometer with sleeve	Reference wet-bulb temperature	Wet-bulb depression	Wind speed
°C	°C	°C	°C	degC	kt
16·5	16·8	16·3	16·35	6·3	14
13·9	14·0	13·8	13·75	3·0	12
16·2	16·5	16·3	16·35	5·4	7
14·3	15·1	14·4	14·25	6·95	2

Conclusions. The standard mercury-in-glass thermometer under the weather conditions experienced at Kew appears to need a wet covering over about 2 cm of its stem in order to be compatible with Meteorological Office humidity tables for screen psychrometers. The resistance thermometer requires a sleeve somewhat shorter than 10 cm along its length in order to be compatible with the same tables.

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OBITUARY

It is with regret that we have to record the death of Mr E. G. Cowler, Senior Scientific Officer, H.Q. Strike Command, Royal Air Force, on 23 March 1973.

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki :

Meteorologika 18*: Evaporation in Thessaloniki—Greece.* By G. C. Livadas and P. Chr. Machairas. 1972.

Meteorologika 19*: Contribution to the study of warm invasions in Greece.* By A. A. Flocas. 1972.

Meteorologika 20*: Contribution to the study of atmospheric refraction index and photogrammetric refraction in the area of Greece by means of meteorological data.* By E. N. Patmios. 1972.

Meteorologika 21*: The cooling power in Thessaloniki—Greece (III).* By Chr. J. Balafoutis and G. C. Livadas. 1972.

Meteorologika 22*: Earth surface temperature.* Part I. Bare-soil surface. By G. C. Livadas and Y. A. Goutsidou. 1972.

NOTES AND NEWS

Retirement of Mr. J. Harding, O.B.E.

Mr John Harding, who has been Assistant Director, Agriculture and Hydrometeorology since 1966, retired from the Meteorological Office on 30 April 1973. He entered the Office early in 1936 after graduating in physics and taking his Master's Degree at Trinity College, Dublin. He trained for a few months at Croydon and then until the beginning of the War forecast for the operation of long-distance flights of flying boats from Foynes and Hythe. During the period 1939 to 1943 he served at the Central Forecasting Office and also at Prestwick, Gloucester and Plymouth before returning in 1944 to CFO at Dunstable, where he remained until 1949 and where he gained his reputation as an outstanding forecaster. He was promoted to Principal Scientific Officer in 1948. From 1949 to 1955 he was deputy to the Chief Meteorological Officer, Middle East, at Ismailia and then was in charge of the Meteorological Office at RAF Wyton until 1960, when he was promoted to Senior Principal Scientific Officer and made Assistant Director, General Services. For the next six years he was responsible for services to the general public and to agriculture and it was during this period that Weather Centres were opened in Manchester, Glasgow and Southampton and that the volume and type of services available to the public were greatly expanded.

With the reorganization of some branches of the Office in 1966 Mr Harding was made responsible for hydrometeorology and agriculture and he remained in this post until his retirement, building a high reputation among hydrologists at home and abroad. He was appointed an Officer of the Order of the British Empire in 1972.

John Harding's considerate, sympathetic and kindly approach to every task or problem was widely appreciated and not least by the Staff General Purposes Committee, which co-ordinates the social and sporting activities of the Office, and of which he was Chairman from 1967 to 1973.

We wish him and Mrs Harding many years of happy retirement.

J. K. BANNON

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

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METEOROLOGICAL OFFICE

the meteorological magazine

AUGUST 1973 No 1213 Vol 102
Her Majesty's Stationery Office

SCIENTIFIC PAPERS

No. 31 The three-dimensional analysis of meteorological data

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

37½p (40p by post)

No. 32 The Bushby-Timpson 10-level model on a fine mesh

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

55p (57½p by post)

METEOROLOGICAL OFFICE Met.O.860

THE METEOROLOGICAL MAGAZINE

Vol. 102, No. 1213, August, 1973

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A PLAN FOR THE DETERMINATION OF THE LARGE-SCALE WEATHER PATTERNS DURING THE PERIOD 1493-1860

By J. M. CRADDOCK

Summary. This paper describes a reconnaissance along a line of thought suggested earlier this year and considers the practical steps by which a co-operative undertaking, depending mainly on voluntary effort, can produce a permanent improvement in our knowledge of weather processes since the Middle Ages. Starting with the general objective of systematizing our knowledge of weather and climate in the period from 1493 to 1860, it arrives at a definite plan, in which both amateur and professional meteorologists can co-operate in different ways, with the prospect of seeing worthwhile returns for their efforts within a reasonable time.

Introduction. In a paper (Craddock[1]) which discusses ways in which the amateur meteorologist, or the retired professional, can still contribute to the development of meteorological science, I suggest the possibility of collecting early information relevant to large-scale weather patterns which may be processed for use in present-day long-range weather forecasting. The beginning of the target period for determining the large-scale weather patterns, 1493, is the year after the discovery of America. Before that time, direct evidence of weather situations over the American sector of the northern hemisphere does not exist, and the interpretation of indirect evidence, such as that furnished by tree-ring studies, is a different problem from the one considered here. The end of the target period is the date from which the records are already arranged in manageable form in the long-range data bank described by Craddock.[2] Within this period, the investigator, besides realizing the general satisfaction of having contributed a little to the organization of knowledge, may help to attain one of two clear and practical objectives.

(a) The first, which applies to the more recent years, is to collect enough information to allow convincing daily weather charts to be plotted for a good part of the British Isles and north-west Europe, so that more years can be included in classifications such as those of Lamb[3] and Hess and Brezowsky,[4] and

(b) for the earlier years, for which the weather conditions on individual days may always remain indeterminate, it may yet be possible to produce valid indices, such as the *PSCM* indices of Murray and Benwell,[5] which give the general character of each month and have applications in long-range weather forecasting.

The date which divides the earlier period for which every scrap of information should be used, from the later, for which attention may be confined to the better sources, is uncertain, but probably lies between 1660 and 1780. Perhaps the best way to find it is to start with the early years for which data are scarce, and work forward until the amount of information per year becomes embarrassing. Making the best of scanty data involves both examining the original records, and considering the circumstances under which they were made, and also examining all the records for a given date or period, presented in chart form, and both types of investigation should be carried out by, or under the supervision of, a competent synoptic meteorologist. Moreover, if the examination of, say, the weather observations on a given day throws doubt on some of the observations, the analyst must be able to check these back to source. For this to be possible, the original records, or accurate copies of them, must be collected at a centre where they are readily accessible both as records for individual stations or observers, and as collections relating to different periods. The need for this dual treatment was brought home to me as I examined the material discussed below.

Some preliminary searches. As the first part of my reconnaissance, I borrowed the *Diary of John Evelyn*[6] (I knew Pepys's *Diary* had been worked over) and read it through, noting every bit of information I thought had meteorological interest. I soon realized that the meteorological notes could not be evaluated without knowing something of John Evelyn: for example, that the first part of the diary was made up from previous notes, while the rest consists of remarks made at the time, almost up to his death at the age of 86. To save future meteorologists the trouble of borrowing the book, and reading the 1100-odd pages, I prepared a short biography of John Evelyn giving only the facts relevant to his remarks on weather followed by over 500 verbatim extracts either of actual weather, or of circumstances from which the weather can be inferred. Two copies of this I have kept for future processing, while others will be deposited in the National Meteorological Library, so that a future meteorologist interested, say, in the year 1684 can read exactly what Evelyn said about it. If the principle of maintaining accurate copies of original material in a readily accessible centre, each accompanied by a report by a synoptic meteorologist, will help to make better use of a comparatively familiar work like Evelyn's diary, it has even greater advantages when applied to rare and inaccessible works :

(a) it minimizes the possibility of copying errors,

(b) it ensures that each observation can be assigned as nearly as possible to the right place, something which is essential if, for example, information from Plymouth and Edinburgh is being combined with London data to place a pressure centre, but which is often omitted in extracts,

(c) it allows the inclusion of information, for example on shipwrecks, or the arrival of news from the continent, from which a meteorologist can infer the wind régime, which a bare catalogue of weather would miss,

(d) it reduces the wear and tear on original records which may be both irreplaceable and difficult of access, and

(e) it allows the meteorologist to form an opinion of the character and reliability of the observer, and of his instruments, if any.

After Evelyn, I examined some works containing meteorological information extracted from other sources such as those of Lowe,[7] Baker[8] and Easton.[9] These all prompt the questions whether the authors have personally read all the works they quote, and whether they have extracted from these works all the original information relevant to weather.

Since Easton deals only with winters, ignoring the other seasons, while Baker is interested mainly in meteorology in relation to agriculture, it seems most unlikely that either writer has exhausted his source material. With Lowe, there are more grounds for confidence, but even with him, the reader should be able to retrace the ground for himself. With these early writers, unlike their modern counterparts such as Lamb[10] and Le Roy Ladurie,[11] the references are so incomplete that the first task, in getting a clear picture of the total weather information for any period, must be to make a full bibliography, without duplication, with adequate references, either to the original source or to the closest point to the source which can be found at present.

Forming a catalogue of sources of information. Forming a catalogue of sources of information involves not only visits to libraries, but also using the bibliographies given by some authors to find others. The bibliography given by Easton,[8] who seems to have been one of the most assiduous collectors, suggests that a comprehensive bibliography for our period would include perhaps 50 main sources and up to 2000 subsidiary ones, with possibly 10 000 or more references to weather in matter which is basically unrelated to meteorology.

An efficient catalogue would contain an entry for every source, with the following properties :

(a) that each entry contains enough information about the form, content and importance of the item concerned, and its place of observation, period and location of the record;
(b) that the catalogue can readily be extended by new entries, and
(c) that it can easily be searched for all items which fulfil reasonable conditions as to content, place or period.

Since such a catalogue will be a good deal of trouble to create and to maintain, it is most desirable that it should be easy to reproduce, both for protection, and for the convenience of intending users. These conditions are quite hard to satisfy with a conventional card index, indeed, I have never had a satisfactory answer from a librarian as to what he would do if his main card index was destroyed by fire, but they can readily be satisfied by means of the computerized cataloguing and retrieval system which I have recently been involved in developing for the World Meteorological Organization, which is described in *World Weather Watch Planning Report* No. 34.[12] This system cannot be described in a few words; it deserves an article to itself, but it is already in use for the cataloguing of information of all kinds relevant to long-range weather forecasting, a field which includes most of the sources of information discussed here, so there is a clear saving in using it in the present plan.

Comments on individual sources and authors. The ideas concerning preliminary researches took a definite shape while I was reading the potential source documents listed below.

Although I read the *Diary of John Evelyn* for relaxation, I found it intensely interesting, giving a clear picture of an upright, humane man in the early stages of the scientific era. He was a founder member of the Royal Society, and a strong Royalist and supporter of the Church of England. His general interest in religious topics suggests that when, as occasionally happened, he was prevented from going to church by wet or cold, the weather was a real deterrent and not a feeble excuse. Although Evelyn travelled as far as Rome and Venice, and gives some useful accounts of crossing the Channel, most of over 500 observations refer to the area London–Deptford–Dorking, and supplement a similar number of observations made by Pepys.

James Yonge was a naval surgeon who lived from 1642 to 1721 (see reference No. 13) and went to sea as an apprentice before he was 11 years old, but rose to be something like a consultant surgeon, a member of the Royal Society, and Mayor of Plymouth. His *Diary* falls into three parts. The first part, written from memory in 1667 when he was a prisoner of war at Rotterdam from notes lost when he was captured, includes accounts of two voyages to Newfoundland and one to Algiers; the second part gives an excellent record of the weather during two voyages from Plymouth to Newfoundland and back in 1668 and 1669, with ships' logs; the third, from 1671 to 1707 contains much of medical interest, but only about 20 direct references to weather. Unlike Evelyn, Yonge does not always give his dates explicity, and it will take perhaps a fortnight's detective work to make the best of the weather information in the first and third sections. However, the second section is most rewarding, and taken in all, Yonge's comments on people and affairs make this diary as interesting as those of Pepys and Evelyn.

Both these diaries suggest that more should be made of the marine evidence, ships' logs, records of sea passages, etc. than the compilers seem to have attempted.

E. J. Lowe,[7] a botanist who specialized in ferns, and a Fellow of the Royal Society, produced many meteorological observations from his home at Highfield House, Nottingham. He preserved his modern outlook when looking into the past (this compilation ends in 1753). In his own words 'many phenomena are described in the exact words in which they are written at the time of occurrence; and this has been done because a more perfect estimate can be formed from an author's own words'. He gives short references to the items which he found in unusual sources, and lists a few publications as requiring systematic study. The following extract may be the first record of a sonic boom. '1628 Stone from sky; Hatford, Berkshire, On April 9, 5 p.m., warm, windy, WNW, a hideous noise in the air, followed by a strange and fearful thunder, then another, till twenty peals were heard. A stone fell at Barolkin Green ($1\frac{1}{2}$ miles from Hatford) and was dug up by Mistress Green. It broke, one piece weighed $19\frac{1}{2}$ lbs, and another 5 lbs.' In Lowe[14] he continues his extracts up almost to the date of publication, and also gives more early extracts from other sources. In all, a valuable compilation.

E. T. Baker[8] is a compiler of very different calibre. Although he was a Fellow of the Meteorological Society and gives over 1200 references up to 1792, his main interest lay in agriculture, and probably half refer to the price of wheat. His references are short and cryptic, (e.g. F.A. or Smith) and although over 140 sources are mentioned, only 21 of these produce 10 or more items. He gives over 90 quotations from Lowe, including the above extract, somewhat abbreviated, and given for the year 1627, a mistake which casts doubt on his treatment of other sources. In spite of this evidence of unreliability, Baker's work has its uses. It shows that Holinshed, with entries up to 1586, and Gilbert White, who continues up to 1792, were better observers than most of his sources, and his references, if they can be deciphered, are at any rate evidence that certain authors were active at certain periods.

A. Angot[15] has given a list of nearly 300 observational records made in France before 1850, including in most cases, the elements observed, and the place where the original record is stored.

R. C. Mossman[16] has given a painstaking account of the climate of Edinburgh, in course of which he gives details of one instrumental record for the years 1731–36, and an almost unbroken succession of records for the years from 1764 onwards. Mossman[17] lists representative wheat prices at Haddington for the years 1627–1897, which could be a better starting point than most for an attempt to relate wheat prices to weather.

H. Teonge[18] recounts the diary of a cheerful naval chaplain, which was kept during two voyages from London to Aleppo and back in the years 1675 to 1679. There is a good deal of weather information, mostly for the Mediterranean, but few dates are given explicitly and the positions must be estimated. The diary mentions the ships passing various ports and headlands, so estimation should be possible. It could provide a synoptic meteorologist with an interesting fortnight's detective work.

C. Easton[8] has made a monumental study, with over 300 references, on the winters in the climatic region extending from Bremen to Toulouse. He seems to have been a senior member of the Netherlands Meteorological Service, and his text, which contains sections in French, English, German, Latin and Dutch, is not always easy to follow. The work gives an impression of thoroughness, but the area considered excludes information from most of Germany and the British Isles. Many of the references are incomplete, but they provide a most useful contribution to the total.

C. E. Britton[19] produced about 20 papers, mostly during the 1930s, in which he reproduced some of the early records, or reported research on their authors, and the circumstances in which they were made. These unpretentious papers, which fall naturally into the present plan, will retain their value when many more ambitious contributions have been forgotten.

G. Manley[20] is mentioned here because besides his excellent series of monthly mean temperatures, he gives the sites and periods of many of the early instrumental records. Taking only his sources with those of Mossman would provide a good start for daily weather charts for most dates from 1764 to the present.

E. Le Roy Ladurie[11] started with studying agriculture in Languedoc, and expanded naturally to the study of climate. His evidence on Alpine glaciers, and his bibliography of texts in the French language seem particularly good.

Some of these compilations contain data for years before 1493 and also there is bound to be some duplication; some detective work will be needed before a catalogue of sources for the period can be produced which has any claim to completeness without redundancy.

General impressions. The synoptic meteorologist has the advantage over the old-fashioned climatologist, when analysing data in chart form, because if the time-step between charts is short enough, the weather systems have continuity between one chart and the next. A time-step of one day is used in long-range weather forecasting, as the best compromise which preserves continuity between charts without retaining unnecessary detail, and is also suitable for the present purpose, since enough data are never likely to be found to justify a shorter step. If the objective is to plot a daily chart for each day of the years 1660 to 1859, 73 048 days in all, then the sources already mentioned contain enough data to plot something on almost every chart, and several observations on some. If an average of from 5 to 10 well-spaced observations on a series of charts will support an analysis, then many years within the period can be processed by using known sources of data, and a systematic search for data may bring a good many more years to this standard.

It is difficult to judge the true value of many of the sources until they have been examined and catalogued, but it is worth mentioning that the scatter of sources, which was a handicap to authors like Mossman[16] and Manley[20] who were interested in conditions at a point, is an advantage when it comes to plotting a chart. It is also difficult to judge how much additional information can be found in local newspapers, county archives, etc., but probably there will be a good deal about weather which was out of the ordinary. However, throughout the period there were British ships moving in the English Channel, the Bristol Channel and in the North Sea to ports such as Bergen and Königsberg. Merchant ships often travelled in convoy under the protection of men-of-war, and the number of ships' logs still in existence must be quite considerable. These logs may be the biggest source of information not already tapped by the climatologists.

Comments on the plan. The plan outlined in the paragraphs concerning preliminary researches is for a co-operative effort, not only because it is far too big for one man, but also because different aspects may attract different people. A search through local records such as the *Norwich Register* mentioned by Baker,[8] those for Bristol in Lowe[7] or for the Scottish stations mentioned by Mossman[16] may interest a retired meteorologist living in the district, or form the subject of a school project. Once an interesting record has been found, the meteorological entries should be copied, and a report written about the source. The first copy will often have to be made by hand, but this should be replaced by a clean typed copy which can be checked against the original, and certified correct. The centres which should hold copies have yet to be decided, but it is already clear that any such reliable extracts of original information would be most welcome additions to the National Meteorological Library. If there is a synoptic meteorologist able to make or check the report on the original record, so much the better.

To facilitate future processing, a full reference to the source should be included at least once for each year, so that if the record is cut into pieces, each piece can be traced back to its origin.

Rearranging information according to period. When enough records have been prepared, reported on, and collected at a centre, one copy of each should be rearranged in sections relating to different periods. For printed matter, such as my extracts from John Evelyn, Samuel Pepys, James Yonge, etc., this can be done simply by cutting up one copy of each, and pasting the pieces together in sections corresponding to period. The new listing can be copied, but since there is some loss of quality at every copying, the original should be very clear.

For numerical data, however, it is preferable to punch the data on a computer medium from the original record, or from a direct copy, and to carry out any required scaling, correction or rearrangement by computer. The inclusion of a full reference with every year means that if the analyst in the next stage feels doubt about an observation, he can trace it back to source. This is most important if, as occurs once or twice in Evelyn, remarks for neighbouring days are hard to reconcile, or when there is doubt about the year or the date of the event described. Further the effect of age on meteorological instruments was not understood in early years, and a single incredible value may indicate that a whole record has been affected by instrumental drift and requires correction, by computer or otherwise, as may be most convenient.

Analysing the information for a period. Once enough progress has been made with the collection of information, and it seems unlikely that anything new can upset the consensus of what there is, then the information for one period can be passed to a group of meteorologists who are prepared to analyse it. For years since 1800, there will be a good many observations, and perhaps one year would be enough to tackle at a time. For the 1600s however, it might be better to take a decade. The team taking on each period should preferably include at least one experienced forecaster and they should live close enough together to be able to meet and discuss progress. A supply of blank charts will be essential if daily charts are to be plotted and desirable in all cases and these should come from the central organizing unit. The final product could be a scientific paper suitable for publication, and a series of analysed charts to be returned to the central unit, and in due course included in the National Meteorological Library.

Concluding remarks. The attack is based on the principle that one objective of any sound scientific investigation is to put the reader in possession of the basic facts, so that he can, if he wishes, reconsider these facts and form his own conclusions. In making these proposals, I do not overlook the work of authors such as Professor H. H. Lamb and Dr D. J. Schove, who have spent many years collecting information on this and allied topics. However, the emphasis in the present scheme at this stage is on the collection of basic data, and the keeping of such data in forms convenient for reference at accessible centres, rather than on the possible applications. Moreover, the plan envisages the use of modern technology, (e.g. in forms such as computers and copiers) for tasks which do not involve human judgement, with the aid of the judgement of present-day synoptic meteorologists whenever the material deserves it. Several references have been given to interesting material which should repay careful study, and the comprehensive bibliography which I am collecting is sure to provide many more. If any meteorologist, amateur or professional, who is willing to take part would send his comments to the editor, or to me, then I will try to report progress within the next 6 to 12 months.

Since drafting this paper I have read the first *Annual Report* of the Climatic Research Unit at the University of East Anglia, which shows that daily charts for the area discussed for the years 1782 to 1784 have been analysed by Mr J. A. Kington and classified by Professor H. H. Lamb. This news confirms the practicability of the present proposals, and may encourage others to join in the search for meteorological information in ancient records.

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551.553.11(495)

THE DIURNAL VARIATION AND DURATION OF THE SEA-BREEZE AT THE NATIONAL OBSERVATORY OF ATHENS, GREECE

By J. D. ZAMBAKAS

Athens University Climatological Institute

Summary. Records of pure sea-breezes at Athens Observatory, situated on a promontory, are examined for April, July and October 1961–67 and for January 1938–67 (the longer period compensating for the lower frequency of occurrence in winter); there were 24 such cases in July (7 years) and 26 in January (30 years). Since the sea-breeze is not in balanced motion the ends of the wind vectors during the diurnal variation lie approximately on an ellipse, and the eccentricities of these ellipses are discussed.

Introduction. The diurnal variation of the sea-breeze wind has been given theoretically by Haurwitz[1] for a straight coastline. If equilibrium exists between the general pressure gradient force, the pressure gradient force due to the land–sea temperature difference, the Coriolis force and the frictional force, then the speed of the sea-breeze changes but not its direction. If the wind is not in balanced motion, as is actually the case, owing to its inertia, then the ends of the wind vectors lie on an ellipse and change in a clockwise direction with time. The greater the frictional force the greater the eccentricity of the ellipse.

Gill[2] found that the location of the station and the shape of the coastline near it governs both direction and diurnal variation of the sea-breeze. The ellipse is always approximated to, but the theoretically expected clockwise change in direction of the wind vectors with time round the ellipse does not occur at Wick, a station which is situated on a promontory.

The National Observatory of Athens (Latitude 37° 58′N, Longitude 23° 43′E, height 107 metres above sea-level), for which the above-mentioned sea-breeze characteristics are examined here, lies on a promontory and about 5 km from an indented coastline (Figure 1).

Data. Sea-breeze days occur in Athens all the year round. These days were tabulated for the 7-year period 1961–67 for the months April, July and October. Because of the rareness of this phenomenon during the winter period, January was considered for a 30-year period 1938–67. Only days

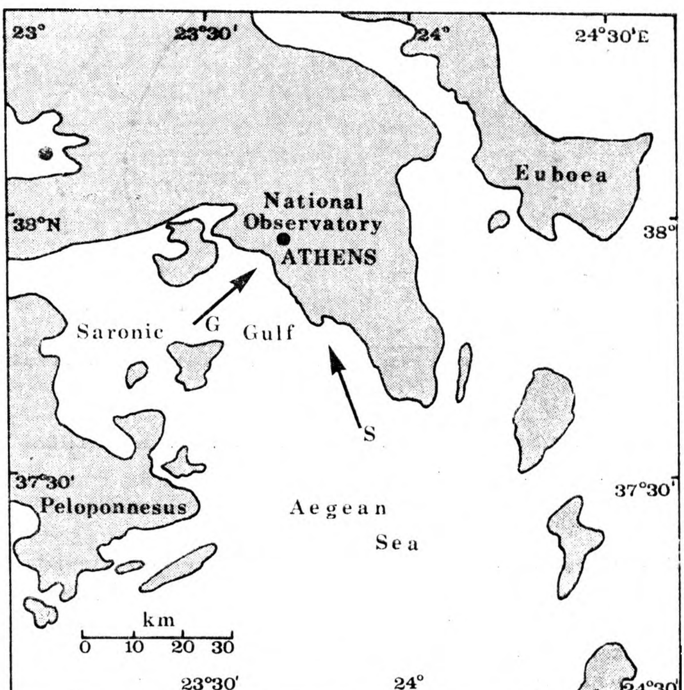

FIGURE 1—LOCATION OF THE STATION USED

with pure sea-breeze were selected to avoid interference by any other wind component during the period of the sea-breeze day. The nights, before and after the chosen day, showed only a light land-breeze or calm. Data were derived from the records of a pressure-tube anemograph, and the hourly vector mean winds were calculated by hand for the above months. It is assumed that the diurnal variations remain reasonably constant over the period of a month.

Duration. The characteristics as regards the duration and the time at which the sea-breeze starts and ends in relation to the time of sunrise and sunset are given in Figure 2. The times when the wind vector was parallel to the coastline in the morning and in the afternoon, have been considered as times of start and end of the sea-breeze, respectively. These times have been computed for all months. The end of the sea-breeze is noted about 2 hours after sunset, whereas Gill[2] found that at Kinloss the end of the sea-breeze occurs 2–3 hours before sunset. This difference is explained by the higher latitude of Kinloss and the consequent smaller heat supply there.

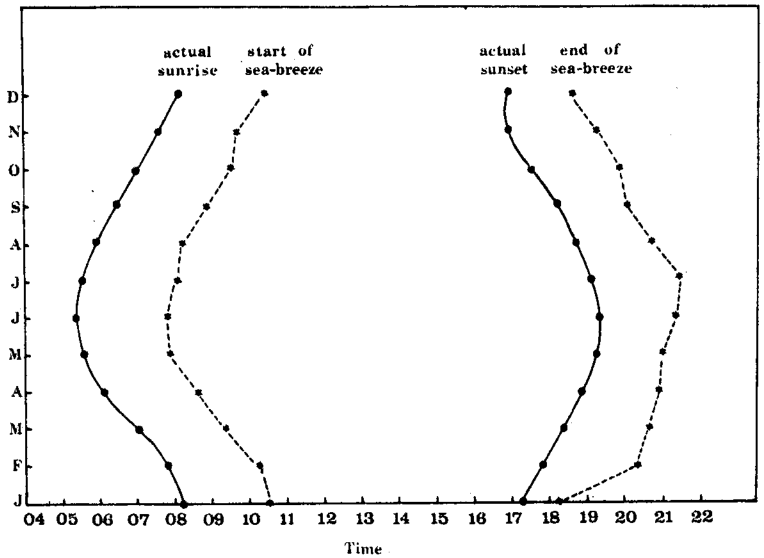

FIGURE 2—DURATION OF SUNSHINE AND SEA-BREEZE AT ATHENS (1961–67)
Times in local zone time (GMT + 2 hours)

Diurnal variation. Figures 3 and 4 show the constructed hodographs for the 26 selected pure sea-breeze days which occurred in January and the 24 which occurred in July, respectively, with the station in the centre of the diagrams. The orientation of the coastline near the station is also shown. The hourly mean wind vectors are plotted from the station towards the direction from which the wind blows. The ends are labelled with the hour to which they apply, in local zone time (GMT + 2 hours). The envelopes of

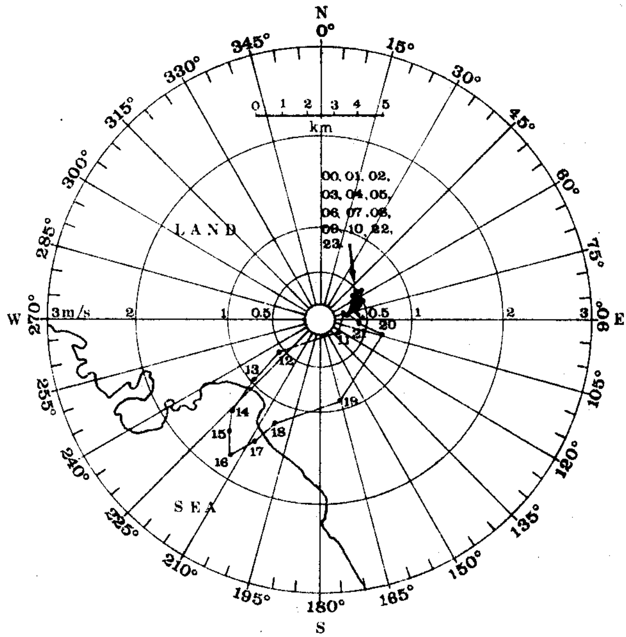

FIGURE 3—HOURLY VECTOR MEAN WINDS AT ATHENS IN JANUARY BASED ON DATA FOR 26 PURE SEA-BREEZE DAYS DURING THE 30 YEARS 1938–67

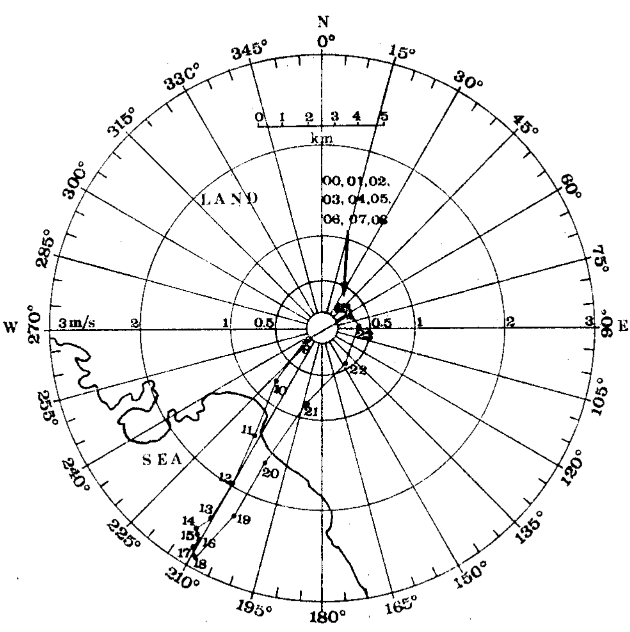

FIGURE 4—HOURLY VECTOR MEAN WINDS AT ATHENS IN JULY BASED ON DATA FOR 24 PURE SEA-BREEZE DAYS (1961–67)

the wind vectors are nearly ellipses. For the other seasonal representative months the results are nearly the same with the following detailed characteristics. During the night and early morning the direction of the wind remains almost unchanged, and the speed is small, in conformity with the expected weaker nocturnal land-breeze. The maximum mean intensities of the sea-breeze occur between 1600 and 1800 local time and range from 1·78 m/s in January to 2·88 m/s in July. The eccentricity of the ellipses ranges from a minimum in January to a maximum in July.

Discussion. The maximum eccentricity in summer indicates, according to the theory, that the mechanism distributing the heat vertically by thermals is stronger in summer, increasing the friction in the lower atmospheric layer.

As to the diurnal variation, in all four months the wind backs and only for short periods during the day does the wind veer in agreement with the theory. A similar backing is traced by Gill[2] at Wick, situated on a promontory too, as is the Athens Observatory. As can be seen the sea-breeze recorded first in the morning is blowing from the Saronic Gulf (G-direction, see Figure 1). Therefore a rough explanation of the backing at Athens may be that the bulk masses of air arriving later from the open sea (S-direction, see Figure 1) and increasing in intensity during the development of the circulation, prevail as a component which conceals the Coriolis effect. Another fact that supports this explanation is that during some relatively weak sea-breeze days, when the component from the S-direction becomes negligible early in the decay stage of the circulation in the afternoon, the wind at Athens stops backing and starts veering.

Conclusion. The theoretically expected ellipses are formed approximately but the diurnal variation of the sea-breeze is governed by the location of the station and the shape of the coastline near to it. At Athens, lying on a promontory, the sea-breeze wind backs in disagreement with the theory. A similar study, with two stations lying on either side of a promontory having the open sea just before it, would be of considerable interest. It would show whether the bulk masses of air arriving later from the open sea affect the diurnal change of sea-breeze direction in an opposite sense on each side of the promontory.

Acknowledgement. The author would like to express his sincere thanks to Professor L. N. Carapiperis for going through the manuscript of the paper.

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551.596.1

SOME METEOROLOGICAL EFFECTS ON GUN AND SHELL DETONATION NOISE AT DISTANCES ¾ TO 2½ MILES FROM SOURCE

By F. C. JACKSON and P. G. F. CATON

Summary. Sound-level measurements at distances between ¾ and 2½ miles from explosive detonations have been compared with the gradient of sound speed in the lower atmosphere as revealed by surface and upper-air temperature and wind measurements. Relationships have been established for three distances in conditions of negative gradient of sound speed. By interpolation, estimates are made of meteorological conditions necessary to avoid nuisance at various distances and for various types of detonation.

Introduction. The general public, living in the neighbourhood of Experimental Establishments or Practice Camps, are becoming increasingly sensitive to the nuisance and occasional damage caused by gunfire and other explosive detonations. It is important to be able to predict the meteorological conditions in which guns may be fired or explosives detonated without causing serious nuisance to members of the public living close to firing ranges. This paper considers the problem at distances ¾ to 2½ miles from the noise source, and excludes description of the sound focusing effects which often occur at greater distances.

A blast wave formed by gunfire or detonation attenuates rapidly to become similar to a sound wave and the laws of propagation of sound may be applied. The speed of sound (c) in still air is given by

$$c = \text{const. } T_V{}^{\frac{1}{2}},$$

where T_V is the virtual temperature in kelvins. Thus, in the real atmosphere, the speed of sound is dependent on temperature, humidity, and wind speed and direction. It follows from Snell's Law of Refraction that if the speed of sound in the atmosphere increases or decreases with height a sound wave originating near the surface will be turned towards or away from the ground and the resulting overpressure, measured at a distant position near the ground, will be modified from that obtained in an atmosphere with uniform sound speed.

Sound-level measurements were made to ascertain whether a correlation could be obtained between gun and shell detonation noise measured at distances between ¾ and 2½ miles from source and the change in the speed of sound in the atmosphere from the surface to a height of 500 feet (150 metres), derived from surface and upper-air temperature and wind measurements.

Observations. The sound-level measurements were made at the radiosonde station at Landwick (51° 33′N, 00° 50′E) during the course of routine proof and experimental firing on the Shoeburyness Ranges. The measurements, at height 3 feet above ground, used a Bruel and Kjaer Impulse Precision Sound Level Meter, Type 2204, with 1-inch microphone, Type 4145, extension rod and windscreen orientated towards the noise source. The instrument was calibrated before and after each set of measurements with a Sound Level Calibrator Type 4230.

The Impulse Sound Level Meter, according to its manufacturers, is 'an instrument that approximates a subjective impression of a short duration sound' and for these experiments it provided sound-level values without analysis of frequency content and duration of the noise. In view of the expected low-frequency content the 'C' scale was used in preference to the 'A' scale (see Figure 1). It is significant also that the low-frequency content of the noise may lead to rattling windows and other vibrations inside buildings, thus causing annoyance not experienced in the open.

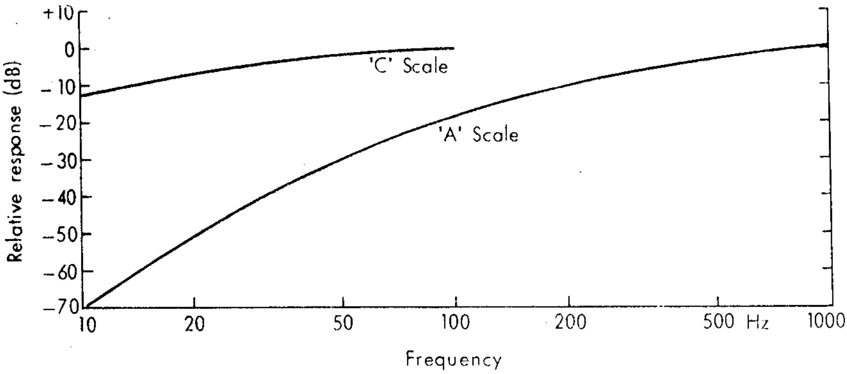

FIGURE 1—SOUND LEVEL METER RESPONSE

The radar wind measurements were supplemented by pilot-balloon observations so that upper-wind data were available at half-hourly intervals. Upper-air temperature data were obtained normally every 4 hours.

The area around Landwick is flat with unobstructed line of sight from the position of measurement to two gun batteries at distances 1380 and 1750 yards, at which the majority of firings were made. Sound-level readings were also obtained from shell detonations on sand at distances 4300 to 4650 yards (approximately 2½ miles).

The change in the speed of sound from the surface to a height of 500 feet was calculated for the relevant azimuth from the temperature lapse rate and vector wind change. Humidity was not taken into account, as changes of the speed of sound in air due to changes in humidity are relatively small. Owing to turbulent motion near the surface and the limitations of wind-finding techniques in indicating shear over narrow layers, scatter was expected in sound-level readings with the same measured sound speed structure.

All measurements were made in temperature lapse conditions, the temperature decreasing by between 0·5 and 3·2 degC from the surface to 500 feet. Further, the vast majority of measurements were made in conditions of *negative* gradient of sound speed.

Results.

(a) *At distance 1380 yards.* Figure 2 shows a plot of the data obtained from 133 firings of Gun 'A' during the period 13 July–4 August 1971. The means of a number of sound-level readings measured over a short period of time are plotted against the change in the speed of sound from the surface to 500 ft (expressed as a sound speed gradient in units feet per second per foot, i.e., in SI units, reciprocal seconds or s^{-1}). The number of sound readings and their range in decibels is shown alongside each plotted point. All sound pressure levels are measured in decibels relative to a reference pressure of 2×10^{-5} Pa.

Good linear correlation is obtained. The calculated regression line $y = 550\,x + 104{\cdot}2$ is drawn, and the correlation coefficient is $+\,0{\cdot}90$.

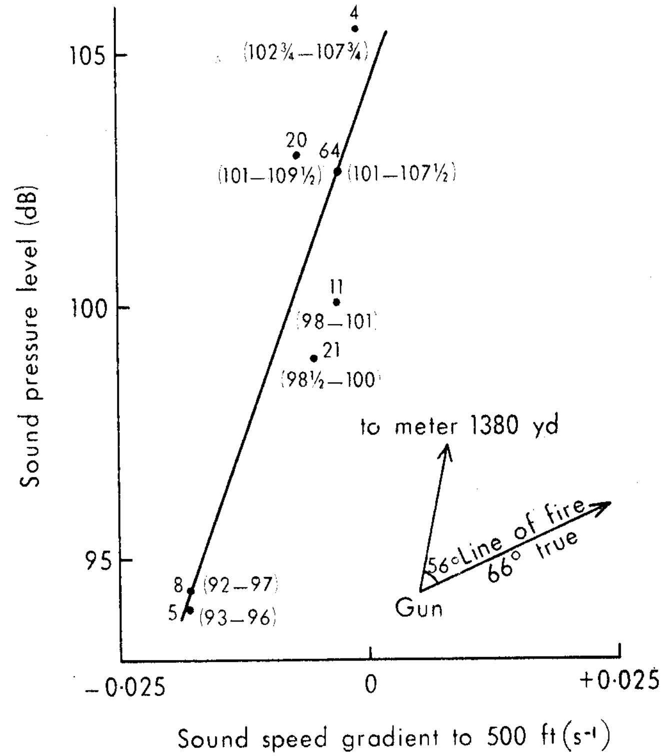

FIGURE 2—SOUND PRESSURE LEVEL MEASUREMENTS FROM GUN 'A' AT DISTANCE 1380 YARDS

Sound pressure levels are measured in decibels relative to a reference pressure of 2×10^{-5} Pa. Numbers adjacent to plotted points indicate numbers of observations and, in brackets, the range in decibels of the observations.

(b) *At distance 1750 yards.* Figure 3 shows the results obtained from 159 firings of Gun 'B' during the period 6 April 1971–9 December 1971. The data are separated into two groups (i) charge weights $6\frac{1}{4}$ to $7\frac{1}{4}$ lb and (ii) charge 'super' heated, corresponding to different noise levels at source. Also, unlike the Gun 'A' firings, the range of azimuths of 'line of fire' varied randomly over about 30 degrees, possibly requiring consideration of an additional variable. As in Figure 2 comparison is between the mean of sound meter readings and the gradient of sound speed from the surface to 500 ft.

In group (i) linear correlation (coefficient $+\,0{\cdot}76$, regression line $y = 690x + 105{\cdot}1$) is obtained, by discarding the 13 observations plotted at 98·4 dB. These observations were made on 3 August 1971, when a cold front with waves was in the vicinity of the station. The wind observations before and after the firings were consistent in indicating a positive gradient of sound speed from the surface to 500 ft, but there was considerable change in magnitude; further, in the wind observations after the firing the gradient of sound

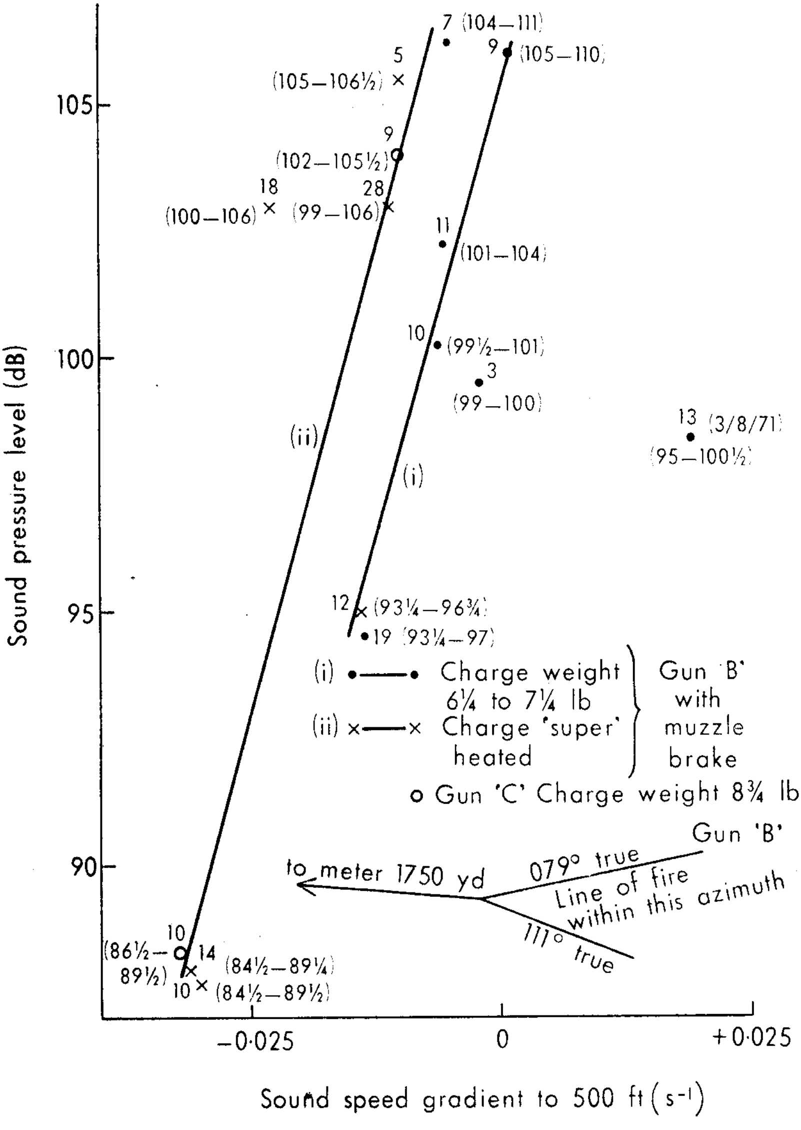

FIGURE 3—SOUND PRESSURE LEVEL MEASUREMENTS FROM GUNS 'B' AND 'C' AT DISTANCE 1750 YARDS

See notes under Figure 2.

speed was negative above 500 ft. It may be that even at these distances a layer of atmosphere deeper than 500 ft is important, and that the simple correlation breaks down when the gradient of sound speed is complex.

In group (ii) linear correlation (coefficient $+0{\cdot}81$, regression line $y = 720x + 111{\cdot}0$) is obtained, with the slope of the regression line very similar to that for group (i). However it must be admitted that the crosses plotted at 95·0 dB, $-0{\cdot}014$ s^{-1} and 103·0 dB, $-0{\cdot}023$ s^{-1} are respectively 6 dB and $8\frac{1}{2}$ dB off the line. No explanation is available in the first case other than the possibility that noise differences at source may account for part of the discrepancies. In the second case the wind profiles measured before and after the firings were unusual, and it is possible that a lower value of gradient of sound speed, -0.012 s^{-1}, would be more representative.

Finally, data for two occasions totalling 19 rounds from Gun 'C' are plotted on Figure 3. They confirm the slope derived from the previous data, but it is of course coincidental that the ordinates fit so closely those of Gun 'B' with 'super' heated charge.

(c) *At distances 4300 to 4650 yards.* Figure 4 shows sound-level measurements made on three occasions (28, 29, 30 April 1971) corresponding to detonations on sand of 67 shells fired from guns of the same calibre. The values of sound-speed gradient are those from the points of detonation (not from the guns). It will be seen that linear correlation is possible (coefficient $+0.97$, regression line $y = 1220x + 105.6$). The line must be regarded as provisional, being based on three data points only.

(d) *Use of surface wind measurements alone.* At a number of Establishments upper-air temperature and wind measurements are not available. It is important therefore to see what success is possible when surface measurements alone are used. Broadly speaking, the temperature lapse conditions (surface to 500 ft) to which all the data refer may be identified by forecast from the nearest meteorological office, and in these lapse conditions the wind shear to 500 ft usually contributes the larger term in the calculated sound-speed change. Further, unless the surface wind is very light or the local topography is uneven, the wind shear to 500 ft often bears a rough relation to the surface (10-m) wind. Therefore, in temperature lapse conditions, there is prospect of useful results using surface wind data alone, provided that it is recognized that a proportion of failures will occur.

Figure 5 shows all of the data at distance 1380 yards (Gun 'A' charge 5) plotted against the component of the surface (10-m) wind in the direction gun to meter. Good linear correlation is obtained (coefficient $+0.99$, regression line $y = 0.22x + 98.1$), by excluding the data for 3 August 1971—the wind structure at the time of these observations was unusual.

Figure 6 shows the data at 1750 yards (Gun 'B') subdivided according to charge as in Figure 3. In these cases also linear relationships are obtained, but the slopes of the lines corresponding to the subdivisions are different and the lines are not displaced vertically as in Figure 3. These discrepancies make physical interpretation of the 'best-fit' lines very difficult. The use of surface wind measurement alone as a successful indicator of sound level at distance requires, ideally, that the vertical wind shear increase as the surface wind speed increases, or, at least, that wind speed increase with height. A study of the data used for Figure 5 showed an increase in wind speed with height for all points plotted, whereas for 5 of the 13 points plotted on Figure 6 the wind speed decreased with height in the lowest layers. Clearly there are limitations to the use of surface wind measurements alone.

Discussion. Consideration of Figures 2, 3 and 4 shows that the slope of the regression lines increases with increasing distance. Thus the influence of the gradient of sound speed increases as the distance from a detonation increases. For example, if the change in the speed of sound from the surface

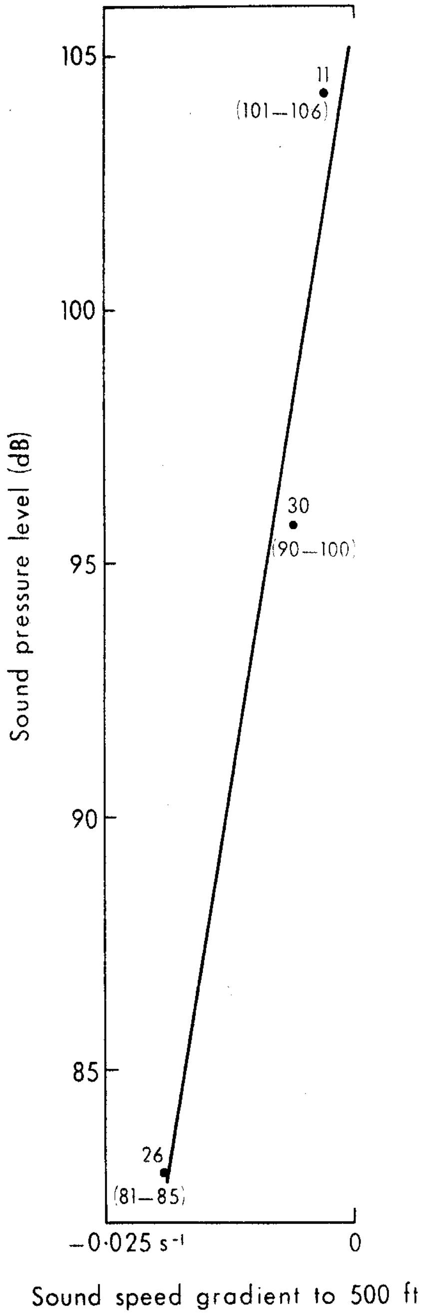

FIGURE 4—SOUND PRESSURE LEVEL MEASUREMENTS FROM SHELLS DETONATING ON SAND AT DISTANCES FROM 4300 TO 4650 YARDS

See notes under Figure 2.

to 500 ft is $-$ 5 ft/s (gradient $-$ 0·010 s^{-1}), the observed noise at distances of 1380, 1750 and 4500 yd will be attenuated respectively to 5½ dB, 7 dB and 12¼ dB below the levels which would obtain in a uniform sound-speed field.

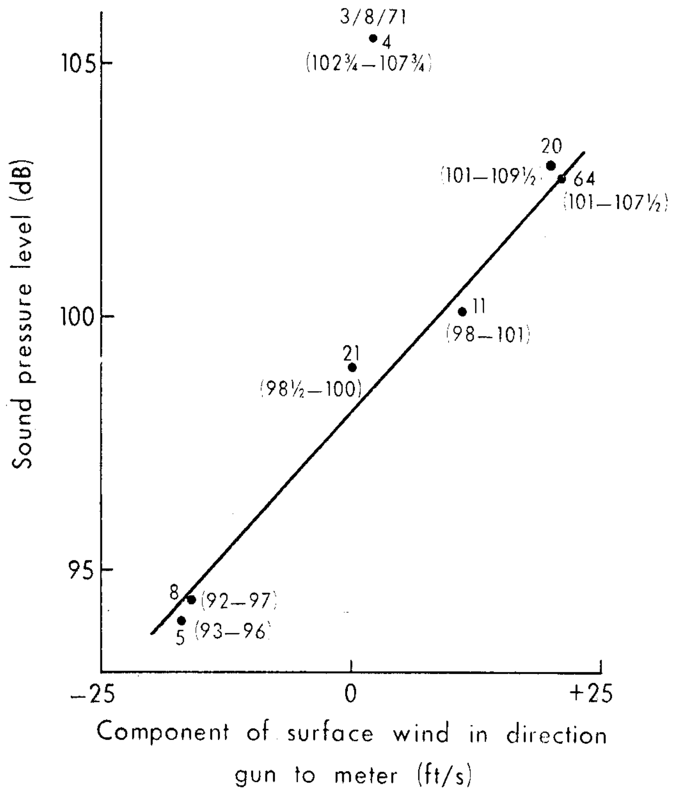

FIGURE 5—SOUND PRESSURE LEVEL MEASUREMENTS FROM GUN 'A' AT DISTANCE 1380 YARDS COMPARED WITH COMPONENT OF SURFACE WIND

See notes under Figure 2.

These results appear physically reasonable and in Figure 7 the slope of the regression lines (indicating change of sound level at fixed distance per unit of gradient of sound speed) is plotted against distance, using a logarithmic scale. The three points fall close to a straight line. The line provides a *provisional* basis for extension of our results to other distances within the range 1380–4650 yd (approximately ¾–2½ miles). For example, at distance 3000 yd, Figure 7 suggests a change of sound level of 1 dB for each 0·001 s^{-1} unit of gradient of sound speed.

Report No. 1240 of the Ballistics Research Laboratory, Maryland, U.S.A.,* contains a graph, reproduced as Figure 8, which relates overpressure at the surface at various distances from detonations of various charges of High

* PERKINS, B. and JACKSON, W. F.; Handbook for prediction of air blast focussing. Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, U.S.A. Report No. 1240, 1964.

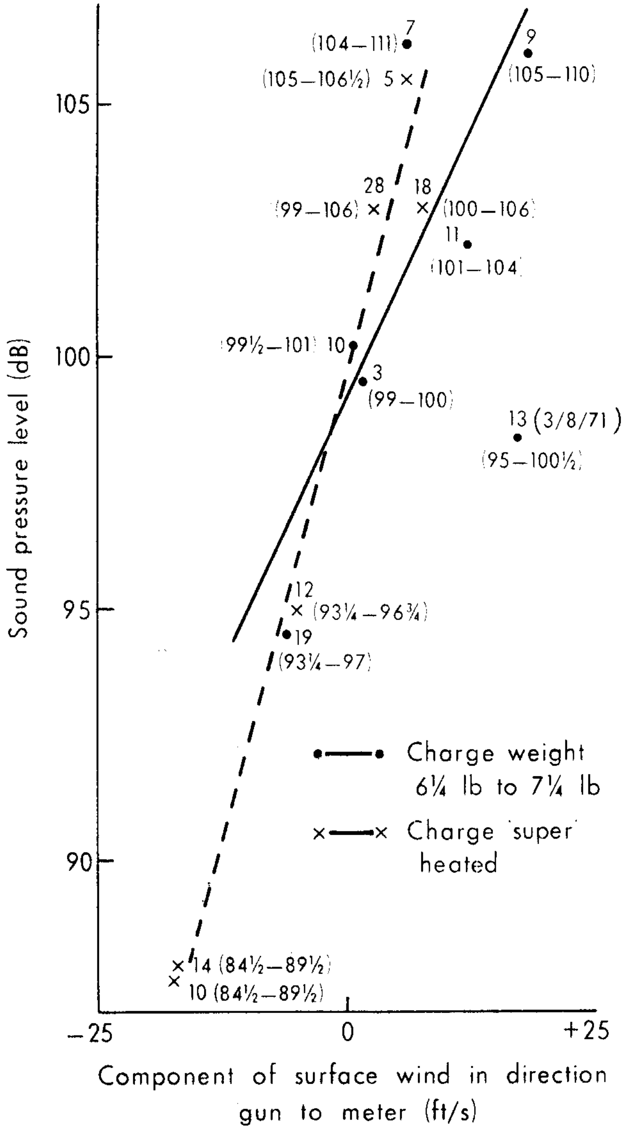

FIGURE 6—SOUND PRESSURE LEVEL MEASUREMENTS FROM GUN 'B' AT DISTANCE 1750 YARDS COMPARED WITH COMPONENT OF SURFACE WIND

See notes under Figure 2.

Explosive (HE) when the speed of sound is unchanged with height, i.e. the vertical gradient of sound speed is zero. It is suggested that this graph may now be extended to conditions of negative gradient of sound speed. For example Figure 8 indicates that 6 lb HE (approximate content of shell) at 4500 yards (13·5 kilofeet) will produce an overpressure of 0·00075 pounds per square inch (p.s.i.) (= 108·5 dB), in conditions of zero gradient of sound

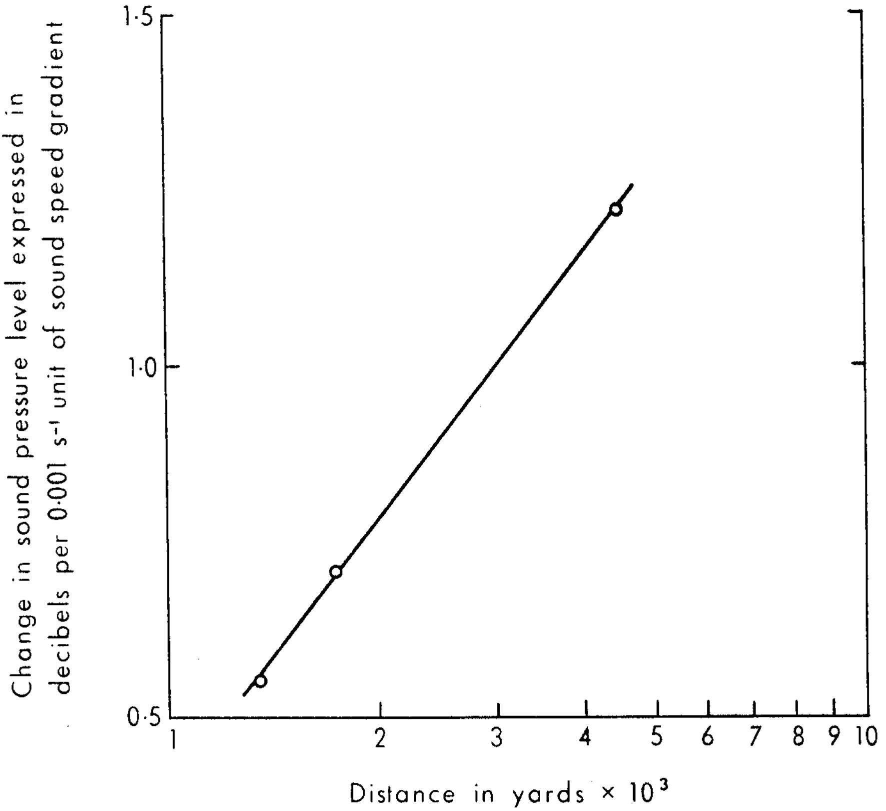

FIGURE 7—COMPARISON OF THE SLOPES OF FIGURES 2, 3 AND 4

speed. This is in reasonable agreement with the value of 105·6 dB indicated by Figure 4, considering that the detonations were on sand. Figure 4 and Figure 7 further indicate that in a negative gradient of sound speed of $-$ 0·010 s^{-1} the overpressure will be reduced by 12¼ dB to 93¼ dB for a detonation on sand. Repeating the calculation for identical conditions and a distance of 3000 yards produces a value close to 100 dB.

Estimation of gun noise is slightly more complicated, since it is necessary to consider the muffling effect of the gun which may well vary according to the angle between 'line of fire' and 'direction to meter'. Thus Figure 8 indicates that 6¾ lb HE detonated in the open will produce at 1750 yards an overpressure of 0·003 p.s.i. (121 dB) in conditions of zero gradient of sound speed, whereas Figure 3 indicates gun noise (Gun 'B') of 105 dB when the meter is sited almost directly behind the gun. Attenuation factors for other guns and other directions relative to the line of fire may be determined experimentally, and thereby permit complete calculations of overpressure at various distances and for various *negative* gradients of sound speed.

It should be emphasized that our useful data are limited to conditions of temperature lapse from the surface to 500 ft, negative gradient of sound speed (zero to $-$ 0·030 s^{-1}) from the surface to 500 feet, and distances of ¾–2½ miles. At this stage we should not feel confident about extending predictions outside these limits.

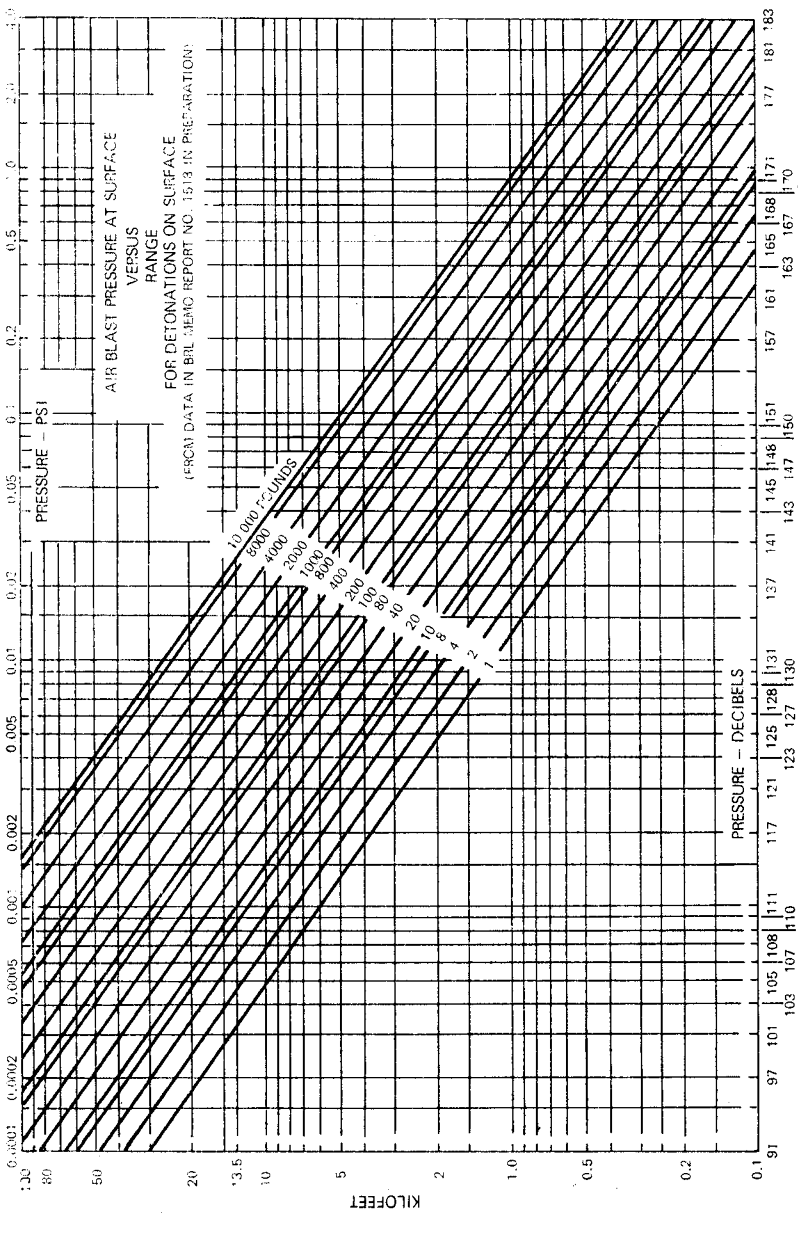

FIGURE 8—PRESSURE VERSUS DISTANCE WHEN THE SPEED OF SOUND IS UNCHANGED WITH HEIGHT

As an alternative to the simple but multi-stage calculations described above we may attempt to define 'GO – NO GO' limits for detonations of various types. Our rough subjective assessments of noise nuisance in the open suggest that with most guns and surface detonations on sand, sound-level values greater than 100 dB ('C' scale) are necessary to cause annoyance. This critical limit is obviously affected by the rate of firing, the frequency content of the noise (especially when indoors) and the conditioning of the populace. In view of the observed variability of sound-level readings, due principally to small-scale variability in the atmosphere, we have designed limits based on an expected average noise level of 97 dB. Table I shows estimates of the minimum negative gradient of sound speed (in units s^{-1} from the surface to 500 ft) in the direction of sensitive areas necessary to avoid nuisance at various distances for some types of detonation. The calculations assume attenuation with distance in a uniform sound speed field in accordance with Figure 8, with superimposed attenuation in negative gradients of sound speed as indicated in Figure 7. The Table should be regarded as a guide, to be modified in the light of local experience. Adjustments will almost certainly be necessary at Establishments not located in flat open country.

TABLE I—ESTIMATES OF METEOROLOGICAL CONDITIONS NECESSARY TO AVOID NUISANCE AT VARIOUS DISTANCES WITH SOME CHARGE WEIGHTS

Noise source	Charge weight	Distance	Minimum negative gradient of sound speed from the surface to 500 ft in the direction of the sensitive area
		yd	s^{-1}
High explosive (HE) in the open	1 lb	1500	− 0·028
		3000	− 0·009
		4500	− 0·004
	10 lb	3000	− 0·019
		4500	− 0·011
	100 lb	3000	− 0·028
		4500	− 0·020
Shell detonating on sand	6 lb (approx. HE content)	1500	− 0·036
		3000	− 0·013
		4500	− 0·007
Gun 'A' (assuming attenuation factor 18 dB)	No. 5	1500	− 0·011
		3000	(+ 0·002)
Gun 'B' (assuming attenuation factor 16 dB)	$6\frac{1}{4}$ – $7\frac{1}{4}$ lb	1500	− 0·015
		3000	zero
Gun 'C' (assuming attenuation factor 11 dB)	$8\frac{3}{4}$ lb	1500	− 0·026
		3000	− 0·007
		4500	− 0·002

Acknowledgements. The authors desire to thank the Ministry of Defence for the provision of facilities and assistance with Trials gunnery data. They also thank the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, U.S.A. for permission to reproduce Figure 8.

551.577.36(595):551.586:634.0

THE PERSISTENCE OF WET AND DRY SPELLS IN SUNGEI BULOH, SELANGOR

By W. C. YAP
Rubber Research Institute of Malaya

Summary. A study was made of the length of dry and wet spells at the Rubber Research Institute of Malaya's Experimental Station at Sungei Buloh. From the results of the study it is learned that after a wet day the probability of the following day being wet increases with the increasing length of the spells, and the same is true of the dry spells. By comparing the rates of increase of the probabilities, dry spells seem to be more persistent than wet ones.

Introduction. The success of crop establishment and growth depends largely on the availability of adequate rainfall. For this reason, planting of seedlings for most crops, including rubber, is usually confined to periods in which there is a good expectation of rain. Long periods of dry weather are avoided for planting if possible.

Weather also plays a large part in the total output of rubber in a particular area. Rain falling during the usual daylight working hours often disrupts or prevents tapping of *Hevea* rubber trees and results in loss of yield. The harvesting of latex is also particularly susceptible to interference from rain, especially when the downpour is heavy enough to result in latex wash-out. Rain, therefore, can cause substantial loss of income to the rubber tappers.

Various aspects of the rainfall pattern in West Malaysia have been studied by Dale[1,2] and more recently by Nieuwolt,[3] Wycherley,[4] and Lockwood.[5] Apart from these aspects, specific investigations of the occurrence and pattern of rainfall within Selangor have also been carried out by Chia.[6] In particular, in Selangor, rainfall records at the Experimental Station of the Rubber Research Institute of Malaya (RRIM) in Sungei Buloh (3° 12′N, 101° 35′E) have been analysed statistically by Narayanan[7] in a study of the daily, monthly and annual variations in rainfall.

The present study analyses the length of dry and wet spells at the RRIM Experimental Station and estimates the probability of their occurrences.

Rainfall data. The data used are the rainfall records collected from January 1951 to December 1971. Days on which at least one hundredth of an inch of precipitation was recorded are classified as wet days. Precipitation has been observed daily at about 0730 local time, and the rainfall recorded for any day refers to the previous 24 hours. The term 'spell' or 'run' is defined here as a sequence of days of the same kind, i.e. wet or dry, and the length of the spell is the number of whole days in it.

Distribution of the length of spells. The frequencies of wet and dry days over the period of 21 years (1951–71) are counted. Wet days exceeded dry ones by about 6 per cent of the total number. The frequencies are classified according to their run lengths and the results for wet and dry spells are shown in columns 2 and 7 respectively of Table I. Although there are only 3631 dry days, these are distributed in 1542 periods whose lengths range from 1 to 23 days. In the case of wet days, the number over the 21 years is 4019, and these are contained in 1540 spells of length 1 to 19 days. Generally, the frequency distributions of the run lengths for both the wet and the dry days are about the same (Figures 1 and 2).

TABLE I—FREQUENCY DISTRIBUTION OF DURATION OF SPELLS OF WET AND DRY DAYS AT THE EXPERIMENTAL STATION OF THE RUBBER RESEARCH INSTITUTE OF MALAYA, SUNGEI BULOH, FOR THE PERIOD 1951–71, TOGETHER WITH CORRESPONDING VALUES CALCULATED FROM THE COMPOUND GEOMETRIC AND LOGARITHMIC MODELS

Length of spell *days*	WET Observed frequencies *(O)*	WET Expected frequencies *(E)* Compound geometric (C.G.)	WET Expected frequencies *(E)* Logarithmic (Log.)	WET $(O-E)^2/E$ C.G.	WET $(O-E)^2/E$ Log.	DRY Observed frequencies *(O)*	DRY Expected frequencies *(E)* Compound geometric (C.G.)	DRY Expected frequencies *(E)* Logarithmic (Log.)	DRY $(O-E)^2/E$ C.G.	DRY $(O-E)^2/E$ Log.
1	686	634·6	743·8	4·16	4·49	758	721·0	791·6	1·90	1·43
2	320	346·5	303·1	2·02	0·94	311	357·2	309·5	5·97	0·01
3	176	192·0	164·7	1·33	0·77	194	188·7	161·4	0·15	6·58
4	123	123·6	100·7	0·00	4·94	107	105·1	94·6	0·03	1·62
5	77	75·9	65·6	0·02	1·98	54	61·2	59·2	0·85	0·46
6	49	47·7	44·6	0·04	0·43	37	37·0	38·6	0·00	0·07
7	33	30·6	31·1	0·19	0·12	18	23·2	25·9	1·17	2·41
8	26	20·0	22·2	1·80	0·65	25	15·0	17·7	6·67	3·01
9	13	13·3	16·1	0·01	0·60	16	10·0	12·3	3·60	1·11
10	10	9·0	11·8	0·11	0·27	10	6·7	8·7	1·63	0·19
11	7	6·2	8·7	0·10	0·33	3	4·6	6·1		
12	10	4·7	6·5	5·98	1·88	1	3·2	4·4		
13	6	3·5	4·9			2	2·3	3·2		
14	1	2·8	3·7			—	—	—		
15	2	2·1	2·8			3	1·2	1·7		
16	—	—	—			—	—	—		
17	—	—	—			— (12)	— (12·2)	— (16·2)	0·00	1·09
18	— (10)	— (9·4)	— (12·4)	0·04	0·46	—	—	—		
19	1	1·0	1·0			1	0·4	0·5		
20	—	—	—			—	—	—		
21	—	—	—			1	0·3	0·3		
22	—	—	—			—	—	—		
23	—	—	—			1	0·2	0·0		
Parameters	$a = 12·64$	$b = 8·86$	$q = 0·815$			$a = 7·14$	$b = 6·27$	$q = 0·782$		
chi-square values		15·80	17·86				21·97	17·98		
$P(\chi^2)$		0·11	0·09				0·005	0·04		

In order to study the frequency distribution of the spells mathematically and to derive certain information from them, the observed frequencies are fitted to three theoretical models, namely the geometric, the compound geometric and the logarithmic.

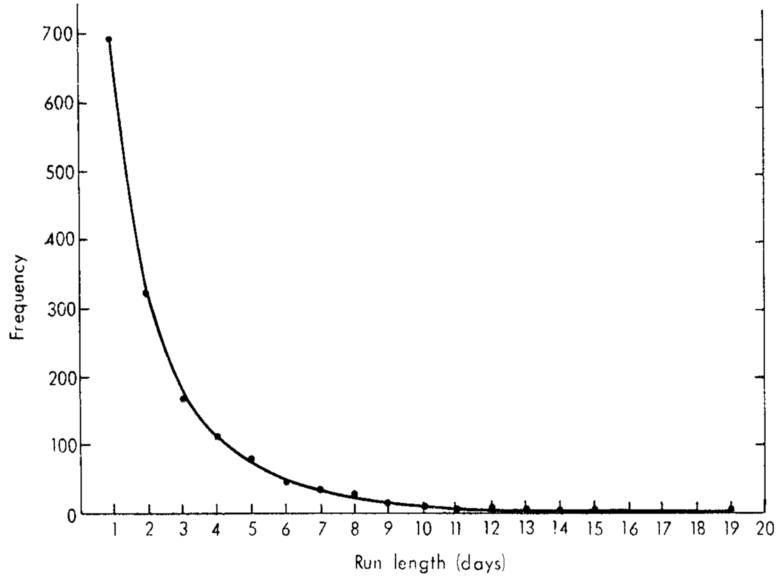

FIGURE 1—DISTRIBUTION OF LENGTHS OF RUNS OF WET DAYS AT RRIM EXPERIMENTAL STATION IN SUNGEI BULOH FOR 1951–71

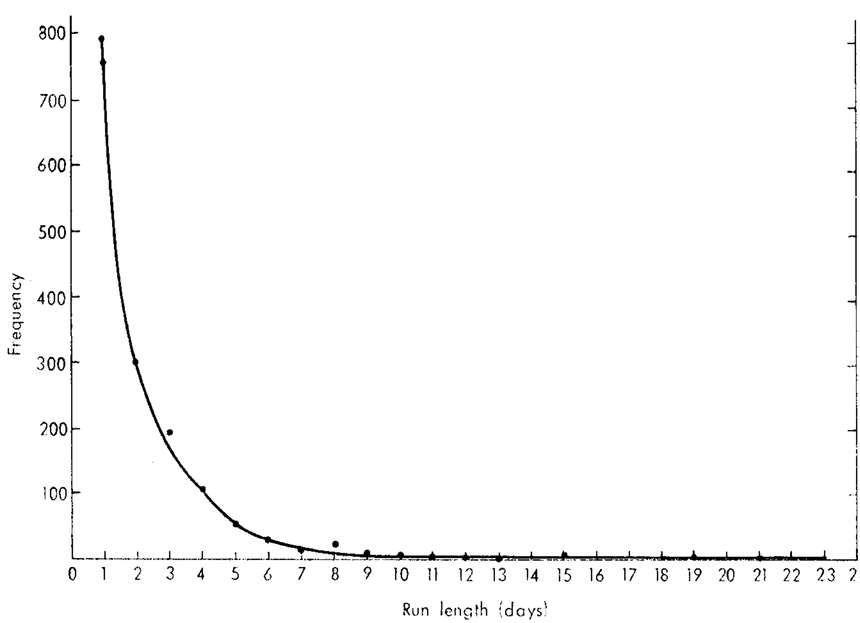

FIGURE 2—DISTRIBUTION OF LENGTHS OF RUNS OF DRY DAYS AT RRIM EXPERIMENTAL STATION IN SUNGEI BULOH FOR 1951–71

The data fail to fit the geometric model, which assumes a constant probability for the spells of all lengths. However, good fits are obtained in the case of the other two models.

The compound geometric model is based on the assumption that the probability of a wet (or dry) day being followed by another wet (or dry) day is p, where p is a random variate having a constant value within any one run, but different values in different runs. Following the approach analogous to that of Skellam,[8] p is assumed to be a beta variate.

Then $$f(p) = \frac{p^{a-1}(1-p)^{b-1}}{B(a, b)} \quad 0 \leqslant p \leqslant 1 ,$$

where a and b are the constants of the distribution. Writing the probability of a run of r days as $P(r)$, this is given as

$$\begin{aligned} P(r) &= \frac{1}{B(a, b)} \int_0^1 p^{r-1}(1-p)p^{a-1}(1-p)^{b-1}\, dp \\ &= \frac{1}{B(a, b)} \int_0^1 p^{a+r-2}(1-p)^{b}\, dp \\ &= \frac{B(a+r-1, b+1)}{B(a, b)} . \end{aligned}$$

Then $P(1) = \dfrac{b}{a+b}$,

and for $r \geqslant 2$,

$$P(r) = \frac{a+r-2}{a+b+r-1} P(1) . \qquad \ldots (1)$$

To derive the parameters a and b, it is convenient to use the factorial moments about the origin. (For a brief exposition on factorial moments, and their relationship with the ordinary moments, see Johnson and Leone[9].) Let the first and second moments be denoted as U_1' and U_2' respectively. Then

$$U_1' = \frac{1}{B(a, b)} \int_0^1 \frac{1}{(1-p)} p^{a-1}(1-p)^{b-1}\, dp = \frac{a+b-1}{b-1}$$

$$U_2' = \frac{1}{B(a, b)} \int_0^1 \frac{2p}{(1-p)^2} p^{a-1}(1-p)^{b-1}\, dp = \frac{2a(a+b-1)}{(b-1)(b-2)} .$$

Expressing a and b in terms of these moments gives

$$b = \frac{2U_1'\,(U_1'-1)-2U_2'}{2U_1'\,(U_1'-1)-U_2'} , \qquad \ldots (2)$$

and $$a = (U_1'-1)\,(b-1) . \qquad \ldots (3)$$

The compound geometric distribution is fitted to the observed distributions of run lengths by estimating a and b. These parameters are found by substituting sample values for U_1' and U_2' in equations (2) and (3). The sample values of U_1' and U_2' are themselves obtained by equating with

$$\sum_r f_r r \;/\; \sum_r f_r \;(=\bar{r}) \text{ and } (\sum_r f_r r^2 \;/\; \sum_r f_r) - \bar{r} \text{ respectively,}$$

where f_r denotes the observed frequency of spells of length r days. The expected proportions are then calculated from equation (1).

The logarithmic model was first used by Williams,[10] who successfully fitted it to runs of wet days and of dry days at Harpenden, England. According to this model, the probability of a spell of r days is $-q^r/r \log(1-q)$, where q is a constant — the probability of runs of unit days. To specify the probability distribution, only the parameter q needs to be estimated. By using iteration, it is easily derived from the maximum likelihood formula

$$-\frac{q}{(1-q)\log(1-q)} = \bar{r} \text{ (the mean run length).}$$

Table I also shows the estimated frequencies of the dry and the wet spells of various lengths obtained from the fitted models. At the bottom of the table are given the estimated values of the parameters of the probability distributions and the chi-square values for the fit. The contribution of each of the cells, $(O-E)^2/E$, to the chi-square is also presented in the table.

Regarding wet spells, both the compound geometric and the logarithmic models are acceptable, but the former is preferred because it gives a larger probability to the chi-square value. For this model, the main contributions to the chi-square values are due to a deficiency of runs of 1 day and of 8 and 12 days and a surplus of runs of 2 and 3 days. For dry spells neither model seems really satisfactory. However, the logarithmic model is preferred to describe the distribution of the run lengths of the dry days.

Conditional probabilities. The chances of a spell lasting one further day are determined by the values of the probabilities of run lengths estimated from the fitted distributions. Suppose a particular type of weather (dry or wet) has lasted one day; the chance that the following day will be similar is $1-P(1)$. If the spell has lasted r days (for $r = 2, 3, 4 \ldots$), the probability that it will be extended another day is

$$\frac{1-\sum_{x=1}^{r} P(x)}{1-\sum_{x=1}^{r-1} P(x)}.$$

These probabilities for the wet and the dry spells up to 15 days are presented in Figure 3. For the wet spells, 59 per cent of first days will be followed by a second, 61 per cent of second days will be followed by a third, and 62 per cent of the third days will be followed by a fourth, etc. The corresponding values for the dry spells are 49, 59, and 63. Persistence of the spells, as indicated by the rate of increase of the probabilities with the run length, is more pronounced for shorter dry spells than the corresponding wet ones (Figure 3).

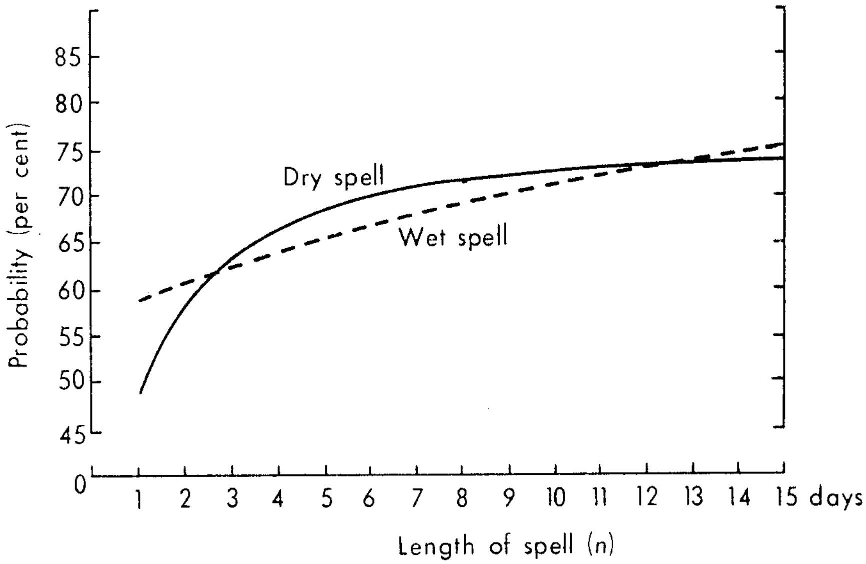

FIGURE 3—PROBABILITY THAT A SPELL WILL BE EXTENDED BY ANOTHER DAY

Acknowledgements. The author is indebted to the Director of the Rubber Research Institute of Malaya for permission to publish this work. Acknowledgements are also due to Mr P. O. Thomas for his encouragement in this study, to the Head of the Botany Division for permission to use the rainfall data, and to Dr P. K. Yoon for helpful discussion.

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REVIEW

An introduction to dynamic meteorology, by James R. Holton. 240 mm × 160 mm, pp. xi + 319, Academic Press Inc., Publishers, 111 Fifth Avenue, New York, New York 10003, 1972. Price: $15·95.

The volume of meteorological research has been increasing markedly over the last two decades, witnessed by the increase in the number of meteorological journals and papers, and there has been a corresponding change in the syllabus for university students in meteorology, at both undergraduate and post-graduate levels; perhaps nowhere has the change been greater than in dynamical meteorology where the advances have been greatly aided by the rapidly developing capability for computation provided by digital computers. The changing courses are reflected by new textbooks distilling the research into easily potable draughts for the student. Such is Professor Holton's book and welcome because there are few books covering quite the same ground.

The first five chapters are given to developing the equations of fluid motion referred to rotating axes and are carefully written so that the reader is proceeding at a gentle pace, with many of the difficult conceptual points well explained. The scale analysis is introduced at an early stage so that the importance of the various terms quickly becomes apparent, leading naturally to geostrophic and hydrostatic approximations and to the important terms in the vorticity equation. The illustrative material in these chapters is excellent and, as throughout the book, is supplemented by examples at the end of the chapters which are designed to make the reader think, often numerically, without being so involved as to take up a lot of time. The treatment of the planetary boundary layer in the sixth chapter is rather cursory and seems to have been added for the sake of completeness rather than as an integral part of the development required for the later parts of the book.

Having set up the apparatus which allows the main features of atmospheric motions to be treated quantitatively, the author then applies it in the next two longish chapters to the fundamental ideas of analysing the current situation in order to infer the likely developments and to laying the foundation of numerical prediction, dealing with both vorticity and primitive-equation models without going into details of any particular model. There follow two chapters dealing with atmospheric oscillations, mainly gravity waves, and instabilities in atmospheric motions. These are often taken before developing the equation for numerical prediction, so that the development of ideas about the general circulation will naturally follow those on short-range forecasting. The author now treats the general circulation and if his order seems a bit strange, there is nothing logically against it. These five chapters form the meteorological core of the book and are clearly and carefully written, with a nice gradation in difficulty; they give the basic ideas upon which the student can build, without developing the detail which may obscure the fundamentals.

The final chapter on tropical motion systems is welcome because, even if it seems to indicate that our knowledge is more numerate than it really is, it does indicate that there are particular problems to be faced which need to be tackled in a quite different way.

This is a textbook which will be welcome to students and teachers alike for its modern and clear exposition, and also for its useful set of problems at the ends of the chapters. A criticism is that the author has not been very helpful to the student in his references for further reading. A number of these references are substantial books, e.g. Batchelor's *Introduction to fluid dynamics* and Greenspan's *The theory of rotating fluids,* and the author might have indicated not only the title but also the sections that are of most value.

E. KNIGHTING

HONOUR

The following honour was announced in the Queen's Birthday Honours List 1973 :

I.S.O.

Mr H. B. Rowles, Principal Scientific Officer, Central Forecasting Office, Bracknell.

NOTES AND NEWS

Retirement of Mr R. F. Zobel, O.B.E.

Mr R. F. Zobel, Assistant Director in charge of the Central Forecasting Office at Bracknell retired on 30 June 1973 after 34 years' service in the Meteorological Office. Prior to this, however, Mr Zobel started work in 1929 in the National Physical Laboratory at Teddington, where he became an expert on the repair of watches and clocks and, whilst still at work, took an honours B.Sc. degree in Physics at London University. This was in the days before study concessions and the achievement of obtaining a degree whilst working at a full-time job was even more difficult and praiseworthy than it is today.

Ron joined the Meteorological Office in 1939 and spent the first few years of the war forecasting for Bomber and Coastal Command operations. He was commissioned as a Flight Lieutenant in the RAFVR (Meteorological Branch) in 1943 and was in at the birth of the 'thickness' development theory, as he was Dr Sutcliffe's deputy at Exning for some time. During the period 1945–47 he served in the Far East as Senior Meteorological Officer, Ceylon, Bengal–Burma, and later in the East Indies. He was promoted to the rank of Wing Commander in 1947 and became Chief Meteorological Officer, Far East and Japan.

Soon after demobilization Ron took up the post of Senior Meteorological Officer, HQ No. 1 Group, RAF as a Principal Scientific Officer and then in 1953 he was appointed to the post of Chief Meteorological Officer at HQ Bomber Command. After a spell of five years at High Wycombe he was posted to Aden as Chief Meteorological Officer. In 1959 he was appointed an Officer of the Order of the British Empire. In 1960 he returned to the United Kingdom and served as Editor of the *Meteorological Magazine* and later in the Aviation Services Branch of the Office.

In 1963 Ron was promoted to Senior Principal Scientific Officer and was posted to the Meteorological Research Flight at Farnborough and then in 1966 he became Assistant Director in charge of the Central Forecasting Office, where he stayed for the rest of his Office career. In this post he was almost immediately asked to introduce the three-level numerical forecasting model into operational practice on the KDF9 computer in order to supply, for the first time in the Meteorological Office, numerical forecasts of upper-air charts on a routine basis.

Mr Zobel has contributed several papers to the literature, probably the best known being a paper on the heating below an inversion in summer time and another showing that, at 200 millibars, gradient winds are a far truer representation of the actual wind field than are geostrophic winds. This fact, of course, plays a large part in the development of surface pressure systems.

Ron has wide interests in fields other than meteorology. In his spare time he made himself expert in the Russian language so that his services as a translator have often been used in the Office. He is also an expert on everything pertaining to motor vehicles and this has always been one of his relaxations, especially from his worrying job as AD Met O(CF). In his younger days he was a keen and very good cricketer and though no longer an active player still follows the progress of his county — Sussex.

We all wish Mr and Mrs Zobel many years of happiness and good health in their retirement.

V. R. COLES

PUBLICATIONS RECEIVED

Fog and road traffic, by R. L. Moore and L. Cooper (TRRL Report LR 446). 300 mm × 200 mm, pp. iv + 43, *illus.*, Transport and Road Research Laboratory, Department of the Environment, Crowthorne, Berkshire, 1972.

Readers' guide to books on geography, 2nd edition. The Library Association County Libraries Group. 180 mm × 120 mm, pp. 52. The Library Association, County Libraries Group, County Library Headquarters, Column House, 7 London Road, Shrewsbury, Salop SY2 6NW, 1973. Price: 25p.

CORRECTION

Meteorological Magazine, April 1973, p. 110. The date in the first line of the Summary should read 9 May 1972.

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NOTICES

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THE METEOROLOGICAL MAGAZINE

Vol. 102, No. 1214, September, 1973

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BRITISH ARCHITECTS OF THE INTERNATIONAL METEOROLOGICAL SYSTEM

By D. G. HARLEY

In this centenary year of 1973 many things will be written and spoken about the International Meteorological Organization (IMO) and its successor the World Meteorological Organization (WMO). The international system constructed by them is wonderful in its complexity, its flexibility and the methods of its control. Formed of independent national services, which work in continuous daily or hourly contact with each other, it is governed entirely by consensus of the professional heads of those services. Since the beginnings in 1873 the technical developments have been enormous, but the records of the early years show how far-seeing were the men who laid the foundations, and how well designed was the structure that rose on them. What C.-G. Rossby wrote in 1956 fits well the early leaders of IMO: 'During the last decades the technological development has time after time shown the dreams of a visionary mind to be closer to reality than the commonsense judgement of the realists'.

The IMO, which began in Europe, was naturally strongly influenced by European meteorology, as indeed WMO still is. It is not surprising then that although no permanent seats have ever been reserved for any person or country, certain founder countries have nearly always been represented in the governing body. Of these the only one with unbroken continuity from 1873 until today is the United Kingdom. In these one hundred years a great many British meteorologists have played important parts in the developing scene, but during the 78 years of IMO's existence four in particular played leading roles. Those four were R. H. Scott, Napier Shaw, Ernest Gold and Nelson Johnson.

R. H. Scott and the early years. The development of electric telegraph services in Europe stimulated the growth of meteorological services, and soon the mutual exchange of reports was begun. Even before this stage the first step in international meteorology was taken, when Maury of the U.S.A. and Quetelet of Belgium organized a conference of 10 countries in Brussels in 1853 on maritime meteorology. The main object of this conference was to achieve a uniform system of meteorological observations at sea.

By 1872 many meteorologists were convinced of the need for uniformity of practice and for international co-operation on a large scale, so 52 directors of meteorological services and a number of other scientists met in Leipzig to plan a formal intergovernmental conference to take place in the following year. Immediately there arose the problem of who should be invited, as many eminent meteorologists were not directors of their country's central services, and some countries indeed had several institutions of similar standing. Thus early began 'political meteorology', that inescapable incubus of international action.

Governments agreed, and in September 1873 there assembled the first International Meteorological Congress in Vienna, whose centenary will be celebrated in the same place in September 1973. The Congress was a great success, took a number of important technical decisions, and chose a Permanent Meteorological Committee (PMC) to see to their implementation and to call another Congress in a few years. The PMC met immediately, and elected as its President Buys Ballot of the Netherlands who had been the moving spirit and leader of events, and as its Secretary Dr R. H. Scott of the U.K.

Scott, a Dubliner, had become in 1867 Secretary of the Meteorological Committee of the Royal Society, and Director of the Meteorological Office. The Office was then a very small body — its total budget for the year 1874–75 was £11 685 10s 6d — and in low repute scientifically. In 1866 the issue of forecasts had been suspended as being scientifically unjustified, but the public outcry was such that by May 1867 the Board of Trade asked the Meteorological Committee to resume giving some intimation of storms. At first this was done by merely repeating actual reports, but before 1876 a storm warning system had again been developed. It is difficult now to realize just how little information was available; no ship reports, British reports for one hour in the morning and one hour in the evening (many of the latter came only with the next morning's message) and, gradually, some reports once daily from neighbouring countries. But these messages contained no cloud reports, no pressure tendency, and there was little uniformity of units. Even the hours of observation differed from country to country, a problem that took many decades to resolve.

From the start the vision of meteorologists saw far beyond these handicaps. Indeed, before Scott arrived, the Meteorological Committee went on record in 1866 as 'looking forward to international co-operation in the indication of the causes of meteorological changes over the greater part of the globe'. Thus in 1873 Scott was named with Alexander Buchan, Secretary of the Scottish Meteorological Society, to represent the United Kingdom at the Vienna Conference, with strict instructions 'to abstain from pledging Her Majesty's Government in any way'. He was in the event able to report back that no decisions had been taken involving expenditure.

Scott seems to have been a good organization man, a cautious and sound science administrator rather than a research scientist, although he was also a Fellow of the Royal Society, whereas Buchan from his less official position spoke more independently as a scientist. For example, when the Vienna Congress discussed the units to be used for observations and the universal use of the metric system was urged, Buchan was all for it, but Scott felt bound to say that his Government was now not so keen and was not likely to be able to accept the proposal.

The PMC had seven members initially, this number being increased to eight in 1878 when the French felt able to accept an invitation. They had been absent from the Congress, no doubt as a consequence of the Franco-Prussian war of 1870, the first of the painful effects of war on the continuity of meteorological co-operation. The second Congress which met in Rome in 1879 elected in its stead an International Meteorological Committee (IMC) to function until another Congress, and this system continued throughout the life of IMO. The PMC and the IMC met frequently from 1874 onwards, generally every two or three years. There was no other organization for continuity, no Secretariat until 1926, no permanent offices or officers. Even the name International Meteorological Organization only appears thus with capital letters in the 1920s when at last a permanent Secretariat was set up. Between the meetings of the IMC the President and Secretary carried on the business by correspondence. Scott was continuously Secretary until he retired in 1900 from the Meteorological Office. In more lowly affairs one might be tempted to suspect that perhaps a Secretary stayed so long because no one else would take on the job, but in this work there were many strong, active and indeed brilliant men, and one can but conclude that Scott was that most useful of men, the industrious reliable continuity man, who underpins the work of his enterprising colleagues.

To one used to today's large organizations for supporting international activities, some features of the early IMO are surprising, such as the publication of reports, language problems and finances. Finance was managed by each country paying its own way, e.g. in 1874 Scott asked the Meteorological Committee for £20 as a contribution to the Permanent Meteorological Committee. There is little or no mention in any of the early reports of the problems of language, whereas nowadays simultaneous interpretation seems indispensable. Yet large agendas were disposed of in meetings of a few days only. Publication of the reports of meetings was done by courtesy of various governments. Scott evidently persuaded his Meteorological Committee at home to support the work, and until the 1920s all the main reports of IMO were published in English by HMSO 'by Authority of the Meteorological Committee'. French and German editions were likewise published by other governments, for the general good. There being no Organization there was no book of rules, but there were the accumulated resolutions and decisions of the various meetings. Only in 1909 was there finally published in London a codex of such resolutions, drawn up by Hildebrandsson of Uppsala and Hellman of Berlin, at the request of the IMC. Until then personal experience and continuity saved the day. The 1896 Paris Conference noted Scott's knowledge of previous decisions and his pressure for consistency. By that time he was one of the only two active survivors of the 1873 Congress, Professor Mohn of Norway being the other (Mohn served from 1873 to 1913!). The Conference accepted Scott's advice that earlier decisions made for good reasons should be adhered to.

After the Rome Congress of 1879 which was, as before, intergovernmental, it gradually became clear that governments did not want any more such Congresses, apparently because the decisions were mainly technical and did not justify the use of such ponderous diplomatic procedures. For several years the IMC could not see clearly how to proceed. Eventually in 1888 it concluded that, as its agenda was finished and it could not call a Congress, its work was finished and it should dissolve itself. It asked its ex-officers President Wild of Russia (who had succeeded Buys Ballot in 1879) and Secretary Scott of the U.K., to carry on and call together the representatives of meteorological services to decide what should be done. So a Conference of Directors was convened to meet in Munich in 1891, many of them uncertain what could usefully be done in their semi-private capacity. However they soon found that they could do useful work, elected a new IMC, and so in practice things went on much as before. Before the next Conference in Paris Wild fell ill and Scott carried on all the preparations alone, because the rules did not then permit a new appointment to be made.

By this time the organization had spread far beyond Europe. From the beginning the U.S.A. had been involved to some degree, and from time to time participants from India, China, Argentina, Australia and Mauritius came to meetings. In the reports of the 1873 Congress and its Permanent Committee there are recorded discussions on the meteorological problems of Samoa, South America and the Congo among others. To the Paris Conference in 1896 which Scott called and opened single-handed, directors from most parts of the globe were invited, although in the event Asia, South America and the West Indies were not represented.

Until the first Conference of Directors in 1891 there were no subsidiary bodies to the IMC, although *ad hoc* conferences on special subjects had been called from time to time. Such were the private Conference on Maritime Meteorology called by Scott in London in 1874 to update the great work of Maury's Brussels Conference of 1853, and the special Polar Meteorology Conference in Hamburg in 1879. There were no Regional Associations until 1935 although Australasian intercolonial meteorological conferences met in Sydney, N.S.W., as early as 1879 and 1881. The first permanent Commission, forerunner of today's Technical Commissions, was established in 1891, and two more in 1896. At this time the long process of laying firm foundations and a good understanding began to allow real development of the science and practice of meteorology. But not until radio-telegraphy allowed services to escape from the limitations and heavy costs of telegrams, and to collect synoptic data from the oceans, and not until user demand from aviation opened the money bags, could meteorology really begin to take off.

In 1900 Scott retired, and was succeeded by Napier Shaw. The IMC thanked him for his 'unfailing zeal' during his long service. Scott died in 1916, before the rapid growth of meteorology had really got under way. It is sad to find that in the two obituary notices of him in the *Quarterly Journal of the Royal Meteorological Society* there is not one mention of all his international activities over so many years. Elsewhere however, someone recorded that Scott had been 'the architect of the international system'.

Sir Napier Shaw as President. Napier Shaw was a physicist of renown at Cambridge, and some were surprised that he took on Scott's job. However his subordinate position as Secretary of the Meteorological Council (imposed on Scott in 1877) was soon changed, and he became Director of the Meteorological Office. Instead of being controlled by the fortnightly meetings of the Meteorological Council of the Royal Society, he now became Chairman of a Meteorological Committee which met only every two months to advise him. The Royal Society and the Treasury were represented on this Committee. Shaw found the means to bring into the Office first-class young scientists and thus set it on a course from which it has never since looked back. Among these new men were Ernest Gold and R. G. K. Lempfert, whose names began to appear on scientific papers which had great influence. Shaw himself led this work enthusiastically and for the rest of his long life produced many writings on meteorology culminating in his four-volume *Manual of meteorology*, written mostly after his retirement in 1920. Shaw was given the place on the IMC vacated by Scott, and Hildebrandsson of Sweden took over as Secretary. Mascart of France had succeeded Wild as President of IMC, but in 1907 he was seriously ill and had to resign. The IMC, then in session, came to his bedside where Shaw, who had been chosen to succeed Mascart, spoke movingly of the task before them and quoted a French saying to the effect that 'the most terrifying difficulties are those that do not really exist'.

By this time, 1907, radio had begun to be fitted on ships, and the IMC had already been quick to pursue ways of getting synoptic reports from ships at sea. Several meteorological services tried to collect radio messages, but in the early years the results were disappointing, partly because someone had to pay for the messages, largely because of the long delays before the messages reached the forecast offices. In 1907 the British and German services reported that in a 2-month experiment less than 18 per cent of messages arrived within 24 hours and less than 50 per cent within 48 hours! Although the system has gradually improved since then some of these problems are still with us.

To meteorologists of the 1970s, used to floods of data from around the world, it is surprising to discover how long it was before synoptic reports were available in Europe from the Atlantic islands and from North America. Cables across the Atlantic began to work properly in the 1870s, and then extended rapidly throughout the world wherever the traffic appeared to justify it, but cablegrams were expensive and reports from North America were of little use in Europe with none from the 3000 miles of ocean in between. From the Azores three telegrams a day began when a cable there was completed in 1893, and a much improved service direct to the U.S.A. and Britain began in 1901 when new cables were completed. This new service resulted from a generous offer from Colonel F. H. Chaves, Portuguese Director in the Azores, and a quick response from the IMC urged on by Napier Shaw. A cable to Iceland was repeatedly suggested in those years but the financial support could never be organized. As the data collection system developed, the inadequacy of the code form agreed in 1874 became more and more apparent, but just how it should be improved took much labour to decide, and much basic work such as the classification of clouds and preparation of a cloud atlas had to be done first. This was done by the Commission for the Study of Clouds set up in 1891. The Commission for Weather Telegraphy made some progress but the old code remained until 1919.

With these growing demands and opportunities, and 30 years' experience of working together, meteorologists recognized that the system of unofficial Conferences of Directors had advantages, and settled down to plan their future development. The 1905 Conference of Directors at Innsbruck asked the IMC to prepare a regular scheme for regulating international meteorological organization, taking account of historical development and the resolutions of past Conferences, IMCs and Commissions. The Conference also agreed that there should continue to be Commissions appointed for special subjects, and especially to organize collective researches. From this time on the fact of the IMO may be said to have been recognized, although it was not so named until later. Also from this time began the rapid acceleration of development which still continues today.

It is worth noticing here some other historical links between IMO and the WMO of today. The IMC, unlike the Executive Committee of WMO, was the only continuing body, and was completely responsible for action between Congresses and Conferences. Later on as the volume of work continued to grow, a smaller Executive Council of five members was set up in 1929 within the IMC. Neither the Executive Council nor the IMC corresponds exactly to the Executive Committee of today. As to the Conferences of Directors, the informality and possibility of direct inter-service working agreements were soon found to be useful, and political difficulties were reduced by the informality of the system. The formality of the intergovernmental Congresses had had the advantage of settling the question of representation. Necessarily there had had to be one principal delegate, although others from the same country might be of equal or greater scientific eminence, and the Conferences of Directors maintained that convention. The institution of Commissions, readily arranged in so informal a meeting, provided the means and opportunity for the scientists and experts to play their full part. When later the inconveniences of being unofficial became apparent, for example the lack of status of IMO decisions *vis-à-vis* those of intergovernmental bodies, there was much reluctance to lose the now accustomed freedom of association and work. In consequence the WMO Convention has firmly built into it to the greatest extent practicable these methods of representation, work and organization devised by IMO. One of the most valuable legacies of IMO to WMO, as noted by President Viaut in 1960, is 'the principle of effective and constant participation by the meteorological services of Members in the life processes of the Organization'.

Under Napier Shaw the IMO was working up steadily and energetically when catastrophe struck the world with the outbreak of the first World War. During the war meteorology, radio and aviation all developed enormously, and by 1919 a new situation faced the survivors. Shaw as President of IMC summoned a meeting in London of six members, and representatives of others, and a new Conference of Directors was summoned in October of the same year in Paris to set the new course. Not only were there new demands from the customers, new systems of observing and reporting, and new scientific methods to absorb, but there were new organizations to cope with. On the one hand the new International Commission for Air Navigation (ICAN), a fully intergovernmental body, had its own subcommission for meteorology, and on the other was the establishment also in 1919 of the non-governmental body of scientists called the International Association for Meteorology. The latter body freed IMO to concentrate on practical matters, of which it now had more than enough to cope with. The former body was a potential rival with whom to come to terms.

Under Shaw's vigorous leadership, the 1919 Extraordinary Conference took firm grip of the situation and established nine Commissions (the IMC set up three more in 1921) nearly all on urgent practical matters. Shaw was selected as President of the new IMC, and although he retired as Director of the Meteorological Office in 1920, he was maintained as President until the next Conference in 1923, when he was made an Honorary Member of the IMC and so remained until his death in 1945. For several years from 1921 he was also President of the Commission for the Study of Clouds, and of the Commission for the Investigation of the Upper Air, which has since become

WMO's Commission for Atmospheric Sciences. Until 1919 Shaw had for twelve years been President of both the Commission for Storm Warnings and Maritime Meteorology, and of the Commission for Weather Telegraphy.

Ernest Gold and the development of synoptic meteorology. In this last Shaw was succeeded in 1919 by Colonel E. Gold, one of those he had brought into meteorology a dozen years before. The Commission soon changed its name to Commission for Synoptic Weather Information, and under the pressure of circumstances and the qualities of its President it became the focus of developments in international meteorology. Gold remained President until 1947, during which turbulent time the world-wide meteorological system now known as World Weather Watch grew into much of its present form. He then retired but is fortunately still with us. In 1958 he was awarded the third IMO Prize, the first of three British meteorologists to be so honoured.

When Gold took over the Commission for Weather Telegraphy the need for urgent action was unmistakable. Not only had the pre-war system of exchanges of telegrams been disrupted, but under the pressure of military needs meteorological services were using a variety of codes including new elements, had greatly increased both the frequency of reports and the numbers of stations, and had developed the use of radio. There was no question of return to the pre-war poverty of data, but the immediate problems were to bring international order to the riot of national arrangements. Nor could the defeated Central Powers be left out of the new plans, as meteorology was now clearly more international than ever. Gold set up two permanent sub-commissions, one on codes and specifications directed by himself, and one on radio transmissions of weather reports under Delcambre of France, and also developed working arrangements with the Commissions serving aviation and marine meteorology. The 1874 code was replaced immediately by one drawing largely on British and Allied experience, and successive revisions based on experiments culminated in the classic SYNOP code adopted in Copenhagen in 1929 for world-wide use, together with all its variants and associated codes. Aviation codes were included and were adopted by ICAN, which thus acknowledged IMO's primacy in meteorological affairs. This was not altogether surprising, because Gold was also President of ICAN's sub-commission of aviation meteorology! Starting from scratch, a whole structure of scheduled national, regional and continental radio transmissions was developed enabling any station to receive all its data needs, using only two radio operators in the daytime (one by night) on a standard set of frequencies. This process of forming a single comprehensive and uniform world-wide system for exchanging data from a great number of national systems was an enormous and unprecedented feat of standardization, reached entirely by the free consent of all concerned. From almost the start the meteorological services of the Central European powers were brought into consultation, and from 1923 Austria and Germany were back in IMO. Russia returned to the IMC in 1929, and Japan and India had never left.

As IMO had no Secretariat until 1926 (although the idea was first considered in 1873) voluntary help was the only way of circulating the flood of decisions. The British Meteorological Office publication *Wireless weather messages* was thus for some years the only comprehensive manual of reporting stations, codes and broadcasts and was widely used. Later the new Secretariat was able to take over the task with its *Fascicule* No. 9.

In the twenty years 1919–39 the Commission for Synoptic Weather Information (CSWI), as Gold's Commission became, held 11 sessions. Its membership rose from 16 in 1919 to 59 in 1929 and 80 in 1937, at which time its work was distributed among 11 subcommissions for joint meetings with other Commissions. In 1939 world war again broke out, and again rapid developments left IMO with quite a new situation at its end. In 1946 Gold and the CSWI set about remoulding the structure, with again new and diverse national practices to reconsider and new requirements, mostly from civil aviation, to meet. In the final 3-week session of CSWI at Toronto in 1947 revised world-wide codes and specifications were agreed. In substance these are the ones which are still in use today. These codes were approved by the immediately-following Conference of Directors in Washington, and became known as the Washington codes. It was true then, and is even more true now, that the growing scale of meteorological operations and the variety of purposes served by the codes makes agreement on changes increasingly difficult to achieve.

At the end of the Toronto session of CSWI Gold retired from the Presidency after 28 years, and was succeeded by J. R. Tannehill of the U.S.A. He was himself named Honorary President of CSWI.

Sir Nelson Johnson and the IMO/WMO transformation. When N. K. Johnson succeeded Sir George Simpson in 1938 as Director of the Meteorological Office and as member of the IMC and Executive Council, the IMO was already deep in discussion of its future status. The disadvanatges of its non-governmental status, as already mentioned, were apparent in the 1920s, when the formation of ICAN in 1919, with its intergovernmental status, had soon caused difficulties for IMO. Agreements affecting meteorology reached in ICAN, and elsewhere as the applications of meteorology developed in many fields, had full governmental backing, whereas those of IMO did not. IMO attempted to meet the ICAN problem by giving its Commission for Aeronautical Meteorology a special official status. This 'cuckoo in the nest' showed the growing absurdity of the situation. The Directors sat in IMO treasuring their informality, while their subordinates sat in the other bodies where the users took the effective decisions. Many Directors decided that the time had come for change so that intergovernmental decisions on meteorology could again be concentrated within the one organization. Progress was made, though slowly, in drafting a new intergovernmental Convention, though with fears that it would endanger the principle that scientific considerations should be the chief basis for any decision.

Came the war, during which the IMO continued in the form of the Secretariat in Lausanne (reduced to Dr Cannegieter and two others). Throughout the war the Secretariat maintained contact with the members of the Executive Council and with the President, Dr Th. Hesselberg, in Oslo. At the end of the war, as in 1919, all had to be rebuilt, and London again seemed a good place to start. An Extraordinary Conference of Directors gathered in London in the spring of 1946, but without the representatives of the defeated countries. The address of welcome given by the Under Secretary of State described meteorology as the 'key science of the world'. The Conference re-established the Commissions and put them to work, elected a new International Meteorological Committee of 20 members, and charged it with finalizing the new Convention. Dr Hesselberg stepped down from the Presidency and Sir Nelson Johnson was elected in his place. The new IMC met the same July in Paris, and 14 months later a new Conference of Directors assembled in Washington. This session was preceded by simultaneous sessions in Toronto of the 10 Technical Commissions, from which emerged several hundred resolutions for the consideration of the Conference. The agenda also included the reports of four Regional Associations (three had met in the previous year) and such major matters as relations with the new United Nations Organization and with the new International Civil Aviation Organization. Above all there was the new Convention to be considered and, if all went well, decided on. The Conference, in 31 sessions during three weeks, adopted 220 resolutions and finished the new Convention. The struggles over the Convention were long and of great difficulty. Under the President's patient guidance all the crises over equality of rights, membership, the world-wide character of the organization, and professional representation as distinct from political, were successfully overcome. In the final meeting of the Conference the new Convention of the World Meteorological Organization (WMO) was signed. This was a most remarkable feat by all concerned, and speaks much for the reality of the international spirit of meteorology and of meteorologists.

Sir Nelson Johnson remained as President until IMO met for the last time in 1951, to die and be immediately reborn as the new WMO. The final Extraordinary Conference of Directors lasted three days and was followed directly by the first Congress of WMO. Sir Nelson Johnson opened the new Congress, and was elected President for its duration. He was then succeeded by Dr Reichelderfer of the U.S.A. as President of WMO. The final action of that Congress was to pass by acclamation a resolution proposed by Dr Reichelderfer. That resolution recognized how much the accomplishments of Congress were due to the 'experience, insight, skill, careful planning, and patient perseverance of its President', and expressed its lasting appreciation to Sir Nelson Johnson 'for his unselfish service and devotion to the aims of the Organization and for his distinguished services in launching the new WMO'. Sir Nelson Johnson retired in 1953 but did not long survive.

The twenty months of intense IMO activity, from London in the spring of 1946 to Washington in the autumn of 1947, bore heavily on all concerned, but especially on the President on whom lay the burden of leadership. Sir Nelson as Director, and Ernest Gold, President of CSWI, as Deputy Director of the Meteorological Office, had at the same time to rebuild the Office for post-war tasks as the flood of wartime staff receded. Their international labours at this time completed the structure, built by so many hands, which was bequeathed to WMO by the International Meteorological Organization.

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SOME CURRENT WORK ON METEOROLOGICAL SATELLITES

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Summary. The Meteorological Office is developing an instrument to measure temperatures in the stratosphere from a satellite; it will be included in the TIROS N series of operational satellites to be launched by the U.S.A. from 1977 onwards. The Office is also co-operating in the European project to provide a geostationary cloud-observing satellite. Work on these projects and on the analysis of the data that will flow from them is described.

Introduction. This report deals with work being done by the High Atmosphere Branch of the Meteorological Office in connection with two meteorological satellites, the low-polar-orbit satellite TIROS N being developed by the U.S.A. for launch in 1976–77 and the geostationary METEOSAT being developed by the European Space Research Organization (ESRO) for launch at about the same time. In each of these projects almost all the work of instrument development is being done outside the Office; the main work of the Office is in project definition, organization and management, and in preparations for dealing with the data when received.

TIROS N

History. Meteorological satellites of the U.S.A. fall into two classes; the NIMBUS and Applications Technology Satellite (ATS) (geostationary) series are research and development satellites intended to try out new instruments and techniques of observation, while the TIROS and GOES* are operational series intended to provide a continuous service of observations from well-tried instruments.

The present operational satellites, based on the TIROS M design, will continue in use until 1976–77, when it is intended to replace them by a more advanced design known as TIROS N. When the broad specifications for this design were drawn up in the U.S.A. two years ago it was decided that the three main components of the payload should be a multi-channel imaging system, a location and data-collecting system and a temperature-sounding system. The temperature sounder was to be based on instruments developed in the NIMBUS programme, measuring the radiation emitted by the atmosphere at various well-defined wavelengths in the infra-red. About 14 channels were required for sounding the troposphere (including water-vapour and 'window' channels) and the wavelength selection for these channels could be done by narrow-band filters. In addition, it was decided that measurements in three or four channels in the 15-μm band of CO_2 should be made by using the selective chopping principle, as used by the Oxford and Reading (later Oxford and Heriot-Watt) universities in experiments on NIMBUS D and NIMBUS E.

* Names are very confusing. TIROS originally meant Television and Infra Red Observation Satellite and nine satellites bore this name with a number. The name is now used for the series of satellites providing similar observations; a letter is added to denote classes of spacecraft within this series, in particular the first of any class (e.g. TIROS M, TIROS N) but individual spacecraft within a class may have different names (e.g. ITOS D in the TIROS M class) and may then be renamed after successful launch (ITOS D became NOAA 2). The Geostationary Operational Environmental Satellites (GOES), whose first two models are also called Synchronous Meteorological Satellites (SMS) are a planned operational series developed from ATS.

The measurements will provide estimates of temperatures in the stratosphere, in the 1–30-mb region. It was agreed that the instruments for these stratospheric measurements should be provided by the Meteorological Office, while the instruments for the tropospheric sounding would be provided by the National Environmental Satellite Service (NESS) of the U.S.A. Preliminary specifications defining the instruments and their interface with the spacecraft were drawn up in May 1972 and have gradually been made more definite over the past year. It is expected that a formal agreement between the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Office will be signed during 1973.

A contract for the first stages of design and development work on the instrument was placed with Marconi Space and Defence Systems (MSDS) Limited in June 1972 and this has recently been completed with the production of a design report and a plan of work for the next stage.

Requirements. The proposed British contribution to the sounding system is now known as the Stratospheric Sounding Unit (SSU). It is required to make measurements of radiance similar to those provided by the three selectively-chopped channels of the Oxford–Heriot-Watt instrument on NIMBUS E, that is to say with weighting functions peaking at three heights in the 1–20-mb region. (The weighting function measures the relative contribution to radiation leaving the top of the atmosphere which originates at different heights and the region where the weighting function is at a maximum is the region whose temperature is effectively measured by the instrument.) In comparison with the NIMBUS E instrument, the SSU has many fewer channels but is required to make measurements at eight angles across the satellite track instead of only vertically downwards. Its accuracy (noise level and systematic errors) must be much improved and above all it must be designed and made as an 'operational' and not an experimental instrument, with great emphasis on reliable performance.

Design. Three possible design configurations were studied (by the Heriot-Watt group under subcontract to MSDS Ltd) based on the variants of the selective chopping method used respectively in NIMBUS D, E and F. The choice between the three methods was difficult because the F-method was clearly superior in principle but was at an earlier stage of development and therefore involved more risk. Despite this, the F-method was chosen and so far there is no reason to regret the choice.

The principle of the F-method (suggested and developed at Oxford) is that of pressure modulation. The radiation to be measured passes through a cell containing carbon dioxide whose pressure can be varied cyclically ($\approx$40 Hz). This varies the strength and width of the CO_2 absorption lines and hence modulates the radiation selectively at the CO_2 absorption wavelengths. It can be shown[1] that the weighting function for the modulated component of radiation passing through such a cell has its peak at a pressure-height in the atmosphere proportional to the mean pressure of gas in the cell, so that by using cells filled to different pressures, weighting functions peaking at different heights can be obtained.

Because the wavelength selection and chopping are done by the gas itself, the pressure-modulation system is inherently independent of changes in filters, windows and choppers which affect other systems. The most critical part of the design is the pressure modulation itself. This is done by connecting the absorption cell to the head of a sealed cylinder in which a close-fitting piston oscillates. The clearance between piston and cylinder (1/1000 inch) is sufficient to avoid contact, wear and friction but is small enough to prevent any serious leakage of gas in the period of one oscillation. The piston is mounted on springs and driven by a moving-coil loudspeaker-type system at its natural resonant frequency, which is largely determined by the mean gas pressure in the cylinder. The simplified diagram (Figure 1) shows the basic components of one channel of the SSU; three such channels are combined to form a complete SSU (the mirror and black body being common to all three).

The optical system is very simple. A plane mirror at 45° to the optical axis (which is horizontal, along the direction of flight) can be rotated to direct radiation into the system from different fields of view on the earth, across the sub-satellite track, or from space or from a calibrating black-body target in the instrument itself. The radiation passes through the absorption cell, whose front window is the objective lens of the system, and the filter to a field lens and light pipe which condense the radiation on to the detector. The detector is an uncooled pyroelectric one (tri-glycine sulphate) of the type used in the NIMBUS E and NIMBUS F instruments and the electronic design also follows the principles used in those instruments.

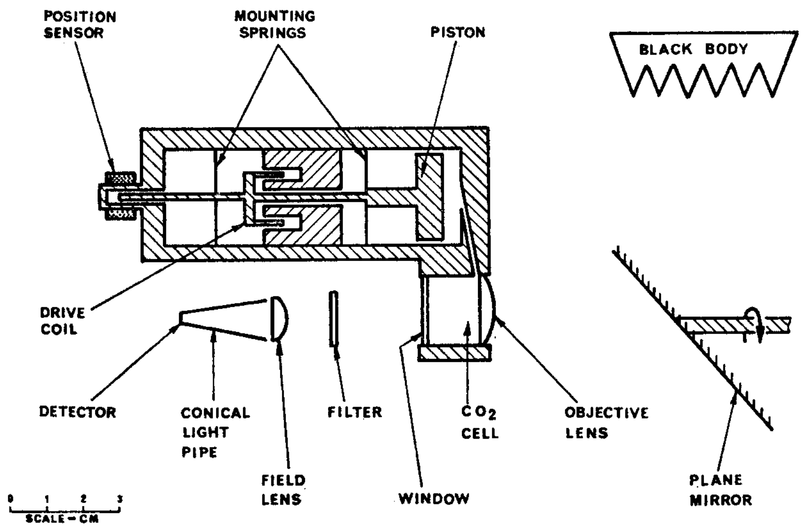

FIGURE 1—SIMPLIFIED DIAGRAM SHOWING ONE CHANNEL OF SSU

Development. Two pressure modulator units have been made to the design just outlined. Tests so far have concentrated on two aspects, the mechanics of the pressure modulation process and the performance as a radiation-measuring device. In the first set of tests the resonant frequency, the sharpness of resonance (which served as a measure of energy loss) and the displacement of the centre of oscillation of the piston were measured as functions of gas pressure. The behaviour is quite complicated, but satisfactory theoretical interpretations of all the phenomena have been found and it has been shown that pressure modulation of stable amplitude can readily be maintained. It has been shown that some increase in the piston–cylinder clearance (1/1000 inch) could be tolerated, which would ease some manufacturing problems.

In the radiometric tests (carried out under subcontract by Oxford University) a modulator unit was assembled with light pipe and detector and was used to measure radiation from black-body targets at various temperatures. The sensitivity and noise level were close to those predicted and appear to meet the agreed SSU specification. A major doubt in adopting the pressure modulation system for the SSU had been whether a predicted but unwanted component in the output signal would be sufficiently stable. This component arises from adiabatic heating and cooling of the gas in the pressure modulation cycle. The heated gas itself emits radiation which the detector receives as a signal of the same frequency as the radiation from the target chopped by the pressure variations in the cell — the wanted signal. Although there was no reason to think that the unwanted signal (which is comparable in amplitude to the wanted one) would not be perfectly steady so that it could be treated as a simple zero offset, it is very satisfactory that the radiometric tests have verified its steadiness and given confidence that the system behaves as predicted.

Future work. The design and development work just described was presented by the contractors to Meteorological Office and American representatives at a Design Review in mid March 1973. It was agreed that progress was generally satisfactory and that the work done formed a good basis for the next stage of development. This must be aimed at delivering the first model of the instrument in its final form to America in about two years' time, after completing all tests in this country. Before then it is envisaged that one or more development models will be made and that further tests will be made on the units already produced. Much of the work will be concerned with the details of design and manufacturing procedures needed to ensure extreme reliability but three general points which are fundamental to the success of the instrument will also require much attention and are listed below :

Weighting functions. Although the weighting functions for the SSU have been predicted fairly closely from theory and by comparison with those measured for basically similar instruments (NIMBUS D, E and F, in satellite and balloon-borne versions) they have not yet been measured directly. It is important that they should be determined more closely, both by more-detailed theoretical calculations and by measurement, because the optimization of many points in design depends on a good knowledge of these functions. Measurements are currently being made on one of the existing units at Oxford and work is in hand in the Office to undertake the computation of weighting functions, using computer programs provided by Dr Rodgers of Oxford.

Radiometric errors and calibration. All radiometers respond to some extent to radiation from outside their nominal field of view and outside their nominal spectral pass-band. The quality of their measurements depends on the extent to which these 'strays' can be eliminated, or allowed for by calibration. A start on this work has been made in the tests already done at Oxford, but it will need to be continued and expanded as development proceeds.

Gas absorption and desorption. Each pressure modulator unit contains about 20 ml of carbon dioxide at pressures of a few tens of millibars and is required to have a total life of about five years. A change of 1 per cent in gas pressure would be serious and a 20 per cent change would probably constitute failure, so great care will have to be taken to find, test and use constructional materials that neither absorb nor give off carbon dioxide in the conditions existing inside the SSU.

Use of data. The data from a temperature-sounding radiometer consist of a set of radiance measurements made in different spectral intervals and representing a weighted average of the temperature of different layers of the atmosphere — the weights being determined by the weighting function for each channel. In order that the data may be used they must be 'inverted' or 'deconvoluted' to obtain estimates of the temperature profiles which produce them. The inversion problem is a difficult one and many possible methods of solution have been suggested. No one method is clearly the best in all circumstances; the best method depends, among other things, on the nature of the radiometer data (the number and narrowness of the spectral intervals, the size of the field of view and the noise and other errors in the data), the use to which they are to be put and the nature and amount of other information which is available about the temperature profiles being observed. To ensure that the Office makes best use of the SSU data and also of data from the rest of the sounding equipment on TIROS N (and, indeed, on other satellites), studies on inversion methods have been started. The main work so far has been to gain familiarity with several possible inversion methods by applying them to real data samples from NIMBUS satellites and also to simulated SSU data. This will lead to selection of the method or combination of methods best adapted to the nature and use of SSU data. It will also have to be decided whether the temperature profiles provided by the National Environmental Satellite Service by inversion of its own radiometer data enable the Meteorological Office to get maximum benefit from the data or whether we should develop methods — perhaps better suited to our own forecast schemes — of handling the raw radiance data from instruments sounding the troposphere as well as methods for handling the SSU data.

Two investigations with a bearing on the instrument design have already been carried out. The first was a study of the optimum size and spacing of the fields of view of the instrument, taking into account the fact that the accuracy of measurement decreases with the size of the field of view while the accuracy with which the temperature field can be reproduced clearly improves as the number of samples increases — the rate of improvement depending on the space spectrum of the temperature variations. The outcome of the study is that the parameters provisionally selected are not far from optimum; a slight increase in the number of samples would apparently be beneficial but in view of the greater mechanical complexity and the rather inadequate data on which the theoretical study is based, it is not proposed to make any change.

The other study has been on the optimum location (in height) of the weighting functions to be chosen for the three SSU channels. Here again the conclusion is that the preliminary choice is not far from optimum, but since a final choice need not be made for some time yet, this work can be refined and extended as new data become available.

METEOSAT

History. For a long time European meteorologists and technologists have wished to produce a European contribution to space meteorology. Many projects have been discussed and one, for a satellite very similar to TIROS N, reached a fairly advanced stage of definition. In 1971, however, it was decided that this project represented an unnecessary duplication of American effort and that a far more useful contribution to the world observing system would be a geostationary satellite to provide frequent pictures of clouds and so allow wind velocities to be deduced. This decision, by Directors of Meteorological Services, more or less coincided with a decision by the Council of the European Space Research Organization that they should undertake an 'applications' programme with meteorology as one of its three main elements, and with a decision by France to attempt to 'europeanize' her project to develop a geostationary meteorological satellite, METEOSAT. The outcome has been that ESRO has begun development of METEOSAT, under the direction of a Programme Board, on which Directors of Meteorological Services as well as Ministers of Technology are represented. Although the general design is already fairly closely determined by the work previously carried out in France, project definition studies are in progress by two industrial consortia and it is expected that contracts for the full development phase will be placed during the second half of 1973.

Outline of project. It is intended that METEOSAT shall be launched by the end of 1976 and that it shall form one of a chain of four or five (U.S.A., Japan, U.S.S.R.) similar geostationary satellites which will provide complete coverage of low and middle latitudes. It will be a spinning satellite (100 rev/min) with axis parallel to that of the earth and its main sensor will be a telescope scanning the earth from west to east by virtue of the spin and from north to south through a mechanism that slowly tilts a mirror. The telescope will provide a 5000-line picture of the earth's disc at visible wavelengths and a 2500-line one in the infra-red window (11 μm) every half-hour. The resolution at the sub-satellite point will be about 2·5 km and 5 km for the two channels, respectively. The pictures will be transmitted at low power and high data-rate to a well-equipped central station (near Darmstadt in West Germany). This station, and in particular the part known as the Meteorological Information Extraction Centre (MIEC), will process the data to obtain estimates of sea surface temperature, cloud amount and height and, most difficult, wind velocity by observing the motion of clouds from one picture to the next. These reduced data will be disseminated by ordinary meteorological telecommunications. In addition the central station will re-transmit to the satellite a selection of the pictures received, after adding calibration and location data and after suitable changes of format. These pictures will be broadcast by the satellite (at relatively high power) and can be received by two classes of station known as Principal and Secondary Data Users' Stations (PDUS and SDUS). PDUS will be capable of receiving data at higher rates and with better definition than the much cheaper SDUS. It is expected that pictures received at the PDUS and SDUS will be used qualitatively in forecasting in the same way as APT pictures from polar satellites are now used, but some countries plan to use data received at their PDUS in more quantitative fashion.

The other main function of METEOSAT is to collect and send to the central station data transmitted from 'Data Collection Platforms' (DCP), probably mainly in remote or inaccessible locations, but also including stations in ships and on buoys or balloons. This system will operate in the 400–460-MHz band and is being designed to be compatible with similar systems in the other geostationary satellites.

Development of satellite. As already stated, the main features of the design are already fixed. Various modifications have been introduced as a result of pressure from meteorologists, notably an increase in transmitter capacity to allow more pictures to be broadcast and a change in frequency in the DCP system in the interests of international compatibility. Several options are now under discussion. The first is the choice of the exact wavelength range for the visible channel (to achieve the best balance of contrast between clouds and different types of surface). The second is the possible addition to the telescope of a channel sensitive in the water-vapour absorption region at 6·3 μm; this would provide some indication of air movement in regions where visible clouds were absent. Another possible addition, on an experimental basis, is a receiver to allow METEOSAT to relay data from polar satellites such as TIROS N or the Russian METEOR. Finally, it has been proposed that the French station at Lannion (in Brittany) might receive pictures from the American geostationary satellite (at 70°W) and re-broadcast them through METEOSAT.

Development of ground facilities. In all discussions on METEOSAT the British representatives have urged the importance of providing adequate ground facilities and this has been followed up by providing a member of the ESRO working group that laid down the general requirements for the ground station, with particular emphasis on the MIEC.[2] This work has been continued by a group that is now drawing up specifications for the computer software needed in the MIEC, particularly for the determination of winds from cloud movements. It is expected that responsibility for this work will soon be taken over by ESRO and that the need for meteorological participation may decrease for a time, but there will obviously be a continuing requirement for close contact with the work to ensure that both hardware and software are fully adapted to meteorological requirements.

Conclusions. Satellite observations will play a vital role in the First GARP Global Experiment and in the World Weather Watch programme.[3] The satellite system envisaged[4] comprises two components, a set of four or five geostationary satellites above the equator and a smaller number of satellites in fairly low quasi-polar orbits. It is satisfactory that, through the work described above, the Office is making a substantial contribution to both components of the world system. However, the making of observations is not an end in itself, and to get proper benefit from our contribution we must learn to make full use of the data flowing from satellites, not only the data that will come from our own future instruments but also the data available now and in the future from instruments provided by others.

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THE ESTIMATION OF WHEAT AND BARLEY ACREAGES IN ENGLAND BY REFERENCE TO THE WEATHER OF THE PREVIOUS SUMMER

By L. P. SMITH, J. COCHRANE and V. BAILEY

Summary. The proportion of cereal land in England sown to wheat in any one year bears a close relationship to the mean estimated soil moisture deficit in such land at the end of the previous September.

Introduction. The greater part of the English wheat crop is sown in the autumn. The extent to which this can be done depends on the speed of clearance of the previous crop and the time available for the cultivation of the fields and the sowing of the wheat. The controlling environmental factors are the state of the soil and the soil moisture content.

Many more days are available for autumn work on the land if the soil has a moisture deficit and has not yet returned to field capacity. Once the return date has been reached and the drains are running, any subsequent rainfall occasions delay while the excess water is drained away before cultivation can be undertaken without damage to soil structure.

It has already been shown by L. P. Smith[1] that the average return-to-capacity date in an area bears a close relationship to the proportion of neighbouring farmland sown to wheat. A further paper[2] showed that in two specimen areas in Warwickshire and Worcestershire, the annual wheat acreage varied in accordance with the changes in return date. This concept was extended in later work[3] to relate the national mean return date to the total English acreages of wheat, barley and fallow. It is therefore possible to form an estimate of future cereal areas once the return dates are known.

Some advantage would be gained if an earlier estimate were possible, and as the return date depends on two factors, namely the soil moisture deficit at the end of summer and the subsequent rainfall, an attempt was made to establish a forecasting method using the first variable only.

Available data. Following the procedures explained in Ministry of Agriculture, Fisheries and Food *Technical Bulletins* No. 16[4] and No. 24,[5] both of which were prepared in the Meteorological Office, and using the details available in the *Daily Weather Report* of the Meteorological Office, a daily check on soil moisture deficits at 24 stations is already made for other purposes.

Some 14 of these stations were taken to represent the cereal growing area of England, and a mean soil moisture deficit at the end of September was obtained by weighting the value at each individual station with the wheat acreage in the area for which it was taken as a sample. Since the stations were chosen because of their presence in the *Daily Weather Report, (D.W.R.)* and for no other reason, they cannot be claimed to be truly representative of the areas with which they are associated.

The allocation, together with the farming details for 1969, was as follows :

D.W.R. station	Counties	Total farmland *thousands of acres**	Percentage in cereals
Leeming	Northumberland; Durham; North Riding	1702	33
Ringway	Lancashire; Cheshire; Derbyshire	1417	19
Finningley	Nottinghamshire; Kesteven; West Riding	1702	42
Kilnsea	East Riding; Lindsey	1454	57
Shawbury	Shropshire; Staffordshire; Herefordshire	1618	26
Elmdon	Warwickshire; Worcestershire; Leicestershire	1187	37
Wittering	Holland; Huntingdonshire; Northamptonshire; Rutland	1059	50
Honington	Cambridge; Essex	1106	59
Wattisham	Norfolk; Suffolk	1713	57
Filton	Somerset; Oxfordshire; Gloucestershire	1744	28
Boscombe Down	Wiltshire; Berkshire	935	45
Cardington	Bedfordshire; Hertfordshire; Buckinghamshire	835	50
Hurn	Dorset; Hampshire	985	38
Gatwick	Surrey; Sussex; Kent	1292	35

Cumberland, Westmorland, Devon and Cornwall, which grow little wheat, were omitted.

Data concerning the English acreages of wheat, barley, oats, mixed corn, rye and fallow were taken from the annual volumes of *Agricultural statistics*[6] prepared by the Ministry of Agriculture, Fisheries and Food, and these figures can now be examined in relation to the weighted mean deficits, namely

1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
5·0 in*	2·3 in	4·1 in	2·6 in	3·1 in	4·5 in	0·7 in	2·5 in	3·1 in	0·1 in

Percentage of cereal land in wheat. It was found that the correlation between the wheat percentage of total cereal land in England and the weighted mean soil moisture deficit at the end of September was 0·92, and the percentage could be estimated from the formula

$$24{\cdot}4 + 1{\cdot}54d$$

where d is the mean deficit in inches.

* 1000 acres = 404·686 hectares; 1 inch = 25·4 millimetres.

TABLE I—ACTUAL AND ESTIMATED PERCENTAGES OF LAND IN WHEAT

Harvest	Actual	Estimated	Error
		percentage	
1960	31·4	32·1	+ 0·7
1961	27·3	27·9	+ 0·6
1962	32·6	30·7	− 1·9
1963	27·2	28·4	+ 1·2
1964	29·5	29·2	− 0·3
1965	31·8	31·3	− 0·5
1966	26·9	25·5	− 1·4
1967	27·4	28·2	+ 0·8
1968	28·8	29·2	+ 0·4
1969	24·4	24·6	+ 0·2
		Mean error (ignoring signs)	0·8

The diagram (Figure 1) shows the actual percentage of wheat and the mean soil moisture deficit for the previous autumn.

Estimation of wheat acreage. In 1960 and 1961 the total cereal area in England was about 6 million acres; during the years 1966–69 it was about 8 million acres. The increase took place almost uniformly between 1961 and 1966 and was probably partly due to the fact that many farmers went out of dairying in those areas of England which were climatically unsuited to the growth of grass. To a great extent the growing of barley took the place

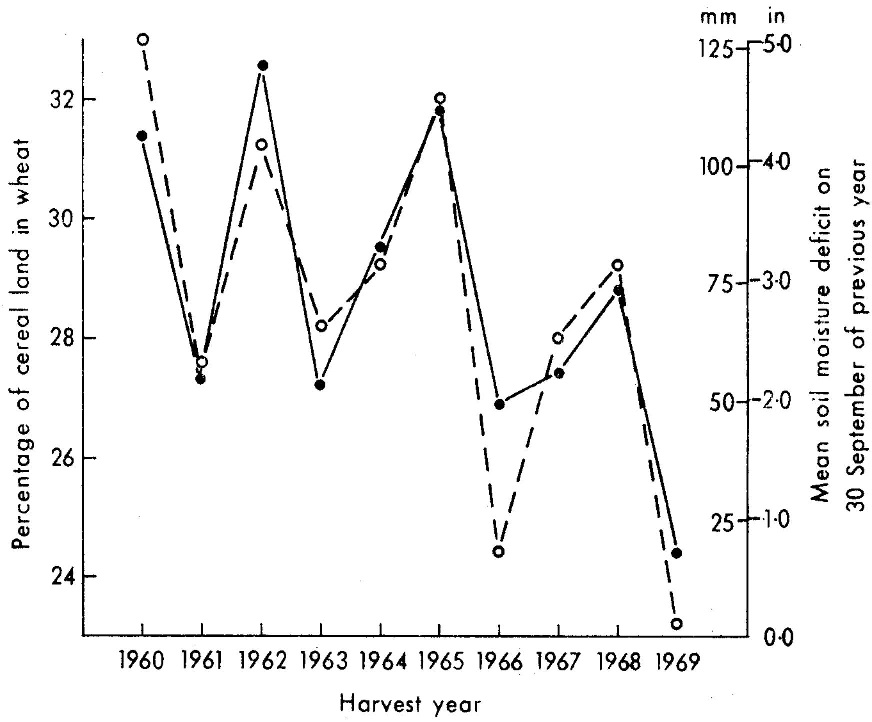

FIGURE 1—COMPARISON BETWEEN THE PERCENTAGE OF CEREAL LAND IN WHEAT AND THE MEAN SOIL MOISTURE DEFICIT ON 30 SEPTEMBER OF THE PREVIOUS YEAR

● —— ● Actual percentage of wheat

○ - - - ○ Mean soil moisture deficit for previous autumn of milk production in the Midlands and in eastern England, while dairy herds increased in size (but not in total number) in the western counties.

To allow for this change of intent, a second independent variable must be introduced, namely n, the number of years after 1961, with a maximum of 5. The correlation between wheat acreage and the mean deficit is 0·30; between wheat acreage and n, 0·61; between the deficit d and n, −0·52. From these figures the derived partial correlations are

Between wheat acres and deficit 0·91
Between wheat acres and n 0·94

and the regression equation is

Wheat acres = $1435 + 125d + 100n$.

TABLE II—ACTUAL AND ESTIMATED ACREAGES OF WHEAT

Harvest	Actual	Estimated	Error
		thousands of acres	
1960	1987	2060	+73
1961	1715	1722	+ 7
1962	2127	2048	−79
1963	1823	1960	+137
1964	2093	2122	+29
1965	2409	2397	−12
1966	2150	2022	−128
1967	2200	2247	+47
1968	2306	2322	+16
1969	1947	1947	0
		Mean error (ignoring signs)	53

The multiple correlation coefficient is 0·94.

Estimation of barley acreage. As the bulk of the barley is sown in spring, it might be thought that autumn weather would not affect the acreage, nevertheless if conditions prevent the sowing of winter wheat, more barley tends to be sown in the spring as an alternative to spring wheat.

As land unsown in spring will remain in fallow, the dependent variable was taken as the sum of the barley and the fallow acreages. The independent variables were the same as those used with wheat, and it was found that the correlations between the barley and fallow acreage and the mean deficit at 30 September was −0·66, and with n 0·98; the correlation between the deficit and n was −0·52. The partial correlation coefficients calculated from these values were between barley and fallow acres and autumn deficit −0·91 and between barley and fallow acres and n 0·99. The regression equation was

Barley and fallow acres = $3805 - 110d + 357n$.

TABLE III—ACTUAL AND ESTIMATED ACREAGES OF BARLEY AND FALLOW

	Actual	Estimated	Error
		thousands of acres	
1960	3200	3255	+55
1961	3631	3552	−79
1962	3600	3691	+91
1963	4271	4193	−78
1964	4465	4475	+10
1965	4684	4658	−26
1966	5396	5413	+17
1967	5304	5215	−39
1968	5139	5149	+10
1969	5389	5479	+90
		Mean error (ignoring signs)	54

Discussion. It is undoubtedly true that the closeness of fit, both for wheat and barley, obtained through the use of these regression equations is largely due to the fact that the increase in acreage between 1961 and 1966 took place in a linear manner. Nevertheless, the high partial correlation coefficients between the cereal acreages and the soil moisture conditions at the end of the previous summer suggest that useful forecasts of future cropping can be made some eight months in advance (the official statistics are based on returns made in June).

Such forecasts would be likely to go astray when a wet autumn follows a dry summer, or when a dry autumn succeeds a wet summer; extreme late-winter conditions, as in 1963, will also affect accuracy.

A further conclusion can be drawn; if end-of-summer deficits tend to decrease in future decades, or more particularly, if return-to-capacity dates become earlier owing to wetter autumns, then there will be a significant change in the wheat/barley ratio of cropping.

Independent check on formulae. In 1970, the mean soil moisture deficit, weighted with respect to the 1969 acreage, was 3·9 inches. The formulae would indicate

30·4 per cent of cereal acreage in wheat
2 422 000 acres of wheat
5 061 000 acres of barley and fallow.

The actual values were 30·2 per cent, 2 376 000 acres and 4 833 000 acres respectively.

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551.515.527:551.577.21(213)

UPPER TROPOSPHERIC DISTURBANCES OF THE EQUATORIAL ATMOSPHERE AND THEIR INFLUENCE ON RAINFALL NEAR THE EQUATOR

By F. E. LUMB

(lately Editor, *Meteorological Magazine,* now WMO Lecturer at the Regional Meteorological Training Centre, Lagos, Nigeria)

Summary. Disturbances of the upper troposphere of the equatorial atmosphere by troughs in the subtropical westerlies and their influence on rainfall at and near the equator are discussed.

Introduction. Sawyer[1] has concluded that 'a very useful approach to the dynamics of the equatorial atmosphere might prove to be through the investigation of the disturbance initiated in the equatorial belt by distortions of the subtropical jet stream and other changes of the circulation around latitudes 25 to 30 degrees from the equator'. In support of this statement, it is well known to meteorologists in East Africa that such distortions can have important effects on the weather even at the equator, especially during the 'rainy' seasons. The linkage between the distortions and the occurrence of dry and wet spells within the 'rainy' seasons can be explained in terms of horizontal accelerations and the resulting horizontal divergence, in the upper troposphere of the equatorial atmosphere. By way of example, two well-marked changes of synoptic type which are known to be favourable for wet spells during the 'rainy' seasons are

(a) change from Duct* to Bridge*
(b) change from Duct to Drift*.

Change from Duct to Bridge. This change of type occurs when upper troughs (say at 300 and 200 mb) penetrate into low latitudes from both hemispheres, at approximately the same longitude, sufficiently to split the subtropical-high cells. Both the duct and bridge patterns are associated with quasi-geostrophic flow almost to the equator. It therefore follows from the well-known relation between the acceleration and the ageostrophic component of the wind that increasing easterly winds on both sides of the equator are associated with horizontal convergence, and decreasing easterly winds with horizontal divergence (see Figure 1). The change from Duct to Bridge in the upper troposphere changes the winds near the equator from easterly to westerly, and is therefore associated with upper divergence. Provided this is accompanied by convergence or simply non-divergence in the lower troposphere (which is usually the case in the 'rainy' seasons) continuity demands upward motion through most of the troposphere. This explains the tendency for increased rainfall. The upward motion feeds moisture into the upper troposphere, and

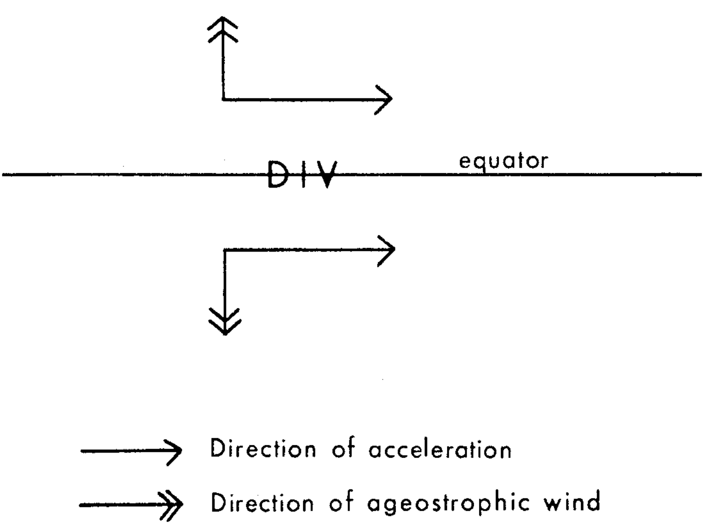

FIGURE 1—DIVERGENCE ASSOCIATED WITH DECREASING EAST WINDS IN BOTH HEMISPHERES NEAR THE EQUATOR

* The terms Duct, Bridge, Drift used in this paper are explained in reference 2.

solar heating then ensures deep convection, which feeds further moisture into the upper troposphere, resulting in a rainy spell which will last several days if the troughs are slow to relax.

Conversely, as the troughs relax and the split subtropical-high cells gradually amalgamate, upper-level convergence results in a damping down and eventual reversal of the upward motion (at least in the upper troposphere), a marked drying of the upper troposphere, and a reduction of rainfall.

Change from Duct to Drift. If a trough penetrates equatorwards and splits the subtropical-high cell in one hemisphere only (see Figure 2), there is still likely to be divergence at and near the equator. It occurs at A where there is marked diffluence between the quasi-geostrophic easterly current and the transequatorial current (Drift); also from A through B to C where the air is being accelerated down the pressure gradient which is seen in Figure 2 to be directed from north to south across the equator.

Hence this change is also likely to be accompanied during the 'rainy' seasons by a marked increase of rainfall. Johnson[3] has discussed the widespread rainfall of 20–21 March 1960 over East Africa, and has mentioned the presence of a small-scale distortion in the 700-mb Drift flow (from northern to southern hemisphere) as a probable explanation of the far northward spread of the rain. However, the 200-mb chart for 21 March 1960 included in the paper by Johnson[3] shows a well-developed drift flow over East Africa (from southern to northern hemisphere), so that upper divergence probably also contributed to the widespread occurrence of the rain.

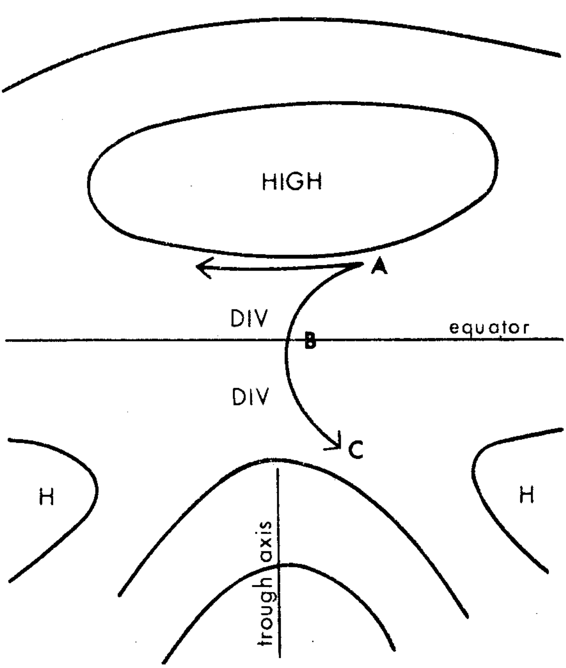

FIGURE 2—TRANSEQUATORIAL FLOW ACCELERATING INTO UPPER TROUGH IN SOUTHERN HEMISPHERE

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NUMBER OF DAYS OF AIR FROST IN THE WINTER MONTHS IN SCOTLAND IN RELATION TO THE MEAN AIR TEMPERATURE — ON A PERIOD-AVERAGE BASIS, AND FOR INDIVIDUAL YEARS AT SELECTED STATIONS

By R. W. GLOYNE and ELIZABETH A. MCKERRELL
(Meteorological Office, Edinburgh)

Summary. The relationships between mean daily temperature $(\overline{T})$ averaged over the winter months (December, January and February) and the corresponding number of air frosts (N) were examined

(a) on a period-average basis, mainly 1960/61 to 1969/70, for 19 stations in Scotland, and
(b) on a winter-by-winter basis for two stations, Edinburgh (Blackford Hill) and Eskdalemuir Observatory (Dumfriesshire) for up to 30 years.

For case (a) the least-squares best fit valid over the range $0°\text{C} < \overline{T} < 5°\text{C}$ and also the best second-degree curve for the range $-7°\text{C} < \overline{T} < 5°\text{C}$ were determined, and for case (b) linear regressions were computed.

Introduction. Place-to-place comparisons, interpolation and extrapolation in time and space, can be rendered more reliable if statistical relationships between allied series of data can be appealed to.

A long-term average of mean daily temperature (on a monthly basis) can now be estimated for *any* site in Scotland with some confidence; the corresponding estimate of days with frost deduced directly from frost frequencies reported from other stations entails a greater degree of uncertainty. This contribution deals with the numerical relationship between frost frequency in winter and the corresponding mean daily temperature.

Attention was concentrated upon the winter period, namely December, January and February, the data assembled being :

(a) period averages (as far as possible for the 10 winters 1960/61 to 1969/70 of mean daily temperature and mean number of air frosts for 19 stations in Scotland);
(b) similar data, but for individual winters for Eskdalemuir Observatory and Edinburgh (Blackford Hill).

Clearly any result will be affected by the magnitude of the mean diurnal range and hence can only be valid for areas in which the mean diurnal fluctuation is sensibly uniform.

Analysis.

(a) *Period-average results.*

In Figure 1 period-average data (mainly for the winters of 1960/61 to 1969/70) of mean daily air temperature and mean number of air frosts for 19 stations (these are listed below) are plotted together with the best-fitting first- and second-degree curves.

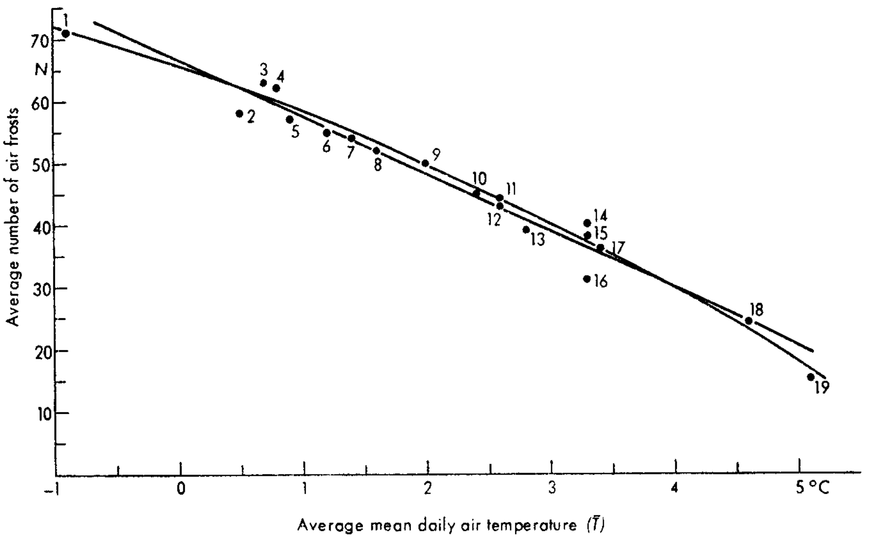


FIGURE 1—RELATIONSHIP BETWEEN AVERAGE NUMBER OF AIR FROSTS AND AVERAGE MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER–FEBRUARY INCLUSIVE)

For identification of stations, see below.

No.	Station	Height above mean sea level *metres*	Period
1	Coire Cas (Cairngorms near Aviemore)	762	5 years within 1963/64 – 1969/70
2	Braemar	339	1960/61 – 1969/70
3	Glenmore Lodge	341	9 years within 1960/61 – 1969/70
4	Grantown-on-Spey	229	7 years within 1960/61 – 1969/70
5	Dalwhinnie	358	1956/57 – 1960/61
6	Carnwath (near Carstairs, Lanarkshire)	208	1960/61 – 1969/70
7	West Linton (Peeblesshire)	244	1960/61 – 1969/70
8	Eskdalemuir Observatory (Dumfriesshire)	242	1960/61 – 1969/70
9	Faskally (Pitlochry)	94	1960/61 – 1969/70
10	Perth	23	1960/61 – 1969/70
11	Dyce (Aberdeen)	58	1960/61 – 1969/70
12	Mylnefield (near Dundee)	30	1960/61 – 1969/70
13	Nairn	6	1961/62 – 1969/70
14	Edinburgh (Royal Botanic Garden)	26	1956/57 – 1969/70
15	Renfrew (Glasgow)	8	1960/61 – 1969/70
16	Wick	36	1960/61 – 1969/70
17	Auchincruive (near Ayr)	45	1960/61 – 1969/70
18	Benbecula (Outer Hebrides)	6	1960/61 – 1969/70
19	Tiree	9	1960/61 – 1969/70

Obviously the maximum possible number of days with frost in any winter (ignoring for convenience leap years) is 90 (31 + 31 + 28) and the straight line cannot be extrapolated to temperatures lower than about -1 °C; furthermore the curve must reach its apex of 90 days at some mean temperature well below 0°C and thereafter remain at 90 days.

If

N = average number of days of frost per winter

$\overline{T}$ = average mean daily air temperature (in degrees Celsius)

then

$N = 66\cdot8 - 9\cdot18\overline{T}$ (best straight line)

$N = 65\cdot5 - 7\cdot00\overline{T} - 0\cdot499\overline{T}^2$ (best second-degree curve)

with, respectively, a linear correlation coefficient of − 0·981 and a multiple correlation coefficient of 0·985.

The apex of the parabola reaches 89·8 (≈90) at a temperature of − 7·0°C. This suggests that if mean daily temperature during the winter is below about − 7°C every winter night will be one with air frost.

As an independent test for the equations, data for some nine stations in Iceland (i.e. a region subject to a maritime climate) were extracted. The results listed below show that the parabola predicts the frost frequency to within an error of at most one unit.

Station	Latitude	Longitude	Mean 'winter' temperature °C	Mean number of days with frost	
				predicted	*actual*
Blönduós	65° 40′N	20° 18′W	−1·5	74·7	74
Húsavík	66° 02′N	17° 21′W	−0·9	71·2	71
Hlaðhamar	65° 16′N	21° 10′W	−2·0	77·3	77
Nautabú	65° 27′N	19° 22′W	−2·4	79·1	79
Reykjahlíð	65° 39′N	16° 55′W	−3·7	84·5	84
Grímsstaðir	65° 38′N	16° 07′W	−4·4	86·4	86
Möðrudalur	65° 22′N	15° 53′W	−5·9	89·3	90
Gunnhildargerði	65° 33′N	14° 23′W	−1·8	76·3	76
Thingvellir	64° 15′N	21° 07′W	−1·9	76·7	76

(b) *Individual winters at Eskdalemuir and Edinburgh and three other stations in southern Scotland.*

The data and best straight line for Eskdalemuir and Edinburgh are set out in Figures 2 and 3. For the latter station the complete series 1940/41 to 1970/71 has been split into two sub-series, namely 1940/41 to 1954/55 and 1955/56 to 1970/71; the Eskdalemuir data are for the later period only.

Clearly from the scatter diagram all the observations lie within the range for which a linear relationship can be accepted. Expressing the relationship in the form

$$N = a + b\overline{T},$$

where N = number of frosts and $\overline{T}$ = mean winter temperature, then the statistical parameters for the several straight lines are as follows :

Place	Period	a	b	r (correlation coefficient)
Edinburgh (Blackford Hill)	1940/41 to 1954/55	68·9	−9·29	−0·946
	1955/56 to 1970/71	70·9	−10·63	−0·869
	1940/41 to 1970/71	68·8	−9·68	−0·899
Eskdalemuir	1955/56 to 1970/71	63·8	−7·88	−0·891

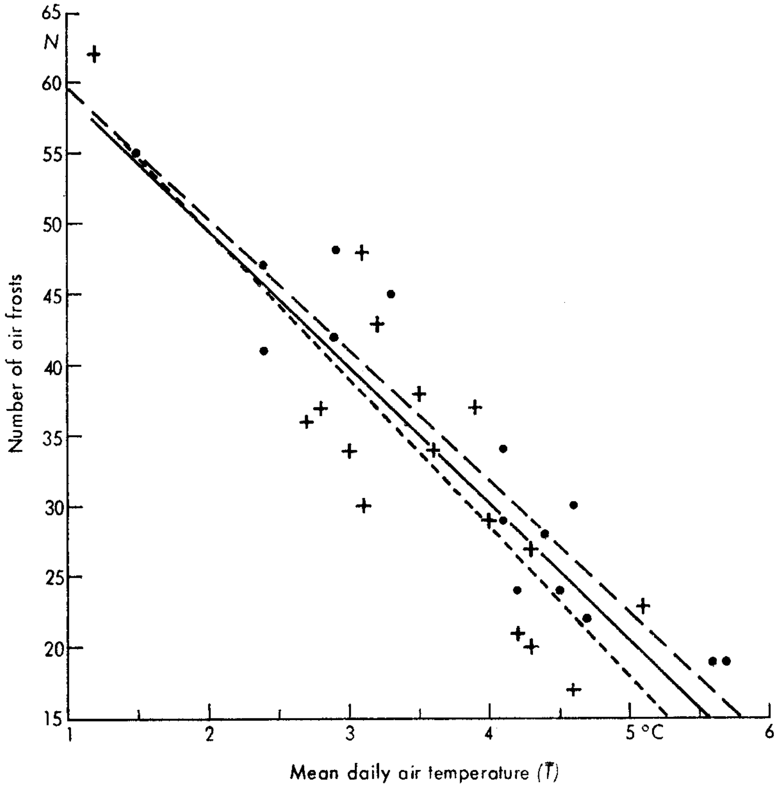


FIGURE 2—NUMBER OF AIR FROSTS AGAINST MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER–FEBRUARY INCLUSIVE) AND BEST-FITTING LINEAR RELATIONSHIPS FOR EDINBURGH (BLACKFORD HILL)

● — — — 1940/41 to 1954/55; + - - - - 1955/56 to 1970/71; ——— 1940/41 to 1970/71.

On the long-period average basis discussed in (a) above the respective coefficients were 66·8 and − 9·18.

When all the straight lines are plotted together, they are found to occupy a narrow band. To the extent that the lines are judged identical it can be stated that, in respect of winter frosts, the area is homogeneous as regards variations in space and in time.

As expected the errors of estimate of data relating to individual winters exhibit a greater degree of scatter than for the long-period values. The standard errors of estimate are :

(a) long-period average data (see Figure 1): 2·7 days.
(b) individual winters
  Edinburgh (Blackford Hill) (see Figure 2)
    1940/41 to 1954/55 : 3·7 days
    1955/56 to 1970/71 : 5·5 days
    1940/41 to 1970/71 : 4·9 days
  Eskdalemuir (see Figure 3)
    1955/56 to 1970/71 : 4·4 days.

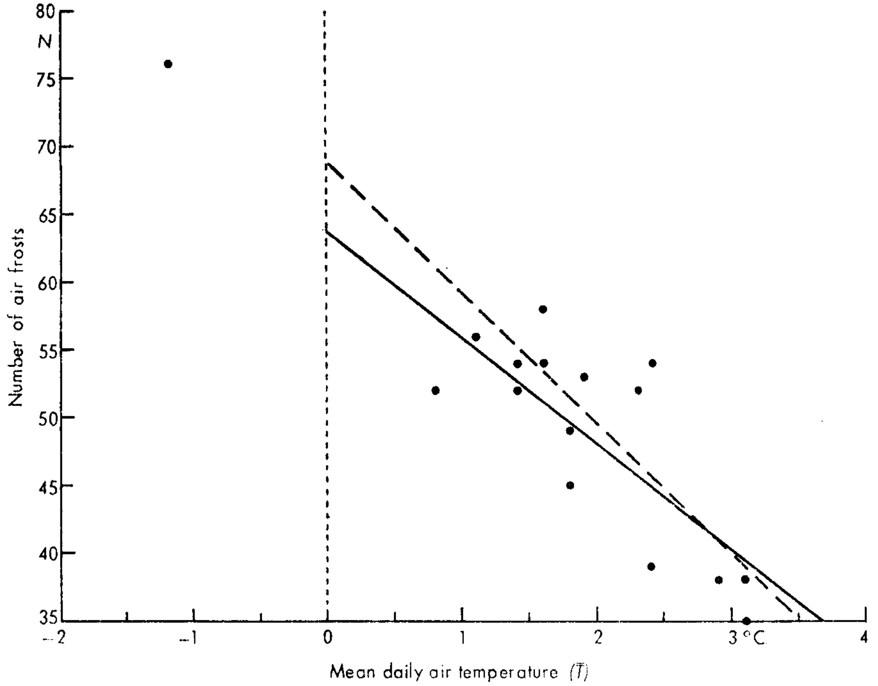


FIGURE 3—NUMBER OF AIR FROSTS AGAINST MEAN DAILY AIR TEMPERATURE FOR THE WINTER MONTHS (DECEMBER–FEBRUARY INCLUSIVE) AND BEST-FITTING LINEAR RELATIONSHIP FOR ESKDALEMUIR OBSERVATORY 1955/56 TO 1970/71; AND, FOR COMPARISON, LINEAR REGRESSION FOR EDINBURGH

● 1955/56 to 1970/71 Eskdalemuir
——— line of best fit for Eskdalemuir
— — — — line of best fit for Edinburgh 1940/41 to 1970/71

For a selection of individual winters, the errors (i.e. estimated minus actual) are given below. Rather surprisingly the largest errors in the 10 winters 1960/61 to 1969/70 are for Blackford Hill in spite of the fact that the linear regression was based upon data for the same station (though for the 31 winters from 1940/41 to 1970/71). Table I indicates the magnitude of the errors.

For individual winters therefore, an error of estimate of up to $\pm$ 10 days in frost frequency can occur although most discrepancies will lie within the range $\pm$ 5 days. For the period-average analysis based upon the linear regression, an error as great as $\pm$ 5 days is exceptional.

A more detailed scrutiny of the data at least suggests that stations could be rationally grouped into :

(a) those at markedly maritime sites or freely exposed on hillsides;

(b) those which are surrounded by rather higher land, even at a considerable distance, and whose site may be judged to tend to have some of the characteristics of a frost hollow.

In the latter case there are, on a period-average basis, more frosts during the winter for a given average mean temperature than for case (a) — this is physically acceptable: a difference of between 5 and 10 days could be provisionally suggested.

TABLE I—DIFFERENCES FROM ACTUAL FROST FREQUENCIES DURING THE WINTER, OF ESTIMATES BASED UPON MEAN TEMPERATURE FOR THE SAME PERIOD; DERIVED FROM LINEAR REGRESSION BASED UPON DATA FOR EDINBURGH (BLACKFORD HILL) FOR 1940/41 TO 1970/71, FOR SELECTED STATIONS AND FOR THE PERIOD 1960/61 TO 1969/70

	1960–61	1961–62	1962–63	1963–64	1964–65	1965–66	1966–67	1976–68	1968–69	1969–70
						days				
Edinburgh (Blackford Hill)	0	0	−4	+7	+9	+6	+7	−5	+6	+5
Edinburgh (Royal Botanic Garden)	−5	−4	0	+1	+3	−1	+2	−9	0	+2
Mylnefield (Dundee)	−3	+1	0	+5	−4	+2	+8	−6	−1	+1
Abbotsinch (Glasgow)	−5	0	−2	−3	−6	+1	0	−8	+4	+1

REVIEW

Meteorology and climatology for sixth forms and beyond, 4th edition, by E. S. Gates. 250 mm × 190 mm, pp. 293, *illus.*, G. G. Harrap and Co. Ltd, 182–184 High Holborn, London WC1V 7AX, 1972. Price: £2·75.

A review of the first edition of this book appeared in the *Meteorological Magazine* for October 1961 and much of what was said then is still true. In this fourth edition the author states that he has revised his book to take account of the successful development of satellites for meteorological purposes and that all units have been rationalized according to the Système International d'Unités.

The new Chapter 13 'Weather watchers in space' describes the various satellite systems and the equipment carried very well, but no effort is made to explain for example how temperature profiles are measured. Even though the book is designed primarily for geographers, surely an intelligent sixth-former would want to know some of the underlying physical principles. What a pity too that so few satellite pictures and nephanalyses have been added to the many excellent plates and diagrams. The section on fronts and depressions for example could have been brought alive by the judicious use of such pictures.

A major criticism of the whole book must be that it shows signs of age, both in approach and format. Wing Commander Gates who is Head of the Department of Liberal Studies at the Royal Air Force School of Technical Training, Halton, is on the fringe of meteorology with limited access to the current literature. Had he been in the main stream of the science in its present exciting development phase one feels sure he would have considered a completely fresh approach based on sound physical principles. His bibliography too would have been revised, for many of the books and papers mentioned have been superseded by later texts which are readily available in libraries. Nor can the book escape criticism in matters of detail. For example on page 97, talking of the mature stage of thunderstorms, we read 'the cloud now assumes a vertical thickness in excess of 6 000 metres, the last few hundred metres being below freezing point'.

Where the book deals with facts it is still of value to the adult amateur of meteorology. The purchaser must not expect it to satisfy him for very many years though.

P. D. BORRETT

NOTES AND NEWS

THE BRACKNELL METEOROLOGICAL OFFICE COMPUTER

The KDF9 computer which was installed in 1965 was operated continuously for several years and was used as the main operational computer at HQ Bracknell until 30 April 1972 when the IBM 360/195 took over that role. Hours of operation of the KDF9 computer were subsequently progressively reduced and the installation was finally closed down on 30 March 1973. The serviceability of the KDF9 had been maintained at a high level throughout its period of use. Almost all the computer tasks have been transferred to the 360/195 and arrangements have been made for running a few residual tasks on other KDF9 computers which are still in use at government establishments near Bracknell.

NOTE ON ACCUMULATED RAINFALL DEFICIT

Special summaries of the accumulated deficit of rainfall have been produced by the Meteorological Office, each month, since March 1973, as guidance in policy-making and planning in water management. The average rainfall over England and Wales from July 1972 onwards was compared with corresponding totals in the past. At the end of March 1973 the 9-month total was the lowest since 1750 and at the end of April, after some rainfall, the 10-month total was the lowest since 1854. May 1973 was a wet month over England and Wales, with 137 per cent of the average monthly rainfall, and the 11-month total was the lowest since 1956. Even so, since 1800, only 1955–56, 1933–34 and 1854–55 had less rainfall in the 11-month period than 1972–73.

TELEMETERING BUOY

The Office's first telemetering buoy — OBOE I (Offshore Buoy Observing Equipment) has now completed two successful sea trials. In the first, it was on station for three months in the Irish Sea, off Aberporth, from June to August 1972; in the second, it was on station for three months in the Thames Estuary, off Shoeburyness, from February to April 1973. The data recovery rate rose from about 90 per cent in the first trial to over 95 per cent in the second trial.

The buoy provides half-hourly observations of wind speed, air and sea temperature, humidity and pressure. Its purpose is to provide a real-time facility for monitoring the performance of marine sensors, and control observations made in the course of the second trial at the end of Southend Pier have shown that the data are of high quality.

Mr R. Dixon — Special merit promotion to Senior Principal Scientific Officer

It is highly gratifying to announce the promotion of Mr R. Dixon to SPSO under the scheme for the promotion of scientists in the Civil Service who have shown outstanding research ability. Mr Dixon is particularly well known throughout the Office as a result of the considerable periods he spent on roster duties first at the Principal Forecasting Office at London/Heathrow Airport and then in the Central Forecasting Office at Headquarters in Bracknell.

Mr Dixon's mathematical equipment is wide-ranging and powerful. Since 1967 he has been engaged on the development of 3-dimentional and 4-dimensional techniques for the objective analysis of meteorological data for direct application to numerical weather forecasting. Furthermore Mr Dixon has made considerable improvements to the numerical (grid-point) analysis systems in current use in the Central Forecasting Office. The new techniques, which are approaching operational status, involve the fitting of a set of orthogonal polynomials to all the relevant data covering the northern hemisphere. By means of these methods all data can be utilized, whether synoptic or non-synoptic, whether or not at standard pressure levels. This is a very notable advance which is particularly important at this time as satellites are beginning to provide a vast increase in the volume of temperature sounding data which, of course, will be non-synoptic.

The potentialities of Mr Dixon's work are widely recognized not only in this country but also among leading meteorologists in countries such as the U.S.A., Australia and Japan.

P.J.M.

551.593.63

LETTER TO THE EDITOR

Halo display at RAF Gütersloh

On 19 May 1973 between 0830 and 0930 GMT at RAF Gütersloh, West Germany (51° 56′N, 08° 19′E), I observed a particularly fine halo display (see attached diagram). The following points are of particular interest :

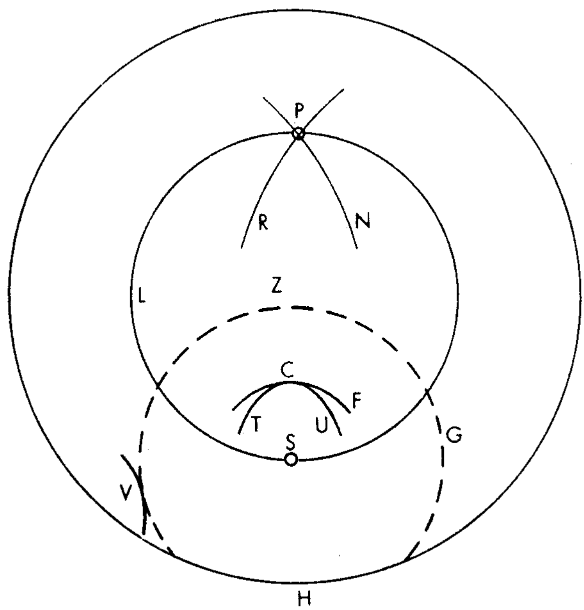
(a) The parhelic circle. This was seen in its entirety and appeared as a well-defined white band.

(b) The anthelion at P. This was particularly bright, with the two oblique arcs, N and R, showing brilliant white.

(c) The arc of contact to the 46° halo at V. This was not very bright, but bright enough to show that it was coloured. The halo itself was not visible.

(d) The 22° halo. This halo was exceptionally brilliant, with red, yellow and a greenish-blue colour apparent (red nearest to the sun). Although it was so bright, the halo was of short length and cleanly cut off (see diagram).

(e) The arcs T U. They appeared as half of an ellipse making contact with the 22° halo at C. They had roughly the same brightness as the arc of contact to the 46° halo and were coloured. I cannot find any reference to these arcs and would be most interested if in fact they have been seen before.



H complete horizon Z zenith S sun P anthelion
F 22° halo G 46° halo (not visible) L parhelic circle
N and R oblique arcs through P T and U elliptical haloes making contact at C
C parhelion (not visible) V arc of contact to the 46° halo

The observer at Gütersloh reported 6 oktas of cirrus at 22 000 ft at 09 GMT.

Meteorological Office,
RAF Gütersloh,
West Germany

H. T. BROOKES


66000 FT.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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EVAPORATION IN THE LONDON AREA FROM 1698 TO 1970

By B. G. WALES-SMITH

Summary. The preparation from the available data (limited in early years) of monthly estimates of (Penman) potential evaporation representative of Kew for the period from 1698 to 1970 is described and illustrated. Measurements made with British Standard evaporation tanks at Camden Square (1885–1955) and Kew Observatory (1949–70) are examined and a simple method of adjusting either record to extend the other (approximately) is proposed.

Introduction. A series of monthly and annual totals of rainfall representative of Kew (1697–1970) has already been assembled and analysed (Wales-Smith[1,2]). Evaporation, the other component of the atmospheric phase of the water cycle, is equally important in studies of water resources, agriculture, drainage and flood control.

Data required for the calculation of estimates of potential evaporation (PE) by Penman's formula.[3] This well-known and widely tested formula makes use of basic climatological data. The variables of which time-averages are required are air temperature and vapour pressure (in the screen), daily duration of bright sunshine and run-of-wind at 2 metres above ground.

Data available.

(a) Temperature: for 1698–1811 monthly estimates based on a variety of records; and for 1812–1970 averages of routine measurements, at Greenwich and at Kew.

(b) Vapour pressure: for 1876–1970 averages obtained from routine hygrometric readings taken at Kew.

(c) Duration of bright sunshine: for 1876–1970 averages of routine measurements at Kew.

(d) Run-of-wind: for 1870–1970, averages of routine anemometer readings (20–23 metres above ground); and for 1957–70, averages of daily readings from an anemometer 2 metres above ground, all at Kew.

Possible length of a series of potential evaporation (PE) estimates. By estimating 2-m wind speeds from 20–23-m speeds it was, clearly, possible to apply Penman's formula, as used in the Meteorological Office (Grindley[4]) to data from 1876 (October) onwards.

The remaining question was to find out if useful monthly estimates of PE could be made with temperature data only. The first step was to plot monthly diagrams of air temperature against PE for the decade 1961–70 (Figure 1). The relationships leave much to be desired, but, as shown by the lines (fitted by eye) the project is not by any means hopeless.

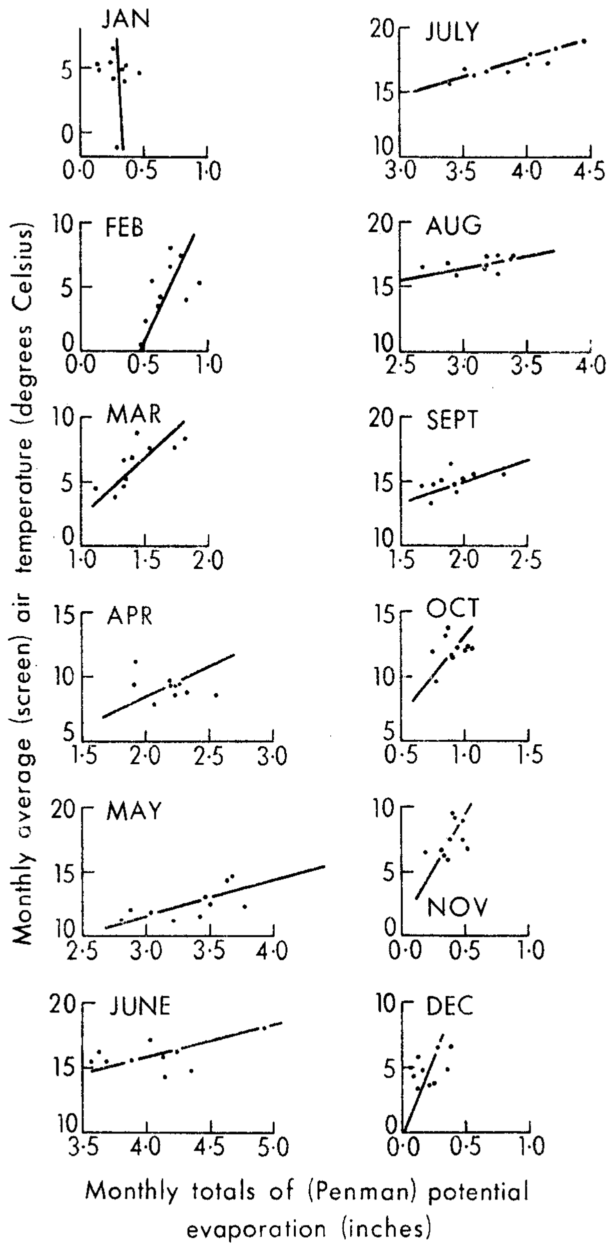

FIGURE 1—MONTHLY AVERAGE (SCREEN) AIR TEMPERATURE AND MONTHLY TOTALS OF (PENMAN) POTENTIAL EVAPORATION (ALBEDO 0·25) AT KEW 1961–70

The next step was to look at relationships between monthly averages of air temperature and vapour pressure and between air temperature and duration of bright sunshine and to see how well long-period average monthly wind speeds approximated to actual monthly averages. These steps were designed to provide means of obtaining estimates to replace missing data and also to approach the problem from a physical point of view.

Monthly averages of air temperature and daily duration of bright sunshine. It is well known that many of the mildest winter days are overcast and that some of the sunniest days in any season are by no means the warmest. The relationship between averages of temperature and sunshine duration would be expected to be poor in winter and not entirely satisfactory at other times of the year. Monthly scatter diagrams of average air temperature against average daily duration of bright sunshine for the period 1921–40, at Kew, are shown as Figure 2.

The winter relationships are poor; those for other months are better but there is a wide scatter of sunshine values for any given temperature. Plausible curves were drawn by eye and then the 1931–60 averages of temperature and sunshine were plotted (as crosses).

Three methods were used to estimate monthly averages of daily duration of bright sunshine at Kew for the decade 1961–70.

(a) Estimates were obtained from temperatures by means of the curves in Figure 2.

(b) The 1931–60 sunshine averages were used as estimates.

(c) The 1931–60 sunshine averages were used from November to February and the temperature-derived estimates, (a), were meaned with the 1931–60 sunshine averages for the other months.

The distributions of errors arising in these three methods were examined. The use of 1931–60 sunshine averages gave fewer large differences from the 1961–70 values than did the use of temperature-derived estimates. The combined method compared favourably with the use of averages and has the advantage of taking into account the radiation–temperature relationship characteristic of the warmer months of the year.

Monthly averages of air temperature and vapour pressure. Monthly temperature averages and averages of vapour pressure (computed from daily mean temperature and daily mean relative humidity) for Kew were plotted against one another for the period 1921–40. Plausible lines of best fit were easily inserted by eye, the month-to-month trend of the slope being used as an aid to positioning the lines for summer months. The relationships are good or very good.

Run-of-wind at 2 metres above ground level. The distribution of monthly averages of 2-m run-of-wind at Kew for the period 1957–70 was tabulated against average to show the greatest errors which resulted from using the 1957–70 monthly averages as estimates of actual monthly averages over 14 years. The errors, never exceeding 1·9 knots, or 53 miles run-of-wind (per day) are acceptably small for the present purpose.

Comparison of Penman PE estimates made with limited and full data. Monthly PE estimates were calculated (using a computer program designed by A. G. Seaton) for the decade 1961–70 at Kew by using real

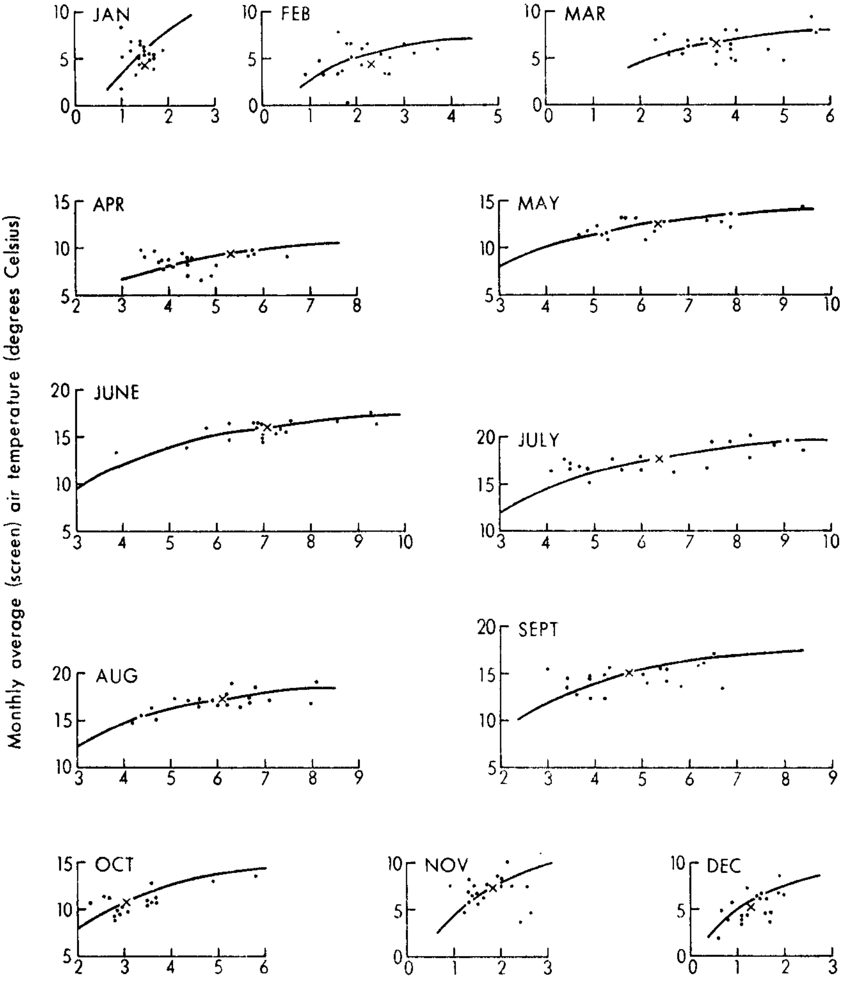

FIGURE 2—MONTHLY AVERAGES OF (SCREEN) AIR TEMPERATURE AND DAILY DURATION OF BRIGHT SUNSHINE AT KEW 1921–40

X averages for period 1931–60

temperature data, estimated duration of sunshine (from temperatures and sunshine averages), estimated vapour pressure (from temperature) and 1957–70 monthly average values of run-of-wind at 2 metres above ground level.

Monthly estimates had also been calculated, for the same decade, using real data. The two sets of 120 estimates were compared; the estimates based on limited data were almost always within ½ inch (12·7 mm) of those based on full data.

Tables to permit PE to be estimated from temperature. Comparison of the two sets of estimates showed that those based on limited data were generally lower than the corresponding full data estimates from October to March. Monthly scatter diagrams of air temperature against limited data PE were drawn and lines of best fit inserted by eye (Figure 3). Monthly tables were produced from Figure 3 but the values for the colder months were multiplied by empirical adjusting factors as follows :

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1·069	1·653	1·351	1·490	1·335	1·099

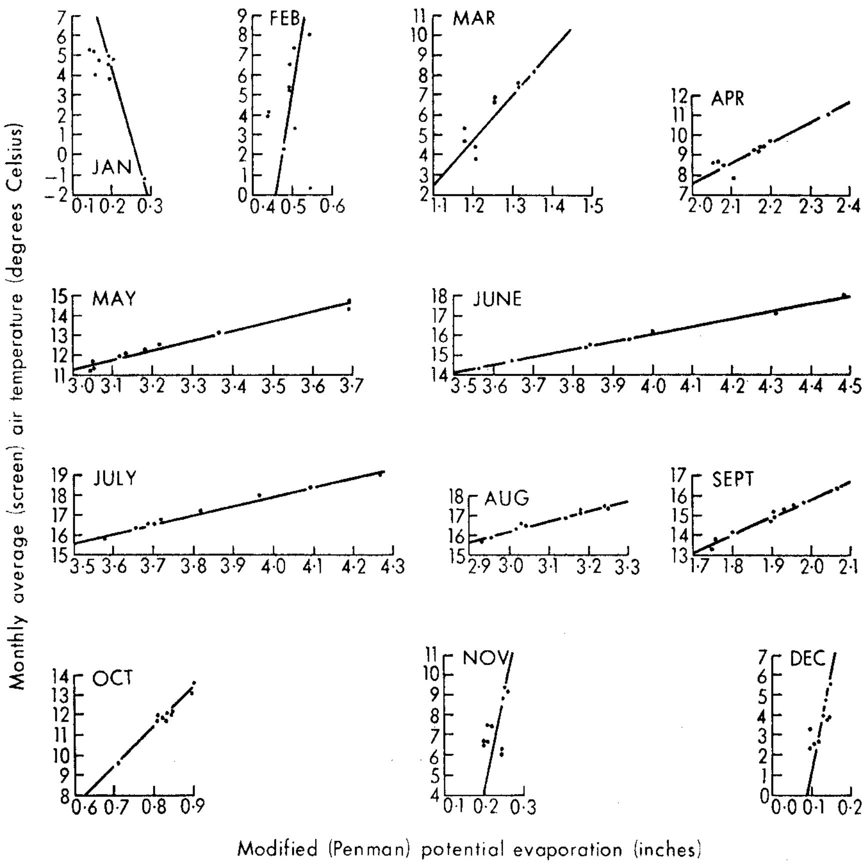

FIGURE 3—MONTHLY RELATIONSHIPS BETWEEN AVERAGE SCREEN TEMPERATURE AND MODIFIED (PENMAN) POTENTIAL EVAPORATION AT KEW 1961–70

Comparison of PE estimates obtained from the tables with those obtained from Figure 1. Although it has been shown that missing data can be quite well estimated using the above methods and that useful monthly PE estimates can be obtained from average temperatures, it remains to be shown that the method is as good as a direct regression of temperature against known PE. Estimates of PE were read from the lines on Figure 1. These estimates and those obtained by using the tables (Figure 3 values with winter half-year adjustments) were compared with the corresponding PE estimates obtained from full data for 1961–70 for Kew. The distribution of errors was examined. It was found that the estimates from the tables were somewhat better than those obtained from Figure 1 (bearing in mind that the lines in Figure 1 are not calculated regression lines).

Sources and adjustment of data. Sources and methods of processing data are given below for those readers who wish to examine them.

(a) Monthly average (screen) air temperature at Kew Observatory.

Sources of data and estimates.

1698–1722	Manley's[5] Central England series adjusted to give estimates for the London Region by a regression obtained over the period 1723–32.
1723–1811	Manley, G.; Temperatures for the London Region. (Typescript communicated to the Meteorological Office 1967).
1812–Oct. 1822	Greenwich Observatory values (Eaton[6]) adjusted to give estimates for Kew by regression, over the period 1871–80.
Nov. 1822–1840	Various sites in the Greenwich area. Values adjusted by subtracting 0·2 degC (to 'correct' from 25–40 ft to observatory height, 155 ft) then adjusted as for 1812–22 (Eaton[6]).
1841–70	Greenwich Observatory temperatures adjusted as for 1812–40 (Brazell[7]).
1871–1920	Kew Observatory Temperatures (Brazell[7]).
1921	*Meteorological and Magnetic Year Book* Kew temperatures.
1922–56	*Observatories Year Books* Kew temperatures.
1957–70	*Monthly Weather Reports* Kew temperatures.

(b) Monthly averages of vapour pressure (in the screen) at Kew Observatory.

Sources of data and estimates.

1870–Sept. 1876	Estimated from air temperatures.
Oct. 1876–1910	*Reports of the Kew Observatory Committee of the Royal Society* and *Reports of the National Physical Laboratory and Observatory Department* (Meteorological Office Library).
1911–21	*British Meteorological and Magnetic Year Books* (Meteorological Office Library). Values for 1911–1913 were obtained from average temperature and average relative humidity. Values for 1914–20 are means of vapour pressures at 09 and 21 GMT. Values for 1921 were computed from daily mean temperature and daily mean relative humidity.
1922–56	*Observatories Year Books* (Meteorological Office Library), computed as for 1921.
1957–70	*Monthly Weather Reports* of the Meteorological Office. Averages of values at 09, 15 and 21 GMT.

(c) Monthly averages of daily duration of bright sunshine at Kew Observatory.

Sources of data and estimates.

1870–Sept. 1876	Estimated from air temperature and long-period monthly averages of sunshine duration. (Jan., Feb., Nov. and Dec. 1931–60 sunshine averages used).
Oct. 1876–1880	*Reports of the Kew Observatory Committee of the Royal Society.*
1881–1920	Brazell.[7]
1921	*British Meteorological and Magnetic Year Book.*
1922–56	*Observatories Year Books.*
1957–70	*Monthly Weather Reports.*

(d) Monthly averages of run-of-wind at 2 metres above ground at Kew Observatory.

Estimates are based on the measured values at 20–23 metres above ground from 1870 to 1956.

Sources of data.

1870–Sept. 1876	Wind tabulations for Kew 1868–77 (Meteorological Office Archives).
Oct. 1876–1910	*Reports of the Kew Observatory Committee of the Royal Society* and *Reports of the National Physical Laboratory and Observatory Department* (Meteorological Office Library).
1911–21	*British Meteorological and Magnetic Year Books* (Meteorological Office Library).
1922–56	*Observatories Year Books* (Meteorological Office Library).

The values from 1957 onwards are measured run-of-wind at 2 metres.

Notes :

(1) Data from 1870–1925 are from the Robinson anemometer, variously stated to have been at 70 ft (21·3 m) and 20 m above ground.

(2) Values for 1870–1905 have been multiplied by 2·2/3 to remove the inconsistency introduced by the change of instrumental multiplying factor.

(3) Data from 1926–1970 are from the Dines pressure-tube anemograph with head at 23 m above ground.

The annual averages of measured winds at 20–23 m were plotted. There had been an apparent, sustained increase from the beginning of the record to about 1930.

Decadal averages are as follows :

1871–80	1881–90	1891–1900	1901–10	1911–20	1921–30	1931–40	1941–50	1951–60	1961–70	
180	178	180	187	188	188	205	200	202	206	miles/day

From this simple table it is easy to derive factors to remove most of the slope from the graph.

For 1871–1900, multiply by 203/180 or 1·128.

For 1901–30, multiply by 203/188 or 1·080,

it being assumed that the increase has been mostly due to greater sensitivity of measuring and recording apparatus over the years.

Thus, starting with the raw, published data the following modifications have been made to produce estimates of 2-metre wind-run (monthly average daily run). 1870–1905 adjusted for instrument factor change. 1870–1930 adjusted for apparent low sensitivity of wind-speed measurements. 1870–1956 values adjusted to give estimates of 2-metre speeds.

The factor to adjust from 23 to 2 metres (0·54) was obtained by plotting monthly averages of measured run-of-wind at 2 metres above ground against average wind speed at 23 metres (converted to run-of-wind) for the period 1957–70. (The points on the graph were all close to a straight line through the origin, where $V_2 = V_{23} = 0$).

Calculation of PE estimates. Estimates for 1698 to 1869 have been obtained from tables based on Figure 3 (with factors applied).

Estimates for 1870 to September 1876 have been obtained by using partly real and partly estimated data.

Estimates for October 1876–1970 have been obtained by using real data.

When seasonal (Nov.–Feb., Mar.–Apr., May–Aug. and Sept.–Oct.) yearly and decadal averages were examined it was found that there was a marked downward 'step' in the 'winter' graph after the decade 1861–70; estimates prior to 1870 were based on temperatures only. Comparisons of long-period averages give the following results :

	1700–1869	(1770–1869) *values in inches*	1870–1969
Winter	1·51	1·51	1·25
	1701–1870	(1771–1870)	1871–1970
Spring	3·45	3·45	3·43
Summer	13·91	13·87	14·10
Autumn	2·61	2·59	2·67

Adjustment was made by subtracting 0·25 in from all winter totals up to 1869 and adding 0·20 in to summer totals and 0·05 in to autumn totals. Monthly adjustments (in inches) were based on long-period average monthly percentages of annual potential evaporation totals as follows : Jan. −0·05, Feb. −0·11, Mar. 0, Apr. 0, May +0·05, June +0·06, July +0·05, Aug. +0·04, Sept. +0·03, Oct. +0·02, Nov. −0·06, Dec. −0·03.

The period 1870–Sept. 1876 had to be treated differently, since real wind as well as temperature data had been used, sunshine and vapour pressure, however, being estimated.

Tank evaporation measurements, 1885 to 1970. Daily measurements of evaporative water loss from a British Standard evaporation tank (6 ft square and 2 ft deep) buried in grass-covered soil with the tank rim 3 inches above ground level have been made at Kew Observatory since 1 January 1949. Daily measurements from a similar tank, (also buried) were made from 1 January 1885 to 31 December 1955 at Camden Square, London.

The early measurements were made by G. J. Symons and later by H. R. Mill, for the British Rainfall Organization, and from 1922 the measurements were made by observers appointed by the Royal Meteorological Society.

The idea of making use of the historic Camden Square record and of the more recent and contemporary Kew record and (possibly) of combining them is attractive. The resulting 86-year record of evaporation from the 6-ft square surface of a 2-ft deep body of fresh water would provide not only a record of actual evaporation but also the data for various analyses of hydrometeorological interest.

The Camden Square record. Data for the more recent years of the record have long been regarded with suspicion and have been the subject of a good deal of expert scrutiny and discussion. Penman estimates of PE have been calculated, for Kew (using all the required data) from 1876 onwards. Figure 4 shows annual and seasonal comparisons between Kew PE and Camden Square tank evaporation. The lines of best fit have been inserted by eye, ignoring points representing annual and summer values for 1943 and later years (shown as crosses in the summer and annual diagrams) and the dated points in spring and autumn which, clearly, are not comparable with values for all other years.

Comparison between the Kew Penman PE series and the Camden Square tank record also suggested that the September tank total in 1906 and the April to August tank totals for 1903 were too large (1903 was the wettest known summer at Kew up to 1970) and adjustments have been made from the lines of best fit (inserted by eye) in month-by-month (scatter diagram) comparisons between Kew PE and Camden Square tank evaporation from 1885 to 1942 (inclusive).

From these monthly 'best-fit' lines and the series of PE estimates for Kew, approximate estimates of Camden Square tank evaporation were obtained for the period 1943–70. These estimates for Camden Square were compared with the Kew tank record from 1949 to 1970 in another set of monthly scatter diagrams. The lines run through the 22-year average values and the origin. The slope of each line has been expressed in terms of empirical factors to adjust either tank record to give an estimate of the other.

Comparison of Penman PE and tank evaporation at Kew. Monthly totals for the period 1949–70 were plotted on scatter diagrams and positions of the lines of best fit were estimated by eye. Points lying well away from these lines were identified and, after the climatological data used in the Penman calculations had been re-checked, these tank estimates were adjusted by half the distance to the line of best fit.

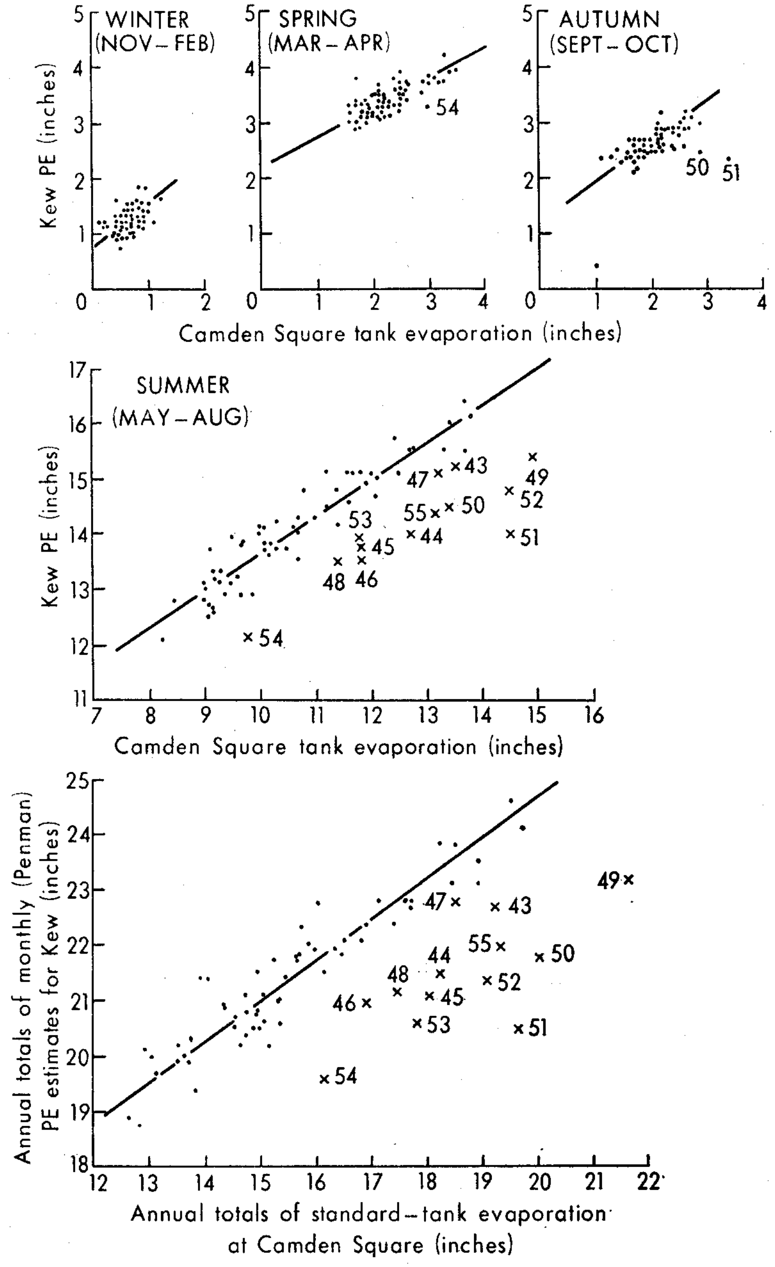

FIGURE 4—COMPARISON OF ANNUAL AND SEASONAL TOTALS OF PENMAN POTENTIAL EVAPORATION (PE) AT KEW AND STANDARD-TANK EVAPORATION AT CAMDEN SQUARE, 1885–1955

Numbers adjacent to plotted points indicate years of observation.

The 1:1 line was inserted on each diagram and it was of great interest to note the following monthly relationships between tank evaporation totals and Penman estimates (made with sunshine data and an albedo value of 0·25) which held on a high proportion of occasions over the 22-year period :

September to January	Tank evaporation $\geqslant$ Penman PE
February	Tank evaporation $\leqslant$ Penman PE
March to August	Tank evaporation $\leqslant$ Penman PE for small totals
	Tank evaporation > Penman PE for large totals.

Records. The series of monthly estimates of PE representative of Kew was originally submitted as Appendix I; the Camden Square and Kew tank series were submitted as Appendices II and III. To save space these appendices have had to be omitted, but copies of the typescript sheets may be obtained from the Editor on request.

35-year and 10-year averages. The averages listed in Tables I and II are provided for direct comparison with Tables III and IV of Reference 1.

TABLE I—35-YEAR AVERAGE POTENTIAL EVAPORATION

35-year period	Representative values for Kew *inches*	*millimetres*
1706–40	21·71	551·4
1741–75	21·57	547·9
1776–1810	21·78	553·2
1811–45	20·72	526·3
1846–80	21·50	546·1
1881–1915	21·49	545·9
1916–50	21·39	543·3

Probable accuracy and sensitivity of PE estimates based on air temperature. It has been shown that the PE estimates are good when based on good-quality temperature data. The accuracy of the early estimates in the series depends upon the quality of the Manley temperature series and these are certainly the best estimates available.

The sensitivity of the temperature-derived estimates was investigated by two methods. First the monthly value of $\pm$ $(M - \overline{M})$ was calculated for real Penman PE estimates and for temperature-derived PE for the decade 1961–70. (M = monthly PE total : $\overline{M}$ = 10-year average PE). Frequency diagrams of $\pm$ $(M - \overline{M})$ were prepared. The temperature-derived estimates are, as would be expected, less sensitive to evaporative conditions than real Penman PE.

Next decadal extreme annual and 'summer' (May–August) totals were compared with corresponding decadal averages. The averages of extreme value differences from decadal average were calculated for the periods 1701–1870 and 1871–1970. Comparing the averages we have

			1701–1870	1871–1970
Whole year	Average decadal	max. minus average	1·37 in	1·93 in
	differences	average minus min.	1·22 in	1·87 in
'Summer'	Average decadal	max. minus average	1·22 in	1·65 in
	differences	average minus min.	0·99 in	1·55 in

Thus the ratios expressed as fractions

	(Max.)	(Min.)
Whole year	1·93/1·37 = 1·41	1·87/1·22 = 1·53
'Summer'	1·65/1·22 = 1·35	1·55/0·99 = 1·57

TABLE II—10-YEAR AVERAGES OF POTENTIAL AND TANK EVAPORATION IN INCHES

Decades	Kew PE	Kew tank	Camden Square tank
1701–10	21·35		
1711–20	21·23		
1721–30	21·79		
1731–40	22·04		
1741–50	21·70		
1751–60	21·55		
1761–70	21·33		
1771–80	22·24		
1781–90	21·58		
1791–1800	21·61		
1801–10	21·74		
1811–20	20·38		
1821–30	20·85		
1831–40	20·51		
1841–50	21·84		
1851–60	21·56		
1861–70	21·95		
1871–80	20·68		
1881–90	20·91		
1891–1900	21·95		15·66
1901–10	21·53		15·85
1911–20	21·11		15·21
1921–30	21·24		15·33
1931–40	21·53		15·78
1941–50	21·79		16·28 (estimated)
1951–60	21·87	23·26	16·38 (estimated)
1961–70	22·39	22·31	16·94 (estimated)
Mean of 27 decades	21·49		

give factors which could be applied to extreme values in early decades to give an approximation to the probable real maximum departures, positive or negative, from decadal averages.

Future plans. The series of evaporation estimates will be analysed along the lines of Reference 2 and in conjunction with the rainfall series (Reference 1).

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AN OBJECTIVE METHOD OF CALCULATING AREAL RAINFALL

By E. J. ENGLISH

Summary. A model is described for the computer-based computation of rain amounts at points of a regular grid from a scattered distribution of rain-gauge values, for the purpose of estimating rainfalls over areas such as river sub-catchments. Some results are presented where computed areal rainfalls are compared with hand estimates.

Introduction. Several hundred estimates of sub-catchment areal rainfall using a gauge network were required in the Dee Weather Radar Project,[1] so it was necessary to develop a reliable computer-based objective method. It had to be flexible enough to accept any combination of the gauges, after one or more had been rejected by quality control procedures, to obtain estimates over areas whose shapes were dictated by river catchments.

Many models have been developed to obtain areal rainfall including a number which rely on weighting factors being applied to the observations, such as the well-known Thiessen's Method; a method based upon producing the weights by surface fitting;[2] and triangulation.[3] These methods require the weighting factors to be changed if one or more gauges in a network do not have valid data, which makes them unattractive for computer application, although Diskin[4] describes a method based on a Monte Carlo procedure for the production of Thiessen's Coefficients using a digital computer.

Inverse distance weighting has been used extensively for interpolation prior to forming areal rainfall, for example by Salter[5] in the Meteorological Office. This method has the drawback that no allowance is made for the position of the gauges relative to the interpolation point, also it cannot produce values at a point which are higher than the maximum or lower than the minimum gauge measurement. To overcome these difficulties surface fitting techniques[6,7] have been developed which attempt to describe the rainfall field as if it were a continuous pattern, much as an analyst does when drawing isohyets by hand.

The model chosen for use here is a combination of inverse distance-squared weighting and the fitting of a linear surface so that the main advantage of each is retained — namely the dominance of observations which are spatially close to the interpolation point and a general dependence upon the distribution of a number of the observations.

Calculations of areal rainfall using the model have been made over 16 areas within the upper catchment of the River Dee in north Wales. Figure 1 shows the location of these areas, which vary in size from 20 to 112 km^2, and also the locations of the rain-gauges forming the network. This network consists of 60 automatically recording flush-mounted rain-gauges, records from which are processed to a computer-accessible form by the Dee and Clwyd River Authority and the Water Resources Board. The rain-gauges used are flush-mounted modified battery-operated Plessey MM37 tipping-bucket gauges, which incorporate a ¼-inch magnetic-tape event recorder with a time resolution of ¼ hour, events being recorded for each 0·2 mm of rain.

Areal rainfall model. The areal rainfall is obtained by finding the mean value of grid-point estimates within the area, with grid-point spacing in the examples presented here of 1 km and point estimates obtained by

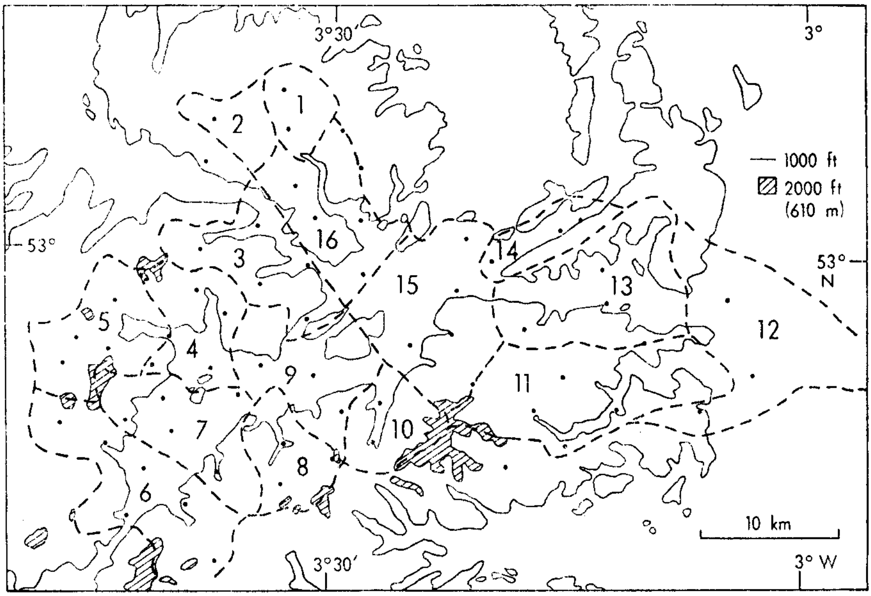

FIGURE 1—SUB-CATCHMENT OF THE RIVER DEE (NORTH WALES) AND RAIN-GAUGE LOCATIONS

applying a mathematical model to a number of nearby gauge observations. This model consists of fitting a linear surface to a grid point with inverse distance-squared weighting applied to the observations. The surface chosen is the one for which the expression $\frac{r}{d} = \frac{ax}{d} + \frac{by}{d} + \frac{c}{d}$, applied to a number of gauge values, has the least-squares solution such that

$$\sum_{i=1}^{N} \frac{1}{d_i^2} (r_i - (ax_i + by_i + c))^2 = \text{minimum}$$

where

- d is the distance of the rain-gauge from the grid point,
- x and y are rectangular displacements of the rain-gauge from the grid point,
- r is rainfall value at the gauge, and
- a, b, c are coefficients.

Mathematical solution. For each of the N chosen observations one can write

$$\frac{r_i}{d_i} = \frac{ax_i}{d_i} + \frac{by_i}{d_i} + \frac{c}{d_i}$$

where $i = 1$ to N.

Written in matrix form the N equations become $\mathbf{R} = \mathbf{X}\,\mathbf{A}$

where **R** is the $N \times 1$ matrix with elements r_i/d_i,
X is the $N \times 3$ matrix of displacements with elements,

$$\begin{array}{ccc} \dfrac{x_1}{d_1} & \dfrac{y_1}{d_1} & \dfrac{1}{d_1} \\ \dfrac{x_2}{d_2} & \dfrac{y_2}{d_2} & \dfrac{1}{d_2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \dfrac{x_N}{d_N} & \dfrac{y_N}{d_N} & \dfrac{1}{d_N} \end{array}$$

and **A** is the 3×1 matrix of coefficients with elements a, b and c. We require the least-squares solution of $\mathbf{R} = \mathbf{X}\,\mathbf{A}$ for the unknown coefficients **A**. The solution is a standard one and can be found in many texts.[8]

$$\mathbf{X}'\,\mathbf{R} = \mathbf{X}'\,\mathbf{X}\,\mathbf{A}, \text{ where } \mathbf{X}' \text{ is the transpose of } \mathbf{X}$$

so that $(\mathbf{X}'\mathbf{X})^{-1}\,\mathbf{X}'\,\mathbf{R} = \mathbf{A}$, where $(\mathbf{X}'\mathbf{X})^{-1}$ is the inverse of $(\mathbf{X}'\mathbf{X})$.
All the left-hand side of this equation is known and coefficients a, b, c can be obtained. If the grid point being considered is taken as the origin of the x, y system of co-ordinates, i.e. $x = y = 0$, the minimum solution gives an expected rainfall value of c at the grid point.

Computer solution. The main steps in the computer solution are to :

(a) select a grid point from a regular array and make this the origin of the rectangular co-ordinates;
(b) select the nearest six suitable observations to the grid point (the nearest six will not necessarily be the best selection and this is discussed further below);
(c) apply the matrix solution to the six observations and take for r the resulting value of the coefficient c;
(d) take each grid point in turn;
(e) calculate areal rainfall by obtaining the mean of the values for the grid points within the area.

The stability of the solution near to and within the area of the observations is normally high and the most likely cause of instability in the solution is when displacements from a straight line are small compared with the distance of the grid point from it. Such situations result in a very low value of the determinant $\mathbf{X}'\,\mathbf{X}$ and this can be used to ascertain the approach of instability which may then be avoided by changing the choice of gauges used until an acceptable determinant is found. The value of the determinant at which the selection of gauges is rejected may be used to control the distance interpolation is allowed away from the area covered by the observations. For the present purpose interpolation is allowed to the limit of a 60 by 40 array in order that isohyets may be drawn by a computer method which requires a complete rectangular matrix of values.

On occasions an observation will lie very close to a grid point resulting in a small value of one of the distances used in the solution, which in turn can lead to a failure of the model. To prevent this situation the distances are tested and if one falls below some set limit, in this case 0·01 of a grid space, the nearest observation is used as the grid-point value. Interpolation into areas of no rainfall often leads to negative values which are then set to zero.

The present model uses six gauge values to obtain its solution although it could be solved with a minimum of three observations. It has been found that six values give the most acceptable results producing a pattern similar, in most cases, to what an analyst might produce by hand, a number less than six often leads to discontinuities and irregularities in the fields, whilst a number more than six tends to produce too much smoothing as well as consuming more computer time.

Results from the model. An example of a rainfall field produced by the model is shown in Figure 2 where the rain-gauge values used are given and the isohyets drawn by a computer method which relies solely upon the computed grid-point values (not shown). This type of output allows the computer solution to be checked subjectively, as if the isohyets are consistent with the rain-gauge values it can be assumed that the interpolated grid-point values are realistic. Interpolations for a field outside the region of the gauge measurements show some discontinuities such as that marked A near bottom centre of Figure 2. These discontinuities are the result of interpolations being carried out at some distance from the observations and are usually in a location where adjacent grid points are calculated from a different selection of the remote gauges. Within the region covered by the gauges the computed fields are similar to those which an analyst might obtain by hand from a knowledge of the observations alone.

In order to make some comparisons between the value derived from the method used here and the value of areal rainfall which one would accept as the correct one, it is necessary to derive the latter. The best field one can obtain by using the gauges is that which is subjectively drawn by the hand of an analyst but even here, as interpolation is necessary, a degree of uncertainty exists. The hand estimates of areal rainfall were obtained by superimposing a matrix of grid points on the hand-drawn charts and finding the mean of the grid-point values in each of the areas. Not all of the 60 gauges were available for each field examined and the data were so sparse in a few areas that an estimate was unreliable.

Table I shows five cases where a comparison is drawn between the results of the model and the hand computations. Except in a few instances the difference between the two values is small and within the uncertainties inherent in any interpolation method. The two main causes of significant differences are :

(a) the difficulty of defining both hand and computer fields owing to lack of suitable observations particularly when a field is not uniform, e.g. area 1 in Figure 2,

and

(b) high rainfall gradients such that the position of the grid relative to the field is critical. This is the case in area 4 of Figure 2 where a strong gradient exists over the south-eastern part of the area and small changes in the position of the grids of both hand and automatic methods can produce areal estimates differing by as much as the discrepancy in the comparison made in Table I.

Both the above effects are accentuated by having areas containing few observations and a grid which is coarse relative to the size of the areas. This is shown by the measures used to describe the differences between hand and

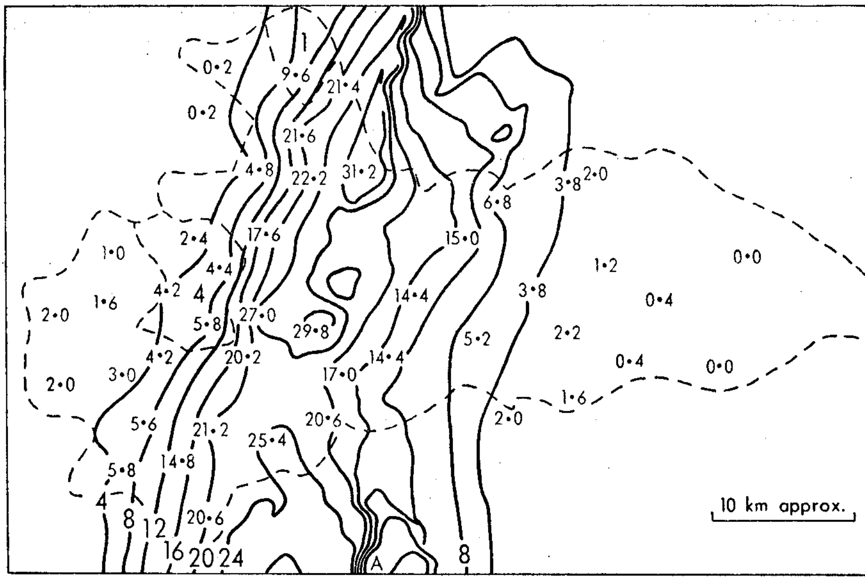

FIGURE 2—RAINFALL CHART FOR 3 HOURS STARTING AT 0545 GMT, 1 AUGUST 1972

Rainfall values are in millimetres and in each case the decimal point indicates the position of the rain-gauge; isohyets are at intervals of 4 millimetres.

TABLE I—COMPARISON BETWEEN HAND AND MODEL COMPUTATIONS OF AREAL RAINFALL

	31 July 1972 1245–1345 GMT			31 July 1972 1345–1445 GMT			1 August 1972 0245–0545 GMT			1 August 1972 0545–0845 GMT			1 August 1972 0845–1145 GMT		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Area															
1	0·3	0·1	0·2	0·0	0·0	0·0	22·7	23·7	1·0	12·1	13·6	1·5	2·4	3·1	0·7
2	0·6	0·3	0·3	0·0	0·0	0·0	18·6	20·4	1·8	4·0	6·0	2·0	0·3	0·8	0·5
3	1·6	1·7	0·1	1·3	1·6	0·3	14·6	12·9	1·7	14·6	15·1	0·5	2·3	2·5	0·2
4	1·5	1·9	0·4	4·0	3·3	0·7	17·9	16·7	1·2	5·1	7·7	2·6	0·1	0·4	0·3
5	0·2	0·5	0·3	2·1	2·4	0·3	15·2	16·7	1·5	1·9	1·9	0·0	0·0	0·0	0·0
6	0·8	0·6	0·2	0·6	0·7	0·1	13·2	12·3	0·9	9·6	10·3	0·7	0·8	1·4	0·6
7	0·4	0·5	0·1	1·8	2·3	0·5	10 0	9·3	0·7	13·2	13·4	0·2	1·2	1·8	0·6
8	0·4	0·6	0·2	2·2	2·5	0·3	2·5	2·1	0·4	24·4	22·0	2·4	8·4	9·1	0·7
9	2·0	1·6	0·4	4·8	5·7	0·9	2·9	2·7	0·2	23·8	22·2	1·6	8·0	7·4	0·6
10	1·4	1·5	0·1	6·4	6·1	0·3	0·5	0·5	0·0	12·3	11·3	1·0	6·4	7·2	0·8
11	1·9	1·9	0·0	3·4	2·8	0·6	0·1	0·1	0·0	2·0	1·4	0·6	4·5	3·3	1·2
12	—	—	—	—	—	—	0·0	0·0	0·0	0·0	0·1	0·1	0·2	0·2	0·0
13	1·0	1·1	0·1	2·0	1·6	0·4	0·1	0·1	0·0	2·0	1·6	0·4	5·2	4·5	0·7
14	0·1	0·3	0·2	1·1	1·3	0·2	0·3	0·2	0·1	4·2	3·2	1·0	8·7	7·8	0·9
15	2·5	2·1	0·4	4·3	4·3	0·0	1·0	1·0	0·0	15·2	11·5	3·7	7·2	7·5	0·3
16	1·8	1·5	0·3	0·7	0·7	0·0	9·0	9·5	0·5	25·0	24·0	1·0	5·6	7·2	1·6
Total	16·5	16·2	3·3	34·7	35·3	4·6	128·6	128·2	10·0	169·4	165·3	19·3	61·3	64·2	9·7
Mean	1·10	1·08	0·22	2·31	2·35	0·31	8·04	8·01	0·63	10·59	10·33	1·21	3·83	4·01	0·61
$\frac{\Sigma Z}{\Sigma X} \times 100\%$		20			13			8			11			16	
$\frac{\lvert \Sigma X - \Sigma Y \rvert}{\Sigma X} \times 100\%$		2			2			<1			2			5	

X = Areal rainfall in millimetres by hand method.
Y = Areal rainfall in millimetres from model.
Z = $X-Y$ modulus of difference in millimetres.
$\frac{\Sigma Z}{\Sigma X} \times 100$ = Percentage error in areal rainfall with areas treated individually.
$\frac{\lvert \Sigma X - \Sigma Y \rvert}{\Sigma X} \times 100$ = Percentage error in overall estimate for the areas treated approximately as one large area.

model computations and given in Table I. The indicator used to describe the size of the differences in individual areas (percentage of sum of differences to total of hand estimates) gives values of 8 to 20 per cent with a mean of 14 per cent for the 5 cases, whilst when all 16 areas are combined into one large area the differences are 5 per cent or less. The combination is not truly a measure of areal rainfall over the total area as all the sub-catchments are not of equal size; nevertheless the comparison of the simple totals is valid enough to make the above point.

Use of a background field. Consideration was given to using a background field in an attempt to improve the interpolation technique; one possibility is the topographic field. However almost all storms produce rainfall totals which, although greatly influenced by the mountains, are not consistently correlated to the ground features on the space and time scale of interest here. For example in Figure 3 is shown a rainfall field, drawn by hand, over a six-hour period in a showery westerly situation on 12 November 1972. It would clearly be unwise to use altitude as a background in such a case, and in consequence this method was rejected.

A second possible background field for use in short durations, i.e. an hour, is the total storm accumulation. Kelway and Herbert[9] used a technique of taking percentage of storm amount at each gauge in order to produce fields of this element and although the method when applied to fields over the Dee Catchment did show the general movement of the main rain features quite well, no noticeable improvement in the interpolation resulted. In fact some short-duration fields show few of the features of the total storm

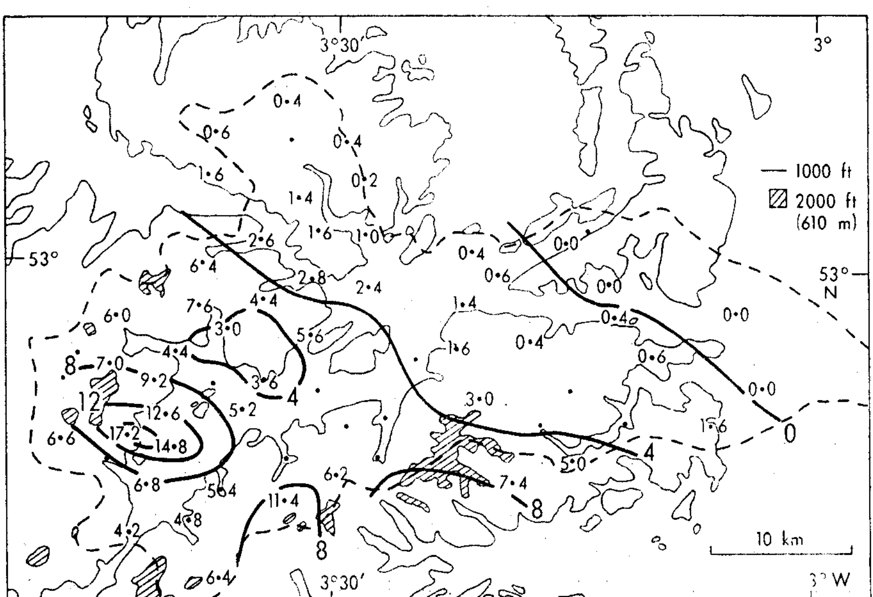

FIGURE 3—RAINFALL IN MILLIMETRES BETWEEN 0130 AND 0730 GMT, 12 NOVEMBER 1972

In each case the position of the rain-gauge is indicated by the decimal point.

amount and the use of such a background on these occasions could degrade the interpolation.

Conclusion. From a scattered array of observations the model allows automatic interpolation of realistic rainfall fields from which areal rainfalls can be calculated over an area of any shape with sufficient accuracy to permit them to be used in routine analyses. For five cases a mean error of 14 per cent was obtained between the model and hand estimates over areas which were relatively small compared with the grid spacing. The model allows isohyets to be drawn by a computer method which permits subjective surveillance of the interpolation.

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METEOROLOGICAL CONTRIBUTIONS TO OPERATIONAL HYDROLOGICAL FORECASTING IN THE UNITED KINGDOM

By A. BLEASDALE

Summary. Meteorologists have an important part to play in aiding hydrological forecasting. The associated problems and the stage now reached in solving them within the natural and organizational setting in the United Kingdom are outlined. In this country, in present practice, hydrological forecasting means, predominantly, forecasting rainfall-produced river floods and issuing appropriate warnings. But there are other forecasting problems within the hydrological field, for some of which interesting and promising developments are taking place. These are also touched on.

Introduction. This note was originally written to suggest material for possible inclusion in a joint paper, with hydrologists as co-authors, on operational hydrological forecasting systems in the United Kingdom. The joint paper was presented at a WMO–Unesco meeting on hydrological problems held at Berne in August 1973. The material was intended to be very freely used and rearranged amongst the hydrological contributions, a course which was in fact taken. Moreover the meeting at Berne was organized on a small scale, primarily to stimulate free discussion, not necessarily with the follow-up of international publication of the full proceedings. The note can stand on its own, though it might well have taken another form, with some differences in wording, given a more independent origin.

As the State Weather Service in the U.K., the Meteorological Office includes among its functions the provision of meteorological services to the community in general. Many regular recurrent needs are met by the frequent issue of weather reports and forecasts through public information channels. It is known that this continually up-dated form of communication can also be used, at least to initiate a preliminary alert based on a specified meteorological threshold, by organizations which have, beyond these thresholds, their own specialized requirements. With or without this tentative alert, special needs are met by arrangements which, in most cases, have been built up gradually over the years, and from time to time undergo significant development. Improvements in this sense often arise as the direct result of an extreme or otherwise unusual weather or weather-influenced event which has presented a problem: great difficulties of some kind, serious loss or damage, or even disaster.

Important examples of special needs are warnings of disruptive weather effects on transport, in particular snow, ice or fog hazards lowering the safety and efficiency of road and rail services, and dangers from strong winds to traffic crossing vulnerable bridges or traversing other elevated and exposed sections of route (to say nothing of shipping and aviation).

Each special need offers its own peculiar problems to the meteorologist, not only because of the intrinsic difficulty of weather forecasting in general, and the very small changes in some meteorological elements which can rapidly transform a safe situation into a dangerous one (slow thawing or refreezing; dispersal or thickening of slight fog), but also because some variations on hazardous conditions cannot be foreseen, or at least in practice have not been foreseen, until they have occurred at least once and have enforced study.

In the past fifteen years it has become increasingly recognized in the U.K. that one of the most important of the specialized meteorological services is the contribution which can be offered to hydrological forecasting. In some of its branches the latter has itself, during the same period, become established, and is now being maintained and developed, on a sound operational basis, so that in this field the totally unforeseen should become a much rarer phenomenon, and there is more opportunity for the most damaging effects of the foreseen to be prepared for and mitigated.

One stimulus towards the new outlook came from the Lynmouth flood disaster of August 1952,[1] though the greatest outburst of productive activity in developing flood-warning systems did not follow until interest was renewed by the notable flood year of 1960,[2] within an organizational setting which was then becoming more favourable. It was again reinforced by the outstanding rainfall-flood events of 1968,[3] but there had also been a less concentrated train of incidents to maintain a useful degree of steady progress.

It is relevant to note that operational hydrological forecasting in the U.K. is very largely concerned with rainfall-produced river floods, and that the North Sea surge of late January 1953,[4,5] which caused disastrous tidal flooding from north of the Humber to south of the Thames, very probably diminished the still lively interest in the Lynmouth event, thereby delaying for some years any concentration of effort on flood-warning schemes for rivers. These two floods remain as yet the latest in the U.K. in which loss of life has occurred on a substantial scale, and the later (1953) far surpassed the earlier (1952) in this respect.

Whilst the tidal surge type of flooding is not hydrological in the usually accepted sense of the term, the Storm Tide Warning Service which has been developed, following 1953, is dealt with here (see page 306) for two reasons: there are possibilities that a tidal surge could coincide with and seriously aggravate the damage and difficulties of a rainfall-river flood, and river engineers in the U.K. are rightly very concerned about this; and secondly, this Service is one in which the U.K. is collaborating with other European countries bordering the North Sea.

There are of course other forms of hydrological forecasting with their own special problems for meteorologists, which will be touched on briefly later. Among the most important in the U.K. are :

(a) snowmelt floods;

(b) short- and medium-term water resources management (the long-term requires planning rather than forecasting).

The meteorological contribution to river-flood forecasting presents problems in three different categories, with varying degrees of difficulty in finding operationally adequate solutions :

(a) a continuous watch on flood susceptibility in river basins throughout the country, to judge when the season arrives to be specially alert for any forecast of substantial amounts of rain;

(b) the general forecasting of heavy or more moderate but prolonged rainfall, with as much information as possible on the likely severity and duration, and the areas likely to be affected;

(c) the more detailed and precise forecasting of intense falls of rain likely to affect small river basins subject to flash floods, and urban storm-water drainage systems.

The arrangements which have been made to attempt to cope with these problems and difficulties illustrate a very important factor towards achieving success: the co-ordination of activities on national, regional and local levels. For the assessment of flood susceptibility the Meteorological Office has continuously developed, since the autumn of 1962, a national service for estimating and mapping soil moisture deficits over the whole of Britain. Bulletins, with maps and tabular summaries showing the (estimated) state of the ground in this sense, are issued at approximately fortnightly intervals throughout the year, except for those months (slightly variable but mainly winter and early spring) when it is estimated that, with negligible exceptions, soils everywhere are at field capacity, and virtually all rain which falls can be assumed to be 100 per cent effective rainfall. In the present context the most interesting period is usually the autumn, when the area of zero soil moisture deficit spreads progressively over the whole country, and one area after another approaches its maximum susceptibility to any threat of flood-producing rainfall. An example of a pair of successive autumn–winter soil moisture deficit maps is given in Figures 1 and 2. Through the development of the computer model on which the preparation of these bulletins is based (they were originally introduced with entirely manual procedures), the service will shortly be extended and improved to provide regular countrywide assessments of potential evaporation, actual evaporation, soil moisture deficits and effective rainfall. To derive maximum benefit from the national service, users (who include many with interests other than the flood-alert application) should if possible employ local checks on the validity of the rather generalized

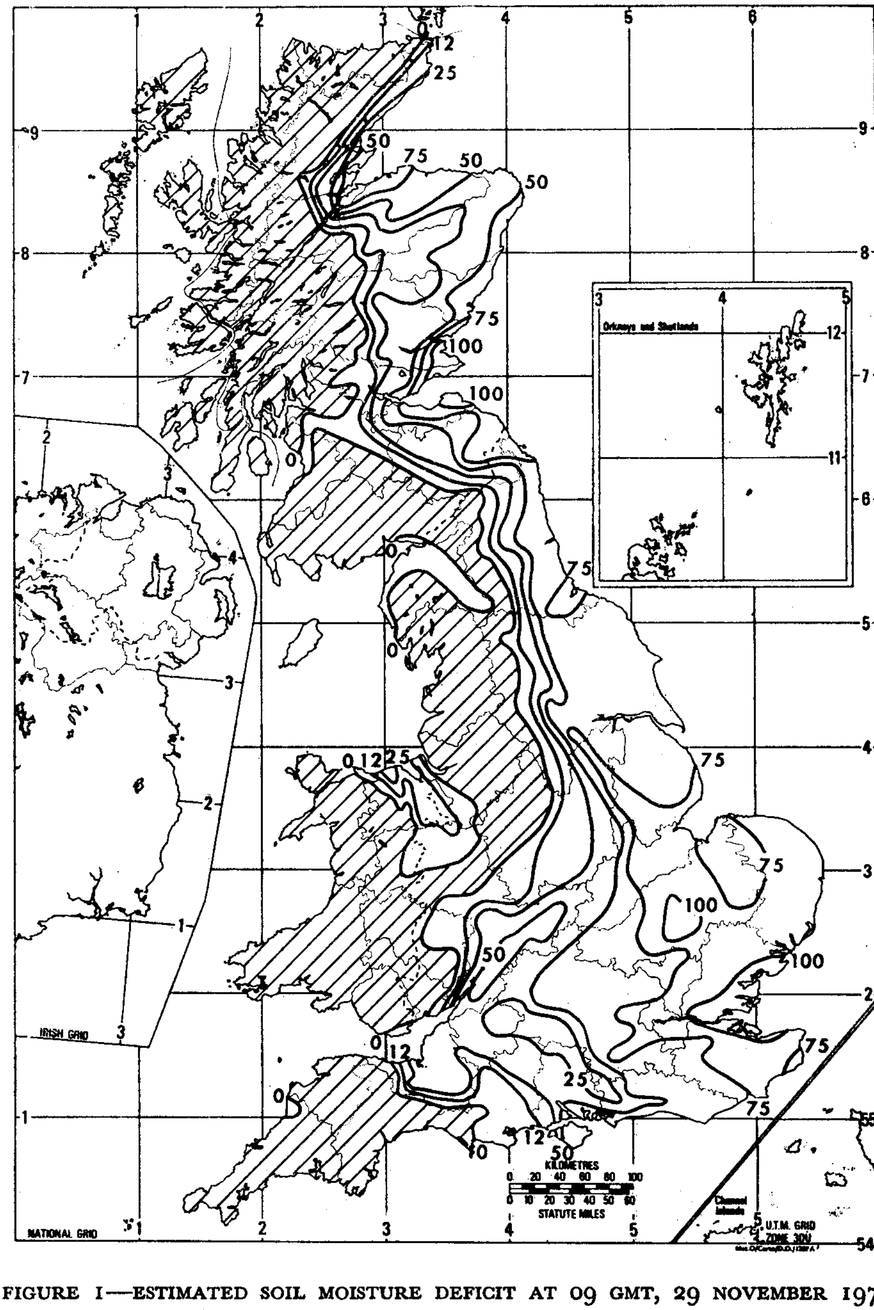

FIGURE 1—ESTIMATED SOIL MOISTURE DEFICIT AT 09 GMT, 29 NOVEMBER 1972

Areas with no soil moisture deficit are shaded. Remaining areas are bounded by lines representing 0, 12, 25, 50, 75 and 100 millimetres.

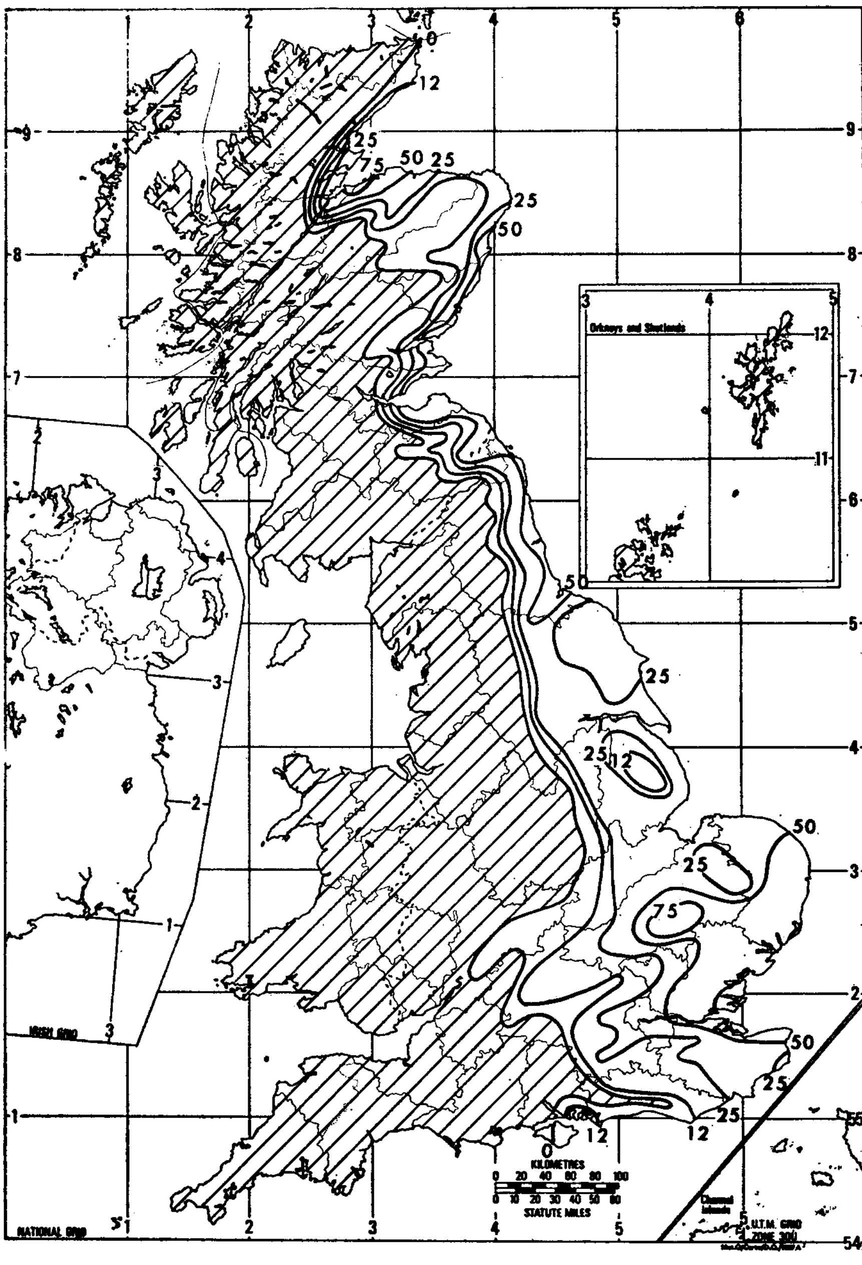

FIGURE 2—ESTIMATED SOIL MOISTURE DEFICIT AT 09 GMT, 13 DECEMBER 1972

Areas with no soil moisture deficit are shaded. Remaining areas are bounded by lines representing 0, 12, 25, 50, 75 and 100 millimetres.

small-scale maps. One such check, used with striking success over a large area in the south-west during the autumn of 1972, is to observe the date on which field drains begin to run, which should be with the first fall of rain sufficient to bring soil moisture deficits back to zero, with at least a little extra. Coincidence of estimates and observations has been achieved within a day or two, though it must also be admitted that there are still occasional anomalies of several days which require investigation in order to improve the data input or the model, whichever seems to be at fault. Reference No. 6 indicates the means to obtain fuller information about this service.

The quantitative forecasting of rainfall is still a major problem, which is being tackled at the national level by the development of the 10-level atmospheric model[7] now being run twice a day as an operational routine on the Meteorological Office IBM 360/195 installed in December 1971.[8] For the flood-forecasting application, however, the Meteorological Office has always encouraged, whatever the mode of forecasting at Headquarters, regional and local interpretation, at Meteorological Office stations manned by trained forecasters throughout the country, of the central guidance on current meteorological developments. The present position is that more than 20 weather centres and other offices have established direct communications with 28 of the 29 river authorities covering the whole of England and Wales, on matters relevant to flood warnings. Example: the office at Gloucester issued to the Bristol Avon River Authority at 20 GMT on 14 January 1973 the forecast :

> 'Continuous rainfall over Cornwall is expected to spread over your area this evening and tonight, persisting throughout the night; 12·5 mm (0·5 inch) or more of rain is expected to occur in 6 hours locally.'

From the soil moisture bulletins already issued it was known that zero deficit had been reached in this area before mid December (Figure 2) and therefore that any substantial rainfall would produce high flows in the trunk river flowing through Bath and Bristol, perhaps also in smaller towns vulnerably situated on the Bristol Avon or its tributaries. At such a point it is for the hydrologists to take over, with any actions which they consider necessary or desirable, including attention to actual measurements of rainfall, for which immediate transmission to an operational centre will have been pre-arranged, in order to check the forecast. In this instance, the forecast proved correct, though a check (perhaps not exhaustive) showed that only two stations strictly within the river basin, on relatively high ground, measured rainfall amounts above the specified threshold; some on lower ground failed to reach half the amount. An area of heavier rain in fact passed slightly to the south of the Bristol Avon basin, and the situation illustrates one of the special difficulties for meteorologists in contributing to flood-warning services, particularly for the smaller rivers: namely the accurate specification of which, amongst a group of neighbouring basins, will be most seriously affected. Especially when the heaviest rain falls on high ground which is a drainage divide, a slight shift in the rain area, from that forecast, could transfer the most serious flood risk from one area to another. A very good account of rainfall forecasting for three river authorities has been given by Holgate.[9]

The difficulty referred to above is greatly enhanced with the problem of forecasting intense short-period rainfall, usually of an irregular thundery type, which may produce flash floods in the smallest natural drainage basins, and serious trouble for urban storm-water disposal. In these conditions, too, quite moderate departures of intensity and duration, from those suggested by an attempted forecast, can sometimes make all the difference between a mere nuisance and real trouble if not disaster; whilst the possible benefits from a substantial soil moisture deficit, which may be experienced with more moderate and prolonged rain in the larger river basins, can be negligible for the most intense short-period bursts, either because any deficit may be nullified during the first few minutes, or because infiltration rates cannot match the rainfall rates (not to mention completely impermeable surfaces). The problems have not yet been solved, but there is a current upsurge of interest in the U.K., arising in a number of ways, and stimulating activities which are likely to converge productively within the next few years :

(a) Following the very exceptional rainfall and flooding of 10 July 1968,[3] it was remarked by some of those concerned, including the Engineer of the Bristol Avon River Authority, that the larger rivers behaved at any rate predictably, whilst much of the serious damage, including the destruction of bridges (at least one of them centuries-old) occurred on the small tributaries. Several similar incidents in small stream basins have happened in recent years to keep interest alive.

(b) The papers prepared for a research colloquium at Bristol University, in April 1973, have drawn attention to the data needs and further investigations required to cover drainage and flood problems in large and growing urban areas.[10] Relevant investigations have already begun or are being planned, but the discussions at the colloquium are likely to stimulate others by bringing out additional requirements not previously foreseen.

(c) Outstanding amongst current investigations is the Dee Weather Radar Project.[11] Started in order to investigate the usefulness of rainfall-radar in a major river-regulation scheme, the Project is also providing data which are very useful for the study of the movement and development of rainfall systems, including the irregular thundery distributions which give so much trouble to the hydrologically-oriented rainfall forecaster.

(d) It may also be mentioned that two flood studies teams, of meteorologists and hydrologists, completed in 1973 a major three-year programme of work, results shortly to be published, which though directed primarily to the hydrological design and not the forecasting problem, assembled much useful background information for the latter.

Even with radar, it is to be doubted whether the flash-flood problem will ever be completely solved, in the sense of prediction, sufficiently far in advance, of the precise small area within which the heaviest deluge in an exceptional fall will occur, and of being able to take full protective measures in time. But there are prospects of much better results than could be achieved with any practicable density of conventional rain-gauges, or any foreseeable refinement of meteorological forecasting techniques. The very fine scale required for intense rainfall forecasting over small drainage areas, goes so very much below the dimensions of any numerical-model grid which can as yet be envisaged, even for the most advanced atmospheric model and the largest and most powerful computers.

The study of snowmelt floods in the U.K. has distinctive problems. A really severe winter affecting most or all of the country does not occur very often. The last was 1962–63, the two before that 1946–47 and 1939–40. In 1947 there were large-scale catastrophic floods, especially in the Fens of East Anglia, in some other parts of south and south-east England, and in several parts of Yorkshire, notably a large area in the plain of York, on both sides of the Ouse from the confluence with the Wharfe to the confluence with the Aire.[12,13] Snow had accumulated for about two months when, towards mid March, a very mild and vigorous south-westerly airstream suddenly caused a very rapid thaw, which was also accompanied by frequent rain. Few people, if any, had realized that disaster might occur on such a great scale. Snow accumulation in 1962–63 was appreciably smaller but a flood danger existed. Special efforts were made by the Meteorological Office to collect snow-lying data and assess the degree of the potential flood risk; in a few places, notably in north-east England, where floods did occur, the assessments proved to be fairly good. But in general the thaw came slowly (slight thaw by day, refreezing at night) over a rather prolonged period, and over most of the country there were no serious floods. There are few opportunities to study severe winters and improve snowmelt forecasting techniques. A much more frequent winter sequence in most parts of the U.K. produces a number of short-lived snow periods, each followed by a milder spell in which there may be floods with a substantial snowmelt contribution. The assessment of the danger is then more difficult. Very often there is not much time to survey the temporary snow fields, which may be largely in hilly and thinly populated areas. A major problem is simply organizational. If snow surveys of any kind are to be carried out, the teams responsible must have other work to do, as otherwise, in some winters, they would literally do nothing at all. Yet the nature of the other work would have to be such that all activity could be suspended completely at very short notice, for any period that might be necessary, whether brief or prolonged. Some progress is, however, being made, both in snow-data collection, when opportunity occurs, and in adapting to British conditions Canadian work on snowmelt computations.[14] Comprehensive instructions have been issued to those Meteorological Office stations maintaining contact with river authorities; the aim is that they should test the method as often as possible, first, as an aid to useful qualitative forecasting; next, on a trial basis and to begin with entirely within the Meteorological Office, until consistently good results can be achieved, as a means of introducing a quantitative method of forecasting snowmelt.

The meteorological contribution to short- and medium-term water resources management is for the most part not yet in a very advanced stage. Continuous efforts are being made to improve short- and medium-term weather forecasting in general, not without some success, but the quantitative rainfall element in these forecasts is certainly amongst the most difficult, perhaps the most difficult of all. Until the forecasts can be improved in quantitative rainfall terms, greatest hopes for a substantial measure of success in aiding water resources management are probably to be found in current developments in river-flow regulation. In so far as these are concerned solely with surface water the Dee investigation[11] is the most advanced in the U.K. In some other areas, including the Thames valley, recent advances have been made in studying the techniques of augmenting river flow, during periods of rainfall deficiency, by pumping from groundwater into the surface channels. For this operation, advances in short- and medium-term quantitative rainfall forecasting would undoubtedly help, but use can already be made, and has been made, of the estimated soil moisture deficit service (page 300 and Reference No. 6) in order to obtain estimates of the natural recharge of the pumped aquifer when sufficient rain has brought the soil moisture deficit to zero. It is interesting to observe that during the period when this note was being drafted (spring 1973) there was a nine-month rainfall deficiency (July to March) affecting most of the U.K., but to a specially serious degree parts of eastern England and Scotland. Deficiencies reaching or exceeding 50 per cent of the nine-month average had accumulated in some areas. For England and Wales as a whole, the deficiency was the most severe for this particular sequence of nine months, as far as can be estimated, since 1749–50. Meanwhile, soil moisture deficits which had accumulated during the summer and early autumn of 1972 had not been eliminated during the winter and were beginning to increase again (rapid increase in rates of evaporation, beginning to match even average rainfall). The subsequent rainfall, during a moderately wet two months, April and May, was of course far short of being fully effective as a contribution to available water resources, the more so in those areas with soil moisture deficits very much above the average for the time of the year. In places, even by the end of March, the excess of the deficits beyond the average amounted to 40 mm or more. The deficiency estimated from analysis of rainfall in isolation was to the same degree enhanced in the water resources sense. There was already a possibility of rudimentary hydrological forecasting, which in a limited way was put into action operationally: given certain threshold values of rainfall minus evaporation in the succeeding weeks and months, the probabilities of which could be estimated empirically from past data, it was a practicable exercise to estimate (and subsequently check) the delays, having the same probabilities, which would occur before any substantial amounts of rain could become effective either as surface water and river flow, or as contributions to groundwater. This type of exercise was in fact the basis and object of the original paper by Grindley,[15] reporting work carried out in arrear for the 1959 drought in the U.K., which led eventually to the present soil moisture deficit service.

The Storm Tide Warning Service came into being after a committee of inquiry[5] had reported its findings on the east coast floods of 1953, and made recommendations on many matters, including the future of the warning system. As at present organized the Warning Service is housed within the Meteorological Office Headquarters at Bracknell in close association with the Central Forecasting Office there, with staff provided by the Hydrographer, Ministry of Defence (Navy), whilst it is administered by the Ministry of Agriculture, Fisheries and Food, Land Drainage Division (MAFF LDD), which has responsibilities at national level covering all forms of flooding. The task of the Service is essentially to keep a continuous watch on variations from the astronomically predicted tides, and maintain close liaison with the meteorological forecasters, in order to observe and forecast the development of any significant positive variation or surge which, if associated with the predicted high tide, could lead to dangerously high levels along vulnerable coasts. The number of tide gauges used, at northern and east coast sites, has been increased to eight (see Figure 3) and the readings of these gauges are

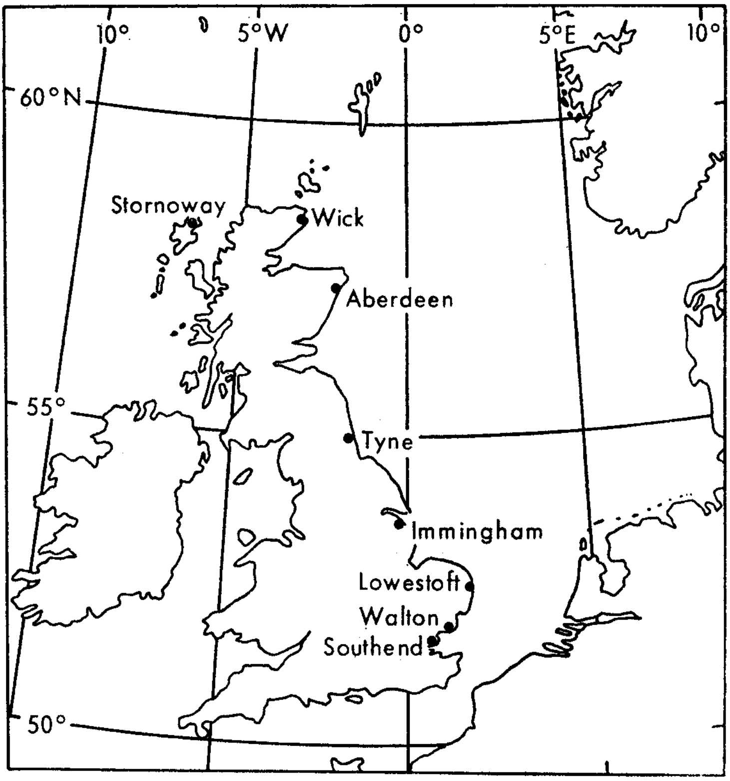

FIGURE 3—LOCATION OF TIDE GAUGES

transmitted continuously to Bracknell where they are visibly recorded on cylindrical drum charts, which already carry the curves representing the cycle of the astronomical tide. The operational season lasts from the spring tides of late August or early September to the end of April, as there is little danger in the meteorologically quieter summer months. During alerts MAFF LDD is kept fully informed and warnings are issued as necessary to the police in the areas which may be endangered, who in turn pass them on to the river authorities responsible for coastal protection. A few other authorities are also involved notably the Port of London Authority, with responsibilities extending along the entire tidal length of the river Thames and its estuary. The number of warnings issued varies greatly from season to season, according to the dominant weather types, but the following are approximate averages per season :

alerts	100
alerts subsequently cancelled	75
alerts continued as 'alert confirmed'	20
alerts leading to danger messages	5

(The alerts or danger messages are issued as necessary to any of five divisions extending from Berwick-on-Tweed to the Straits of Dover, so that more detail and more accuracy can be attempted than with a single forecast of tide levels along the whole stretch of coast.) In addition to the service for the east coast of Britain, the Storm Tide Warning Service provides information twice a day to the Netherlands (Koninklijk Nederlands Meteorologisch Instituut) and the Federal Republic of Germany (Deutsches Hydrographisches Institut). Hourly readings of the tide gauges at Aberdeen, Immingham and Lowestoft are supplied for 0400 to 0900 at 09 GMT and for 1000 to 1500 at 15 GMT. If the situation is such that a night watch is required additional messages are sent at night. The times of high and low water at Aberdeen and Immingham are also provided. In addition Denmark has shown interest and has been provided with information about the nature and organization of the Service. Papers on the scientific investigation of surges have been published.[16]

Conclusion. The current stage of development in hydrological forecasting in the U.K., and of meteorological contributions in this field, represent a very great advance on the situation about 15 years ago, though some of the developments referred to had in fact been initiated even earlier. The period selected may be viewed in retrospect as one of almost continuous activity in this field, triggered off by impressive natural events, some of which were legitimately termed disastrous, and boosted at intervals by other such events. The fact that the activity has been so fruitful, and should be even more so in the future, owes much to the development of appropriate organizational forms at national, regional and local levels, and to energetic and harmonious collaboration between organizations which, working in isolation, would be much less effective.

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REVIEWS

Times of feast, times of famine: (a history of climate since the year 1000), by Emmanuel Le Roy Ladurie (translated by Barbara Bray). 240 mm × 180 mm, pp. xvi + 428, *illus.*, George Allen & Unwin Ltd, Ruskin House, Museum Street, London, 1972. Price: £7·35.

The author of this book is professor of history at the University of Paris. He is to be congratulated on writing a fascinating, readable and very convincing book on the detailed history of climate since the Middle Ages with some, naturally less definite, conclusions concerning climate before then. He marshals his facts and sources of information in a very logical and convincing way which leaves little room for doubt that the story he unfolds is the correct one, at least for the last 400–500 years. Although concerned mainly with continental Europe, the facts he produces indicate that it is probable that the changes of climate he recounts occurred at about the same time in places as far afield as Arizona, Alaska, Iceland and Norway.

Most of the argument is based on careful assessment of the results of recent work on dendrochronology, the dates of European wine harvesting and the history of glaciers, mainly in the Alps. Professor Ladurie, however, takes nothing for granted; in almost every matter he has consulted the original records including a host of surviving documents many of which he has himself unearthed.

He gives an excellent account of the methods of dendrochronology and points out that the interpretation of tree ring data is not always easy. Different species react to different climatic effects; in the near deserts of Arizona for instance a wide ring means a wetter than usual growing season whereas in the Arctic, tree growth is sensitive mainly to summer temperature. In other parts of the world tree growth may reflect both temperature and rainfall to varying degrees and in different seasons. It is first necessary to correlate recent rings with known meteorological data before trying to establish past meteorological régimes from tree remains dug up from peat bogs, etc. Using these methods on the Bristlecone pine, Fritts in Arizona has recognized 9 climatic classes for each season and as a result each season for the last 7000+ years has been classified.

He is equally thorough in his discussion of wine harvests, noting particularly that it is not so much the latitude to which grapes can be grown that reflects the climate but rather the date on which the grapes are ready for gathering. Grape growing may be abandoned in certain areas for economic reasons but the date of ripening in a particular region is highly correlated with temperature and sunshine over the period May to September.

It is, however, in his discussion of Alpine glacier changes that Professor Ladurie comes into his own. The wealth of evidence produced from contemporary documents, engravings, etc. leaves no room for doubt that, after a period of relative glacier recession before about 1550, the glaciers advanced so far that by 1600 they had reached a stage hitherto quite unknown. With minor oscillations this stage lasted until about 1850 since when up to about 1955 at least, an even more noticeable recession has taken place. These changes are correctly attributed more to changes of summer temperature, rainfall and cloudiness than to winter temperatures. It is a pity, however, that Professor Ladurie does not give more attention to the worldwide cooling trend which has taken place since about 1955, of which he is clearly aware but on which he does not comment as regards the glaciers.

The book is also valuable in collecting together many important references and quoting much useful data. Notable in this respect are the wine harvest dates produced by Müller for Germany for every year since 1453 and the Aspen diagrams, pooling climatic information from all sources for the 11th and 16th centuries. The reviewer was also unaware of the monthly mean temperature series available since 1773 for Annecy (France). Another interesting point to the meteorologist is that these early records indicate a high frequency of sequences of years (from about 4 to 12 or 15) of similar weather types (wet summers, cold winters, etc.); the biennial oscillation is much less apparent.

One could criticize some aspects of the book, the paper is of rather poor quality which results in some of the diagrams being difficult to read, the appendices are poorly laid out and difficult to follow while some of the references to the Aspen diagrams in the text are incorrect. Also there is no Figure 31 although one is referred to in the text. The translation is excellent throughout; the only error I noted was 'meridian' for 'meridional' on several occasions in the last chapter.

Altogether I thoroughly recommend this book to anyone interested or involved in the study of the history of climate although at £7·35 I think not many will buy a personal copy!

R. A. S. RATCLIFFE

Weather forecasting for agriculture and industry, edited by J. A. Taylor. 215 mm × 155 mm, pp. xix + 250, *illus.*, David & Charles (Publishers) Ltd, South Devon House, Newton Abbot, Devon, 1972. Price: £5·75.

The arrival of an authoritative book devoted to such important subjects as the value and use of weather forecasts and meteorological services in agriculture and industry, would have been welcome any time in the past decade. In relation to the doubling of inquiries for weather advice given by the U.K. Meteorological Office during this time, and to the fresh problems involving weather-dependent aspects of agriculture and of industry likely to arise as a result of Britain's entry to the E.E.C., the timing of this publication of seventeen papers, presented during the 1971 Symposium of the University College of Wales, Aberystwyth on these subjects, has been a particularly happy one. Each paper has a chapter to itself and was written and delivered at the Symposium by an acknowledged authority on the topic under discussion. So for the most part the writers' findings and proposals can be endorsed with enthusiasm and confidence.

The first eight chapters are concerned with weather and climate forecasting over a wide range of time scales mainly for agricultural purposes. Suggestions for reorganizations of current priorities in our meteorological services recur through the themes developed by these authors, such as the urgent need to improve forecasts of timings of onset and cessation of rainfall in particular districts, and the need to improve the present 30-second coverage of the television weather map which is minimal by its own standards and by several international comparisons. Some writers emphasize the potential value of regular weather forecasts and weather summaries for one week ahead intended specifically for farmers. A most valuable section (pages 46–49) discusses 'the present state of the art' of forecasting and the agronomic uses of forecasts and goes on to consider the value for horticultural activities in numerous instances of forecasts on the five-day, five-month and five-year time scales. In years to come operational forecasters and scientists responsible for planning and administering national forecast services in many countries can well afford to peruse this book at frequent intervals, with advantage and profit to all concerned.

Weather forecasting for industry is concisely dealt with by Mr R. A. Buchanan in a fascinating chapter where he puts in a strong plea for better two-way communication between meteorologists and industrialists. While he leaves the reader in no doubt that the Meteorological Office has many satisfied customers (like the owner of a chain of both fish restaurants and ice-cream shops), it seems a pity that this section scarcely mentions the actual or possible impact of long-range (monthly) forecasts upon industrialists, and that (apparently) no detailed questionnaire has yet been addressed to industrialists, similar to the questionnaire sent to and answered by farmers and growers as described in Chapter 6 and its Appendix.

Longer-range weather and climate forecasting are treated by Professor H. H. Lamb in Chapter 3 in some detail, including a discussion of changes in temperature and rainfall known to have occurred over Britain through nearly three centuries with instrumental records. The probable increase of about 30 days in the length of the growing season between the periods 1680–1700 and 1920–50, and its subsequent slight decrease, sets the problem of climatic change in perspective for agriculturists and other students of human affairs. While techniques used in the Meteorological Office for monthly forecasts are described in detail, the problems of seasonal forecasting receive no mention and climate forecasting for several years ahead, a subject of such vital interest to agriculturists, is dealt with in a single paragraph. The potential importance of climatic forecasting on the scale of 5 to 10 years or longer is however considered by some of the other authors, notably in connection with the design of new reservoirs (Chapter 4), and in connection with actual and possible changes in land use, either in marginal lands on the threshold of unfavourable climates, or due to political pressures caused by population explosions in some tropical countries, or by social–political changes such as those engendered by Britain joining the E.E.C. with its differences in agricultural techniques between the member states.

Although in the preface it is stated that the use of weather forecasts in agriculture and industry is dealt with in particular relation to Britain, it seems unfortunate that so little attention is paid by the contributors in this book to similar uses of forecasts in other countries, particularly those of the third world. This omission weakens a statement in the foreword that 'the contributions to the present volume . . . represent the essential first steps towards the definition, if not the solution of problems of increasing significance in a hungry world'. The broader treatment by Professor A. N. Duckham of the forecasting of biological consequences and of land use reassessment likely to arise due to meteorological and economic factors in tropical and subtropical regions, provides a welcome exception to this situation.

Two loosely written paragraphs on 'climate' and 'standard weather pattern' on pages 87–89, hardly deserve their inclusion in an otherwise interesting chapter. Fog on motorways which receives a lengthy mention in the preface, is not discussed again, except in a few words on page 116. Perhaps less surprising is the paucity of references to any recent original work on weather forecasting to be found in the selected bibliography for Chapter 12 on page 231, partly reflecting the present dominance of the computer in this field. However, should even a few of the suggestions in this book be adopted for bringing forecast services more closely in line with consumer requirements, then indeed the cost/benefit ratio on any national scale should be a high one. Such benefits, deriving indirectly from purchasers and readers of this book, whether impelled by official or by amateur interests in this field, should ultimately make a real and lasting contribution to human welfare in many lands.

R. F. M. HAY

NOTES AND NEWS

CLEAR-AIR TURBULENCE

Pilots' reports collected during the Spring (1972) investigation of clear-air turbulence have been stored on magnetic tape. They cover over 750 000 km of track at cruise level and allow the proportion of bumpy flight to be compared with indices calculated on the Bushby–Timpson fine-mesh 10-level model. Two indices are being tried at present; one assesses the rate of reduction of the Richardson number in a fluid element as it moves in a deforming flow, and the other assesses the rate of dissipation of turbulent energy made available by larger-scale deformation.

OBITUARY

It is with regret that we have to record the death of Mr J. M. Smith, Senior Scientific Officer, Met O 12, on 3 June 1973.


66,000 FT.

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MR P. J. MEADE, O.B.E.

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THE METEOROLOGICAL MAGAZINE

Vol. 102, No. 1216, November, 1973

RETIREMENT OF MR P. J. MEADE, O.B.E.

On the retirement of Mr P. J. Meade, O.B.E., as Director of Services and Deputy to the Director-General, on 30 September 1973, after 37 years of distinguished service, the Office lost one of its most effective and influential figures of the post-war era.

Patrick Meade joined the Office in 1936 after graduating from Imperial College with first-class honours in mathematics and receiving the Lubbock Memorial Prize of London University. He began his meteorological career at the Empire Flying Boat Base, Hythe (Hants), joined the Reserve of Air Force Officers (Meteorological branch) in 1937 and, in 1939, entered on a period of distinguished war service with appointments as Senior Meteorological Officer, G.H.Q. Home Forces, Chief Meteorological Officer, Mediterranean Air Forces, and Chief Meteorological Officer, Air Command South East Asia. His outstanding work for the Allied Air Forces in North Africa and Italy, where he achieved a high degree of co-operation with the 15th U.S. Air Force, was recognized by the award of the O.B.E. in 1944.

After leaving the RAF in 1947 with the rank of Group Captain, Mr Meade returned to the Office as Personal Staff Officer to the Director, Sir Nelson Johnson, and in 1948 became Head of the Training School, first at Alexandra House and later at Stanmore.

There then followed a series of important appointments and rapid promotions. He was Chief Meteorological Officer, London Airport, from 1952 to 1955 during a period of rapid expansion of civil aviation. In 1955 he was promoted to Assistant Director in charge of Special Investigations which, at that time, were much concerned with radioactive fall-out from nuclear weapons and atmospheric pollution. Here Meade made good use of his first real opportunity to carry out sustained research and investigations, and when he was nominated for the Imperial Defence College in 1958 it was clear that he was destined for higher things.

During the last seven years his outstanding qualities of leadership, initiative, foresight and drive have been of crucial importance to the Office during a period of rapid change and modernization. He has been largely responsible for the successful and smooth introduction on a routine basis of computer methods of weather forecasting which has led to wholesale reorganization and centralization of the meteorological services and the re-training of large numbers of staff in new techniques and methods of working. Despite the heavy load imposed by all these new developments and the day-to-day responsibility of directing more than 3000 staff, Mr Meade has found the time and energy to play a very prominent part on the wider international scene. His work in WMO as Chairman of the Executive Committee Panel on Ocean Affairs, and his efforts at both national and international level on behalf of hydrometeorology will have a lasting influence in strengthening the links between these two disciplines and meteorology. Mr Meade has also been deeply involved from the very beginning in the proposals to establish a European Centre for medium-range weather forecasting, his efforts being crowned by the decision to locate this at Shinfield Park, near Reading.

In the last year or two he has devoted much of his energy and advocacy towards ensuring a continuance of the North Atlantic Ocean Station scheme after the existing agreement expires in 1975 and to preparing a case for the Office to build new ships.

All this adds up to an outstanding record of activity and accomplishment which will leave its imprint for many years to come. Meteorology in general, and the Office in particular, owes Patrick Meade a great debt. Much of his achievement is already visible; the rest provides us with a firm foundation on which to build in the future.

Mr Meade's many colleagues and friends, at home and abroad, will, I know, join me in wishing him and Mrs Meade a long, active and happy retirement.

B. J. MASON

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SOME MEASUREMENTS OF CUMULONIMBUS TOPS IN THE PRE-MONSOON SEASON IN NORTH-EAST INDIA

By S. G. CORNFORD and C. S. SPAVINS
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Summary. The heights of some cumulonimbus clouds forming during the pre-monsoon season in north-east India have been carefully measured using airborne radar, cameras and horizon gyroscopes. They were found to extend up to at least 65 000 ft (20 km). One top rose at 1200 ft/min (6 m/s) from an initial height of 60 000 ft. The best indicator of the heights of such storms was the parcel-theory top. At the equilibrium level some parcel-theory updraughts exceeded 100 m/s. High tops may be more frequent in the area than ground-based radar observations have indicated.

Introduction. The severe local convective storms of Bengal and neighbouring parts of the Indian subcontinent are of concern to the inhabitants, shipmasters,[1] aviators[2,3] and meteorologists[3–9] alike. Occurring mostly in the pre-monsoon period from April to early June, the storms usually approach the densely populated area around Calcutta from between west and north-west and are first felt as a squall from that direction. These nor'westers occur in a geographical situation similar to that of the severe local storms in the United States of America, where an extensive dry continental area has a bay of warm sea lying to the south and south-east. In the United States severe local storms are known to reach heights of over 60 000 ft (18 km)[10,11] and to extend into the stratosphere by 20 000 ft or more.[10] This paper reports measurements of similar heights for storm tops in north-east India, based on the use of an airborne radar and camera system and amplifies an earlier report by Spavins.[12] The highest top measured was at 65 000 ft (20 km).

Storm tops at such high levels need to be avoided by cruising supersonic airliners. The pilot's main cue to a storm ahead will be an echo seen on his radar screen. Some of the work on turbulence associated with storm tops has been directed towards relating such echoes and the safe boundaries of storms. Burnham and Spavins have established that turbulence may extend into the clear air for up to 15–20 miles (25–30 km) around a visible storm and up to 5000–10 000 ft ($1\frac{1}{2}$–3 km) above its top.[13,14]

This paper also reports some measurements of visible storm tops and the tops of corresponding radar returns seen from an aircraft close to the storm and from the ground.

There are several quantities which forecasters could supply and which pilots could use to judge whether a storm seen ahead on the aircraft's radar will be high enough to obstruct the projected flight path. As in Roach's study for the U.S.A.[10] the highest tops reported here usually approached the level predicted by the parcel theory. In determining that level practically, though, it was necessary to find which of the local surface temperatures and humidities were most appropriate.

Bhattacharyya and De[15] and Rakshit (private communication) have summarized regular observations made with a radar at Dum Dum Airport, Calcutta. These observations are compared with the present measurements.

Observations.

(a) *Equipment.* A DC-3 aircraft, operated by Fairey Surveys Ltd on behalf of RAE Bedford, was fitted with a motorized single-lens reflex Hasselblad camera to photograph the clouds. The camera was fixed, pointing forward and horizontally when the aircraft was flying in a normal attitude. Its nominal focal length of 80 mm was checked at RAE Farnborough and found to be correct to within less than 0·1 mm. A similar camera was used to photograph the outputs of other specially fitted instruments: the PPI (Plan Position Indicator) display of a gyroscopically stabilized, forward-facing, 31-mm radar; the angle of tilt of the radar; a clock showing Greenwich Mean Time and a counter. Other gyroscopes measured the pitch and roll attitudes of the aircraft and so provided a reference horizon to be used in interpreting the cloud photographs. The output from these gyroscopes was recorded on a galvanometer oscillograph, together with pressure height, indicated airspeed, normal acceleration, elapsed time, and synchronization pulses. The tops of some storms were also measured from the ground using the 31-mm radar at the meteorological office at Dum Dum Airport. The characteristics of this radar and of the airborne radar are listed in Appendix I.

(b) *Period and area of operation.* Between 12 May and 3 June 1969 15 flights from Dum Dum Airport, Calcutta, yielded useful information on 51 storms. All the measurements were made between 1319 and 1810 Indian Standard Time (IST). The storms were in the area shown in Figure 1.

(c) *Observational routine.* The aircraft was flown on days when the forecasters at Dum Dum expected cumulonimbus within about 550 km (300 nautical miles) to the north and west of Calcutta. In the area where the biggest clouds seemed likely the pilot tried to select a large isolated storm and to fly straight towards it at a height of about 6 km (20 000 ft) and from 55 to 75 km (30 to 40 n. mile) on the upwind side. Observations were usually completed when the aircraft was more than 40 km from the storm. In most

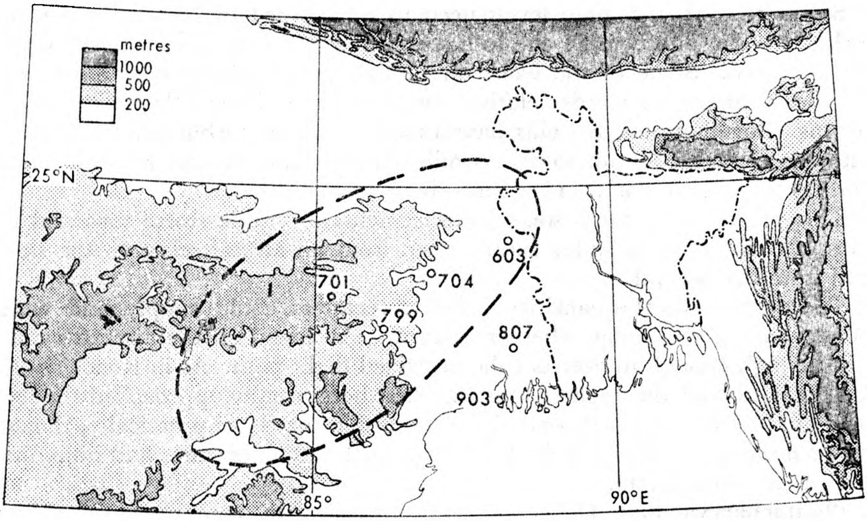

FIGURE 1—MAP SHOWING THE AREA OF OPERATIONS OVER NORTH-EAST INDIA

All the measured storms were in the area enclosed by the heavy pecked line. The six stations are those used to give the regional temperatures and humidities discussed in the section dealing with comparison of the measured storm tops with heights given by some commonly used techniques. They are

603	Berhampore	19 m	799	Jamshedpur	131 m
701	Ranchi	652 m	807	Calcutta	6 m
704	Asansol	126 m	903	Saugor Island	3 m.

instances the pilot then chose another cloud to study, though sometimes several measurements were made of the same cloud. In each case simultaneous photographs were taken of the cloud and of the PPI display of the radar with its scanner horizontal (see Plate I). The scanner was then tilted down until the return from the ground beyond the storm could be photographed and afterwards raised in one-degree steps until the return from the storm disappeared. A photograph of the display was taken with the scanner in each position to give a series of nearly horizontal sections through the depth of the storm (see Plate II — the operator was instructed to allow the afterglow from the paint at one elevation angle to die away before photographing the echo made with the scanner at the next higher angle). Finally, the scanner was returned to the horizontal and simultaneous photographs were again taken of the radar display and the cloud (see Plate III). The whole sequence usually took less than two minutes.

(d) *Analysis of photographs.* From the photographs of the cloud and the radar display the heights of the storm tops were deduced by the method described in Appendix II. Fundamentally the radar was used to give the horizontal range of the storm and the cloud photograph was used to measure the angular elevation of the storm top above the aircraft. Corrections were made to allow for the pitch and roll attitudes of the aircraft and for the curvature of the earth but not for any leaning of the cloud towers. The geometric height of the aircraft was deduced from its pressure height and the

D-value* calculated from the afternoon radiosonde ascent from Dum Dum.

The height of the top of each visible cloud at the beginning and end of each run was assessed separately by two analysts. Their agreed results are listed in columns 4 and 5 of Table I.

The 'radar height' for each storm top was derived from the sequence of photographs taken as the scanner swept in one-degree steps from the bottom to the top of the storm and is shown in column 6.

The errors of the various measurements are assessed in Appendix III. The random error of a single entry in columns 4 and 5 of Table I is about ± 1500 ft (450 m), unless a greater error is indicated by columns 7 and 8. The figures in these two columns are due to a third analyst who re-assessed the data, knowing the first assessment. His check was especially useful in finding possible gross errors arising from interpretation of the photographs. His figures have been adjusted slightly to allow for the D-value correction and the correction for the curvature of the earth.

All the visible tops are probably slightly underestimated because of a systematic effect of attenuation of the 31-mm radar beam in precipitation. This will have produced an apparent shift of the centre of strong echoes towards the radar. It is not easy to assess the size of the shift. One of a mile or two would be equivalent to an underestimate of from 2000 to 4000 ft (600–1200 m) in the cloud top.

The underestimate has not been allowed for in deciding on a 'highest agreed measured cloud top' (Z_s) which is tabulated for each day in column (vii) of Table II. The percentage frequency with which Z_s equalled or exceeded various heights is shown in Figure 2. On arithmetic-probability axes, Figure 2 also shows the percentage frequency with which the highest radar measurement, Z_r, made by the aircraft each day equalled or exceeded various heights. Both Z_s and Z_r fit a normal distribution quite well. However, although the median Z_r is below the median Z_s, the Z_r curve is much steeper. This is thought to be caused by the greater errors in measuring Z_r.

The heights of the tops of the visible clouds have been used to assess the average rate of rise during the two minutes or so of each run. Each height is, of course, an absolute measurement and the change is the small difference between two large quantities. However, each height was initially determined independently by two different analysts and then by the third. The agreement between the three of them as to the sign and magnitude of the change of storm height is encouraging, with a mean difference between the first two analysts of 60 ft/min (0·3 m/s) and a standard deviation about that mean of 600 ft/min (3 m/s).

The variation of rate of rise (and sink) has been examined both with initial height and with initial depth below the parcel-theory top, Z_p. In both instances there was no relationship. They showed, however, as is natural if the tallest tops were chosen, that there was a slight tendency for tops to sink during the run.

The greatest rate of rise measured when all three analysts agreed on the height of the storm top was 1700 ft/min ($\pm$600 ft/min) from an initial height of 57 000 ft. A rate of 1200 ft/min (6 m/s) was measured from an initial

* The D-value is the difference, D, between the actual height, Z, above mean sea level, of a particular pressure surface and the pressure altitude, Z_p (the height of the same surface in the International Civil Aviation Organization Standard Atmosphere) i.e. $D = Z - Z_p$.

TABLE I—COMPARISON OF STORM TOP HEIGHTS IN NORTH-EAST INDIA IN THE PRE-MONSOON SEASON OF 1969 AND VARIOUS PREDICTORS, IN THOUSANDS OF FEET

1 Date and flight number	2 Time IST	3 Storm identification letter	4 Photogrammetric height, 1st assessment. Start of run	5 Photogrammetric height, 1st assessment. End of run	6 Aircraft radar height	7 Photogrammetric height, Ludlam's assessment. Start	8 Photogrammetric height, Ludlam's assessment. End	9 Radar height of top, measured from ground at Dum Dum	10 Z_p 1730 IST	11 Z_e 1730 IST	12 Height of tropopause 1730 IST	13 Highest top given in forecast
12 May	1633	A	42	41	44	Tops at 63 to 61 in storm behind A		—				
(2)	1655	B	64	63	57	As col. 4	Doubtful of col. 5	—	61	49	55	39
	1702	C	—	55	53	As col. 4	Doubtful of col. 5	—				
	1810	D	61	—	58	As col. 4	—	—				
13 May	1646	E	—	—	62	—	—	—				
	1655	F	—	—	39	—	—	—				
(3)	1704	E	—	—	50	—	—	—	65	51	54	46
	1723	F	—	—	39	—	—	—				
	1735	G	—	—	45	—	—	—				
	1747	F	—	—	53	—	—	—				
16 May	1532	H	58	62	54	Fuzzy dome, reliably about 62		—				
	1538	I	62	65	55	As col. 4	Doubtful of col. 5	—				
(5)	1546	I	59	68	53	As col. 4	Doubtful of col. 5	—				
	1622	J	54	54	56	As col. 4	34	—				
	1630	J	— See note 3	—	45	55	59	—				
	1638	J	55	56	53	Main top around 60		—	67	53	55	30
	1647	J	56	53	49	51	As col. 5	—				
	1658	J	57	58	56	As col. 4	As col. 5	—				
	1708	J	56	54	55	As col. 4	As col. 5	—				
	1718	J	56	57	57	As col. 4	As col. 5	—				
	1722	K	52	53	43	Doubtful of col. 4	Doubtful of col. 5	—				
	1733	J	51	54	51	As col. 4	As col. 5	—				
17 May	1533	L	46	43	40	49	50	—				
	1554	M	51	55	44	As col. 4	As col. 5	—				
(6)	1602	M	54	—	51	As col. 4	—	—				
	1613	N	60	55	58	As col. 4	As col. 5	—	64	51	55	33
	1630	N	54	49	41	As col. 4	Doubtful of col. 5	—				
	1645	N	50	47	45	51 is anvil, tops may be higher		—				
	1659	N	47	45	36	63 (different storm from cols. 4 & 5)	58	—				
19 May	1610	O	58	54	47	As col. 4	As col. 5	—				
	1613	P	—	43	38	—	As col. 5	—				
(7)	1623	O	56	55	52	As col. 4	As col. 5	—				
	1650	O	60	57	57	As col. 4	As col. 5	—				
	1700	O	—	—	—	—	—	30*	63	53	52	Cb forecast. Tops not given
	1702	Q	—	—	53	—	—	—				
	1726	Q	—	—	49	—	—	—				
	1730	Q?	—	—	—	—	—	36*				
	1730	R	—	—	48	—	—	—				
	1754	Q	53	51	46	As col. 4	As col. 5	—				

1	2	3	4	5	6	7	8	9	10	11	12	13
20 May	1551	S	—	—	47	—	—	—				
	1600	T	—	—	45	—	—	—				
(8)	1609	U	—	—	48	—	—	—	67	54	53	39
	1617	T	—	—	40	—	—	—				
	1635	V	—	—	48	—	—	—				
21 May	1427	X	61	61	68	As col. 4	As col. 5	—				
	1440	X	61	61	61	Slight doubt about both		—				
(9)	1452	Y	46	43	43	As col. 4	As col. 5	—				
	1504	X	57	58	62	As col. 4	As col. 5	—	69	55	53	46
	1516	X	61	57	59	As col. 4	Doubtful of col. 5	—				
	1527	X	60	60	63	As col. 4	Doubtful of col. 5	—				
	1638	Z	55	54	40	As col. 4	As col. 5	—				
22 May	1345	A_2	51	52	53	As col. 4	As col. 5	—				
	1409	B_2	46	46	38	As col. 4	As col. 5	—				
(10)	1425	A_2	35	35	36	As col. 4	As col. 5	—				
	1430	B_2	—	—	—	—	—	23*				
	1435	A_2	52	53	49	As col. 4	As col. 5	—				
	1440	B_2	57	58	56	As col. 4	As col. 5	—				
	1449	B_2	—	—	—	—	—	> 30, <46**	68	55	55	39
	1450	A_2	—	—	—	—	—	> 35**				
	1455	B_2	67	64	64	65	62	—				
	1510	B_2	—	—	—	—	—	28*				
	1526	B_2	60	61	62	As col. 4	As col. 5	—				
	1542	C_2	57	57	59	As col. 4	As col. 5	—				
	1546	B_2	60	61	60	60	62	—				
23 May	1348	D_2	46	46	45	As col. 4	As col. 5	—				
	1410	E_2	60	61	71	62	63	—				
(11)	1421	F_2	57	57	57	As col. 4	As col. 5	—				
	1425	F_2	—	—	—	—	—	43*				
	1431	F_2	—	—	—	—	—	> 31, <50**				
	1431	G_2	—	—	—	—	—	> 36, <56**				
	1432	E_2	—	—	—	—	—	> 47**				
	1434	F_2	—	—	—	—	—	43*				
	1434	G_2	57	58	55	As col. 4	As col. 5	—	61	50	55	Cb forecast Tops not given
	1437	G_2	—	—	—	—	—	> 33, <59**				
	1441	G_2	—	—	—	—	—	43*				
	1443	E_2	66	64	57	Doubt values in cols. 4 and 5		—				
	1445	G_2	—	—	—	—	—	> 39**				
	1447	E_2	—	—	—	—	—	53*				
	1505	E_2	—	—	—	—	—	54*				
	1550	H_2	57	56	53	58	As col. 5	—				
	1600	H_2	—	—	—	—	—	46*				
	1612	H_2	58	58	53	As col. 4	As col. 5	—				
28 May	1319	I_2	56	58	56	As col. 4	As col. 5	—				
	1334	I_2	61	64	59	As col. 4	Doubtful of col. 5	—	64	52	55	39
(14)	1353	I_2	58	56	55	Doubtful of cols. 4 and 5		—				
30 May	1612	J_2	—	35	36	—	—	—	65	52	55	39
(15)	1616	J_2	37	37	39	—	—	—				

TABLE I—*continued*

1 Date and flight number	2 Time IST	3 Storm identification letter	4 Photogrammetric height, 1st assessment. Start of run	5 Photogrammetric height, 1st assessment. End of run	6 Aircraft radar height	7 Photogrammetric height, Ludlam's assessment. Start	8 Photogrammetric height, Ludlam's assessment. End	9 Radar height of top, measured from ground at Dum Dum	10 Z_p 1730 IST	11 Z_e 1730 IST	12 Height of tropopause 1730 IST	13 Highest top given in forecast
31 May	1434	K_2	41	43	42	As col. 4	As col. 5	—				
	1440	L_2	49	49	41	Doubtful of cols	4 and 5	—				
(16)	1454	L_2	52	50	46	As col. 4	As col. 5	—				
	1521	M_2	58	53	54	As col. 4	As col. 5	—	62	50	55	33
	1530	M_2	—	—	—	—	—	40*				
	1540	M_2	71	> 77	63	Doubtful of cols.	4 and 5	—				
	1602	N_2	55	55	54	As col. 4	As col. 5	—				
	1631	O_2	49	55	50	As col. 4	As col. 5	—				
	1636	O_2	53	53	53	As col. 4	Doubtful of col. 5	—	62	50	55	33
	1652	N_2	58	57	54	As col. 4	As col. 5	—				
	1718	P_2	56	54	55	As col. 4	As col. 5	—				
	1732	P_2	52	51	47	As col. 4	As col. 5	—				
1 June	1356	Q_2	55	54	59	57	56	—				
	1406	R_2	60	63	62	As col. 4	Doubtful of col. 5	—				
(17)	1424	S_2	59	63	61	As col. 4	As col. 5	—				
	1432	Q_2	59	59	61	As col. 4	Slightly doubtful of col. 5	—	65	53	55	39
	1509	S_2	66	65	68	65	64	1500–1520: Tops in same area 56–66*				
2 June	1424	T_2	53	52	53	As col. 4	As col. 5	—				
	1438	T_2	57	57	51	Doubtful of cols.	4 and 5	—				
(18)	1509	U_2	53	51	47	As col. 4	As col. 5	—				
	1634	W_2	56	58	54	As col. 4	Doubtful of col. 5	—	67	54	55	46
	1648	W_2	—	—	—	—	—	54*				
	1648	X_2	—	—	—	—	—	> 47**				
	1703	X_2	55	56	48	Slight doubts about cols.	4 and 5	—				
3 June	1405	Y_2	60	61	53	As col. 4	Doubtful of col. 5	—				
	1417	Z_2	61	54	48	Doubtful of cols.	4 and 5	—				
(19)	1430	Z_2	61	63	52	Slight doubt about col. 4	Doubtful of col. 5	—	67	55	55	Cb forecast Tops not given
	1509	A_3	60	57	41	As col. 4	As col. 5	—				

Notes : (1) In column 3 a question mark denotes some doubt about whether the ground and aircraft measurements refer to the same storm.
(2) In column 9 a single asterisk denotes that the measurement was made by the usual method employed at Dum Dum. A double asterisk denotes a top deduced from a sequence of PPI photographs taken at 1-degree intervals of scanner elevation.
(3) The different analysts selected different storms on the photographs for 1630 IST on 16 May. No meaningful average is possible.

TABLE II—PARCEL-THEORY HEIGHTS OF STORM TOPS Z_p, CALCULATED USING DIFFERENT TECHNIQUES

Date	Manual tephigram construction	Roach & James's original program		Roach & James's program modified to use regional mean surface data lifted by 30 mb		Highest agreed measured storm top, Z_s	Updraught at level Z_e from Roach & James's modified program
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
	1730 IST	0530 IST	1730 IST	0530 IST	1730 IST		1730 IST m/s
12 May	61	57	53	63	63	64	68
13 May	65	⩽50	53	63	>65	—	97
16 May	67	63	>65	63	63	62	78
17 May	64	>65	63	>65	63	60	92
19 May	63	63	63	>65	63	60	86
20 May	67	57	63	63	>65	—	95
21 May	69	63	>65	>65	>65	61	104
22 May	68	63	57	>65	>65	65	106
23 May	61	57	63	63	63	61	66
28 May	64	63	57	63	63	61	83
30 May	65	⩽50	57	63	>65	37	95
31 May	62	57	57	63	63	58	68
1 June	65	⩽50	57	>65	63	65	77
2 June	67	⩽50	57	63	63	58	86
3 June	67	57	63	>65	>65	60	99

In columns (ii) and (vii) heights are given in thousands of feet.

In columns (iii), (iv), (v) and (vi) heights are indicated according to the following code :

⩽50	$Z_p \leqslant 50\,000$ ft (15·2 km)
53	50 000 ft $< Z_p \leqslant 55\,000$ ft (16·7 km)
57	55 000 ft $< Z_p \leqslant 60\,000$ ft (18·2 km)
63	60 000 ft $< Z_p \leqslant 65\,000$ ft (19·8 km)
>65	65 000 ft $< Z_p$

height of 60 000 ft (18 km). No tops above 60 000 ft (or nearer to Z_p than 4000 ft below it) subsequently rose.

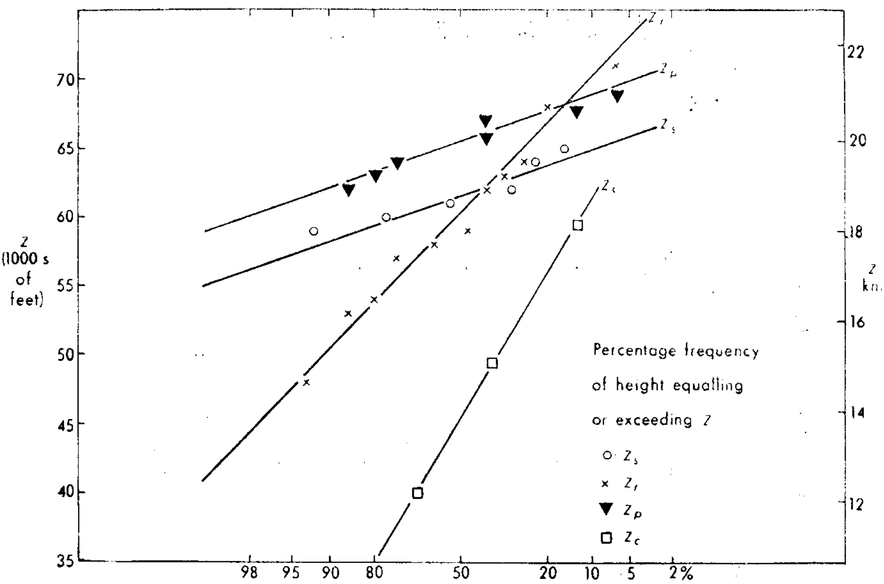

FIGURE 2—RELATIVE FREQUENCY OF TOPS EXCEEDING SPECIFIED HEIGHTS

Z_s is the highest agreed measured storm top for each of the 13 days of flights (see col. (vii) of Table II).
Z_p is the parcel-theory storm top for days of flights, found by hand.
Z_r is the highest echo top measured with the airborne radar on days of flights.
Z_c is the climatological highest daily echo top for May from ground-based radar data due to Rakshit.

Measurements made from the ground. The heights of the tops of some storms were measured from the ground using the 31-mm radar at Dum Dum Airport. (The characteristics of this radar are listed in Appendix I). The measurements are listed in column 9 of Table I. Those marked with a single asterisk were measured by the technique used as routine at Dum Dum. Those marked with two asterisks were estimated using PPI photographs at one-degree intervals of scanner elevation. Mostly, the tops are lower than the radar tops measured from the air. In 16 of the 20 measurements the storm was 200 km or more from Dum Dum, so that accurate height finding by the radar might not be expected. On 31 May, though, storm M_2 was only 30 to 40 km away so that the measurement of 40 000 ft at 1530 IST might have been expected to be accurate. Measurements from the air show a growth of the radar echo top from 54 000 ft at 1521 to 63 000 ft at 1540 IST. Allowing for half-beam-width corrections and other effects, the lowest likely air measurement for 1521 would be 47 000 ft and for 1540 IST 56 000 ft. The measurements from the ground and the air are not synchronous, however, and it is possible that the top may have subsided between 1521 and 1530 IST. Photographs of the visible cloud show that it was developing into its mature stage and it seems much more likely that synchronous observations would have shown a discrepancy between the ground and air observations of between 10 000 and 20 000 ft. Such discrepancies are not understood, especially as measurements of the height of the survey aircraft using both PPI and RHI gave differences not exceeding 1 km (3300 ft) at ranges up to 100 km and at aircraft heights of up to 5 km (16 500 ft). No storm had its top underestimated because of attenuation by other storms intervening between it and the ground radar.

Overall it must be concluded that the agreement between the ground and airborne radar observations is poor. The reason is not known.

Comparison of the measured storm tops with heights given by some commonly used techniques. The measurements were made primarily to provide information for aviators. From one planning point of view it is enough that the occurrence of storms at certain heights should be established beyond doubt. From another, extrapolation from the measurements towards a climatology of storm tops is desirable. Because of the way in which the storms were necessarily chosen, the present data cannot be used in a statistically meaningful way. However, the possibility of deriving a climatology indirectly is discussed later. Another aviation requirement, though, is for assessments of the likelihood of tops exceeding certain levels on a particular flight in the near future. Since such forecasts would be based on data available as routine to the forecaster, the measurements of visible tops have been compared with three quantities derived from routine radio-soundings (see columns 10, 11 and 12 of Table I).

The tropopause (column 12) was penetrated by storms on every flight (except flight 15 on 30 May, when there was comparatively little convective activity). The level Z_e (column 11) was similarly exceeded. This is the equilibrium level of the so-called 'parcel theory'[10,16] at which buoyancy is reduced to zero (see Figure 3). In the United Kingdom it is often used as a guide to the height of the tallest air-mass convective clouds. In parcel theory, where no entrainment is envisaged however, Z_e is the level of maximum updraught. To calculate Z_e, the tropopause height and the updraughts at Z_e (also listed for convenience in Table II), the sounding at 1730 IST from Dum Dum was used. A temperature representing the air near the ground during the afternoon was found from the mean of the maximum temperatures measured at the six stations shown in Figure 1. A representative humidity mixing ratio was found from the dew-points reported by these stations at 1730 IST. In making the tephigram constructions it was found that these regional temperatures and humidities sometimes would have failed to release convection. As deep convection usually starts over the hills and a comparison of average daily maximum temperatures at Ranchi (652 m), Jamshedpur (131 m) and Asansol (126 m) in May and June showed that surface temperatures there fall with height at less than half the dry adiabatic lapse rate, it seemed appropriate to use the regional temperatures at a lower surface pressure. It was found that by attributing them and the regional humidities to a pressure 30 mb less than that at Dum Dum convection was always released. It is noteworthy that the sounding for 0530 IST gave a similar Z_e (and Z_p) on all occasions except one where a major change occurred between 0530 and 1730 IST.

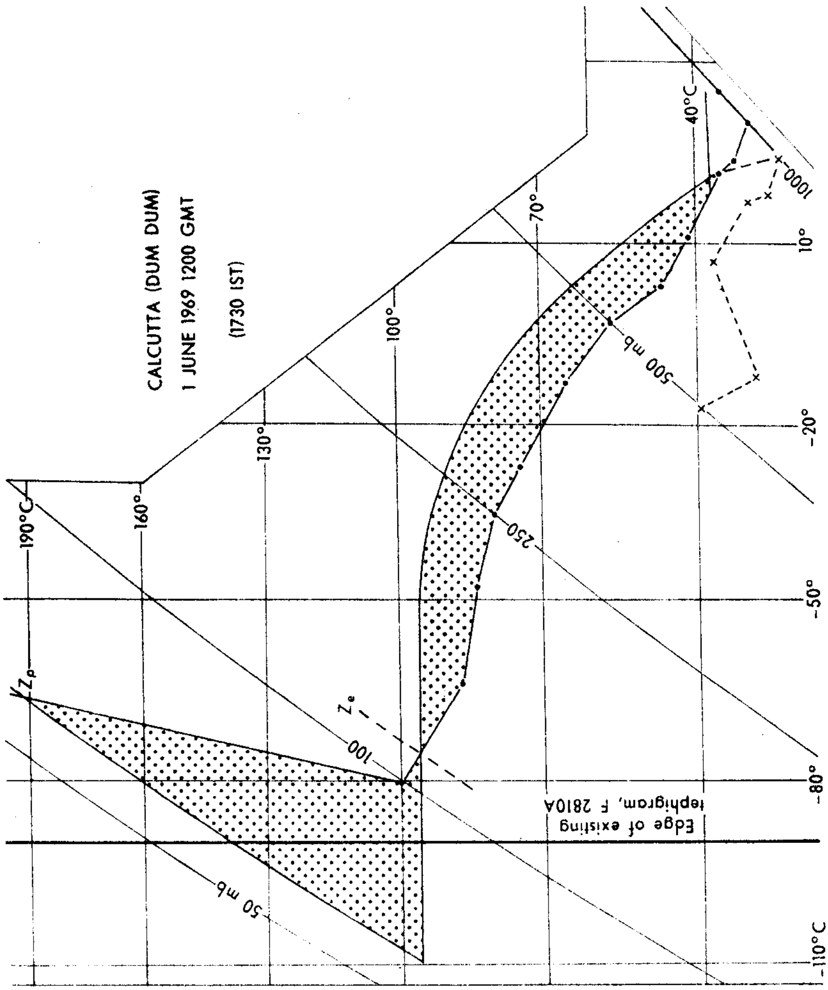

FIGURE 3—SCHEMATIC TEPHIGRAM FOR THE AFTERNOON WHEN STORM S_2 WAS MEASURED ON FLIGHT 17
Environment and ascent curves are shown. Z_e and Z_p are the parcel-theory equilibrium and storm top levels.

The tephigram was also used to estimate the parcel-theory top of the storm Z_p (see Figure 3). This was found to be nearer the heights of the highest tops observed each day than Z_e or the tropopause; if the measurements of visible tops on which all three analysts did not agree are eliminated, then on only 1 occasion out of 13 was Z_p exceeded (by 3000 ft). On 11 of these occasions the highest top rose to within 9000 ft of Z_p. In this set of data, however, there is no significant statistical correlation between the highest observed top on a given day, Z_s, and Z_p for that day. Perhaps none should be expected because of the narrow spread in both quantities and the way the clouds were selected. Although the pilot would probably choose the highest storm he could see, it is unlikely that he could choose to study the storm that was destined to be the tallest that afternoon and even less likely that he would work on it when it was at its tallest. On the other hand this comment would be less valid if many storms reached the same highest level, as Ludlam and Saunders[17] found with cumulus in Sweden.

Before each flight the pilot received a forecast for his general area of operations which in most cases included a statement of the expected heights of the highest cumulonimbus tops. These heights are listed in column 13 of Table I. The high tops that were measured were clearly not expected. In passing it may be noted that neither the tephigram used at Dum Dum Airport nor any in use in the U.K. Meteorological Office would have allowed forecasters to make the construction to find full parcel-theory tops for these occasions without an extension of the diagram.

Use of Z_p to assess the probability of high tops. Roach and James[18] have used radio-soundings from selected parts of the world to calculate the proportions of occasions on which Z_p falls in selected height bands in different months of the year. For the initial state of the buoyant parcel they used surface temperature and humidity data at the sounding station. They gave some weight to temperature and humidity at 850 mb and ignored any negative area at low levels which would have inhibited convection from the ground altogether. At all times of year storms in this area (apart from cyclones) are locally convective and so Roach and James's computer program has been modified to use for the initial state of the parcel the regional mean afternoon temperatures and humidities referred to in the previous section. Applied to air with a pressure 30 mb less than that at Dum Dum these values lead to the distribution of Z_p shown in Figure 4. From a comparison with Z_p for the days of flights, it can be seen that observations were made on days whose median Z_p is 9000–11 000 ft (3 km) higher than at Calcutta for May and June in 1961–66*. Flights were made on 15 days or 15/61 ($\approx\frac{1}{4}$) of the days in May and June. Z_p for this one-quarter of a May and June exceeded 62 000 ft, and it can be seen that the top one-quarter of the climatological curves also exceeds that height. The coincidence is notable and implies

**Note.* This comparison is worth less than one would wish because a new type of radiosonde was used from 1 May 1968. The new sonde allocates temperatures to higher pressures than did the one used in 1961–66. Fortunately Z_p is insensitive to this change as it depends on both the tropospheric lapse and the stratospheric inversion. A comparison of some monthly mean soundings showed that the monthly mean Z_p (based on ascent beginning at 850 mb with zero buoyancy) did not vary systematically with the introduction of the new sonde. Insufficient data from the new sonde are readily available to permit a longer-period comparison. No correction for the change in sondes has been made.

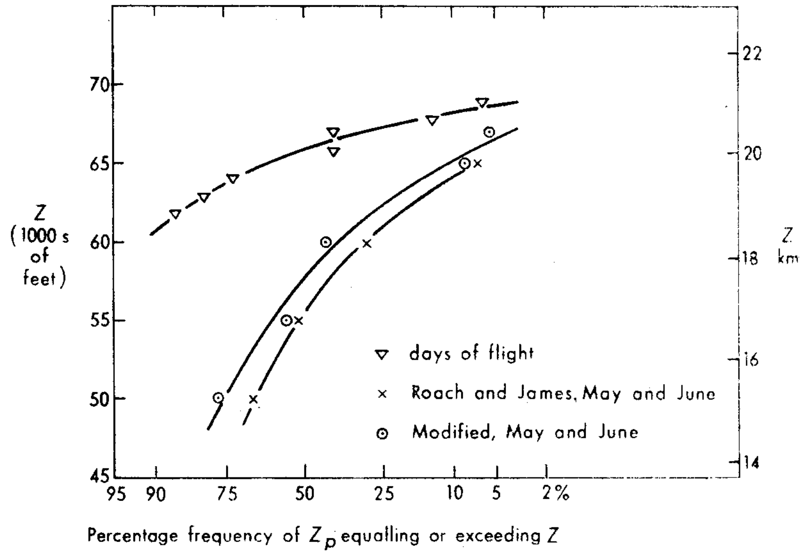

FIGURE 4—RELATIVE FREQUENCY OF Z_p EXCEEDING SPECIFIED HEIGHTS

Days of flights are compared with mean values for May and June 1961–66.

either a remarkable choice of days on which to fly in a normal year or an abnormal year with Z_p higher on the whole than in 1961–66. Days for flying were indeed chosen to be days of tall storms but it is likely that Z_p was higher in May and June 1969 than the average for 1961–66.

A day-by-day comparison of Z_p, made by using a planimeter to equate the positive and negative areas on a tephigram, by using Roach and James's original computer program, and by using the modified program, is given in Table II. Except in a few marginal cases the agreement between the manual construction and the modified program (columns (ii) and (vi)) is good.

A comparison of the manually calculated Z_p for days of flights with the Z_s for those days is also shown in Figure 2. Both sets of measurements fit a normal distribution quite well. The mean (and median) Z_s lies 4000 ft (1·2 km) below the mean Z_p but a pair of parallel lines fits both arrays of points quite well so that they have similar standard deviations (2600 ft). In Appendix III it is suggested that Z_s may have been systematically underestimated by 2000–4000 feet. If this is truly so then the agreement between the distributions of Z_s and Z_p is good indeed. Of course the present results are based on a small sample and more general agreement should not be assumed; nevertheless the agreement found between Z_s and Z_p, and that of Z_p found manually with Z_p found using Roach and James's modified computer program encourage extension of Roach and James's work on Z_p to find seasonal values of the daily maximum storm height in other tropical areas.

Comparison with earlier radar climatologies of the area. Bhattacharyya and De[15] have analysed routine hourly observations of the heights of cumulonimbus tops made with the radar at Dum Dum, the characteristics of which are listed in Appendix I. Their analysis covered the pre-monsoon and monsoon seasons of 1959 to 1962. Rakshit in a paper to be published (private communication) has extended the analysis to include 1963 and 1964. He found higher frequencies of high tops in the pre-monsoon season than Bhattacharyya and De. He also found that the highest top each day was more often above 15 km and 18 km in May than in any other calendar month. His results for May are shown as Z_c on Figure 2. The frequency of high tops from this radar climatology is much less than was found during the flights of this investigation. The number of flights is, of course, small and flights were made on days when the forecasters expected tall storms. However, even if one assumes that on the 23 days between 12 May and 3 June 1969 storms above 50 000 ft (15 km) occurred only on the 13 days when the aircraft made optical measurements, high tops were still more frequent than in the radar climatology. A comparison of columns 4 to 8 of Table I with column 9 suggests that the ground-based radar observations were often underestimates and that therefore the summaries of similar observations should be regarded as frequencies which can be expected to be exceeded.

Conclusions. There is little doubt that storms with tops exceeding 60 000 ft (18 km) occurred on most days when measurements were made. On some days tops reached at least to 65 000 ft and probably to around 68 000 ft. One storm top at 60 000 ft was rising at 1200 ft/min (6 m/s).

Because the storms which were measured were, for good practical reasons, chosen neither systematically nor entirely randomly, no conclusions may be drawn about the relative frequencies of tops exceeding specified levels. However, the measurements indicate that high tops were more frequent in May and early June 1969 than in the existing summaries of ground-based radar measurements. Although Z_p was higher during the flights than during 1961–66 it still seems very likely that the existing radar summaries for Calcutta will underestimate the frequency of high tops at all times of the year.

Although there was little agreement between the day-to-day variations in the heights of storm tops, Z_s, and the parcel-theory tops, Z_p, nevertheless Z_p was a better indicator (and predictor) of Z_s than either the equilibrium level Z_e, the tropopause or the heights given in the forecasts issued for the flights. Agreement was best between Z_s and the mean value of Z_p over the days when flights were made.

Acknowledgements. Most of the data were obtained and reduced by Fairey Surveys Limited for the Royal Aircraft Establishment, Bedford. It is a pleasure to acknowledge the persistence, integrity and professionalism of Mr F. Worton, Captain G. Milsom and the crew of G-AHCT.

The India Meteorological Department co-operated fully in providing a variety of meteorological facilities as well as the use of its 31-mm radar at Dum Dum. Mr U. R. Acharya, Officer-in-charge of the meteorological office at Dum Dum Airport, and his staff could not have been more helpful. Mr D. K. Rakshit and his team operated the radar with skill and enthusiasm.

Professor F. H. Ludlam acted as third analyst. His contribution in making available his wide experience of observing clouds was invaluable. Mr K. Weston (also of Imperial College, Department of Meteorology) took an active part in obtaining and interpreting the ground radar measurements of storms being worked on from the aircraft.

Mr M. H. Freeman has contributed advice and constructive criticism of the manuscript.

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APPENDIX I—CHARACTERISTICS OF THE RADARS USED

Characteristic	Airborne radar	Radar at Dum Dum Airport
Type	Ecko 290	JRC NMD-451A
Wavelength	31 mm (9375±3 MHz)	31 mm (9345–9405 MHz)
Pulse duration	4 μs	1 μs
Pulse repetition frequency	400 pulses per second	300 pulses per second
Peak power	30 kW	>225 kW
Beam width (to ½ power)	3°	1·2°
Beam	Conical	Conical
Sidelobes	No information No effects observed	25 dB down at 2° Second lobe at 4°
Iso-echo inversion	12 dB above minimum detectable signal	None
Display	Plan position indicator	Range–elevation, range–height and plan position indicators
Max. displayed range	50 nautical miles	540 km in a chosen direction, 300 km all round.

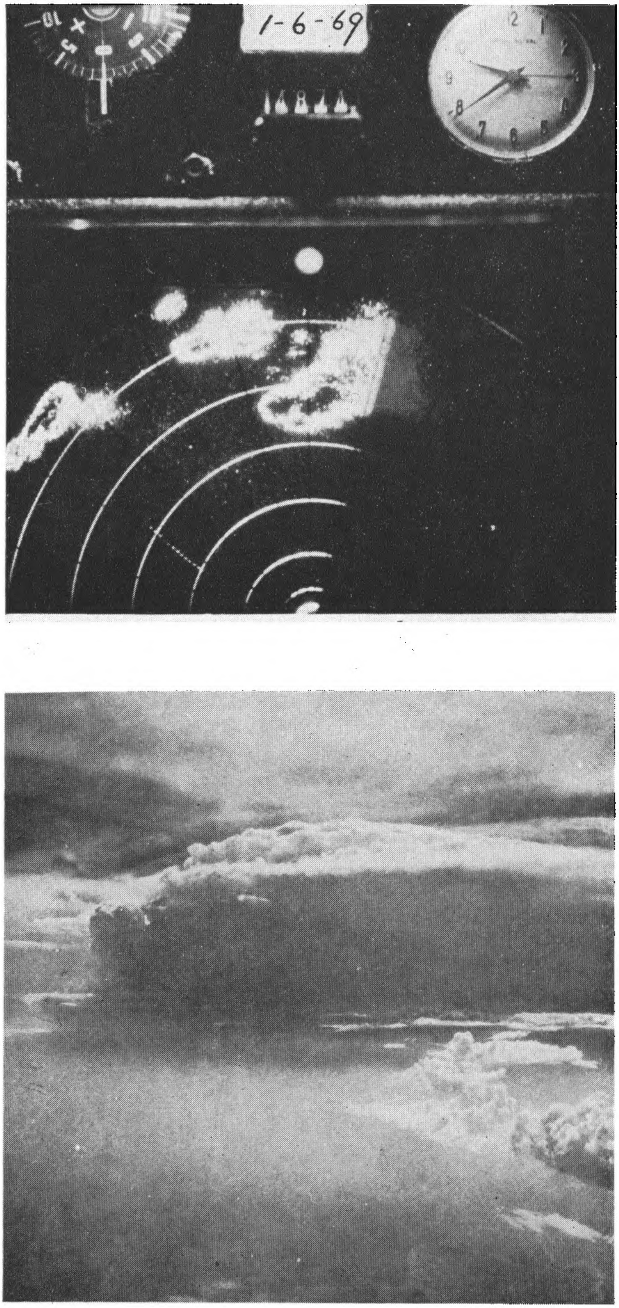
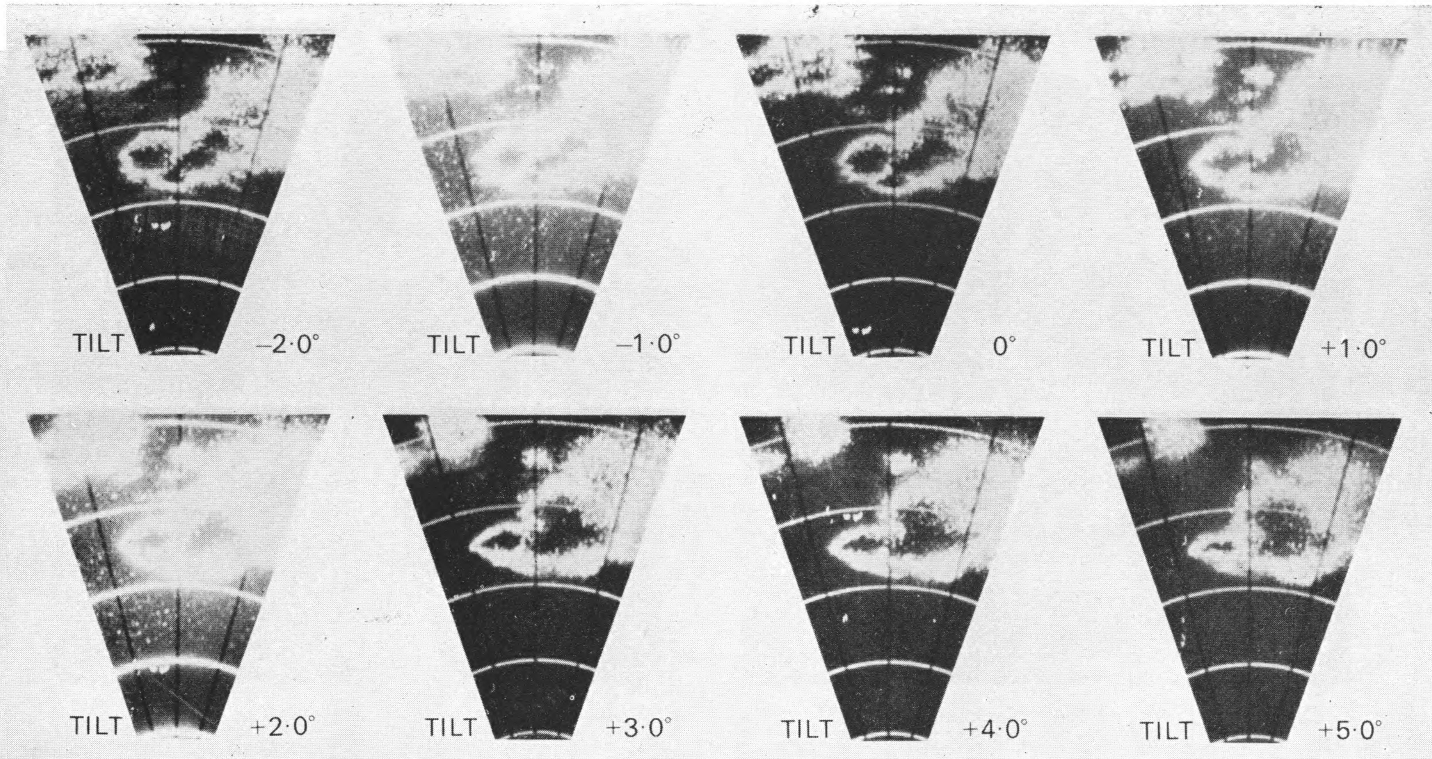


PLATE I—SIMULTANEOUS CLOUD AND RADAR PHOTOGRAPHS OF THE 65 000-ft (19·5-km) TOP OF STORM S_2 AT THE BEGINNING OF RUN 5, FLIGHT 17

Note the cirrus above the storm top. Time is GMT (=IST $-5\frac{1}{2}$ hours).


TILT −2·0°
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TILT +5·0°

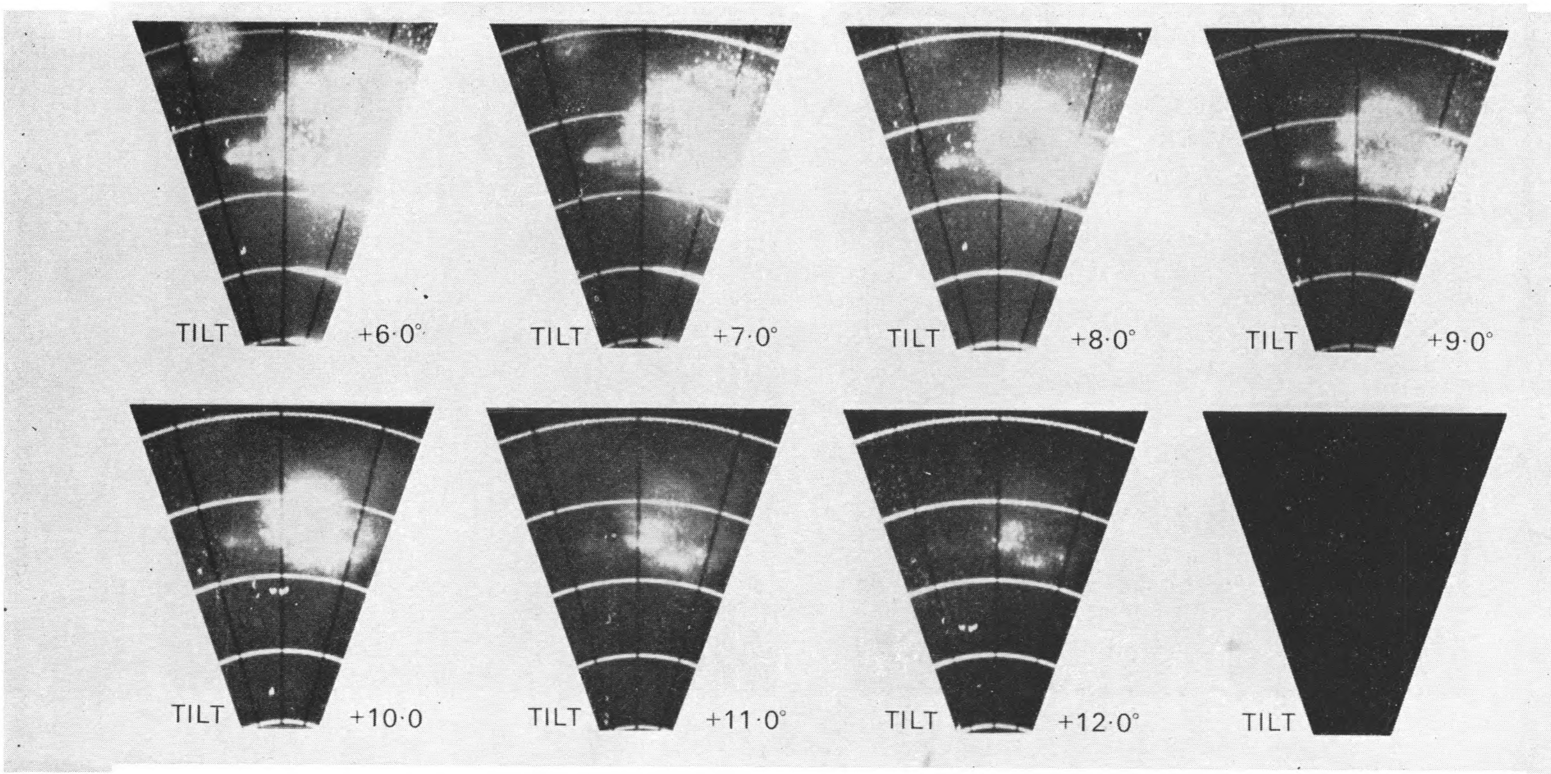

PLATE II—RADAR RETURNS OBTAINED WITH THE SCANNER RAISED BY 1-DEGREE STEPS, RUN 5, FLIGHT 17

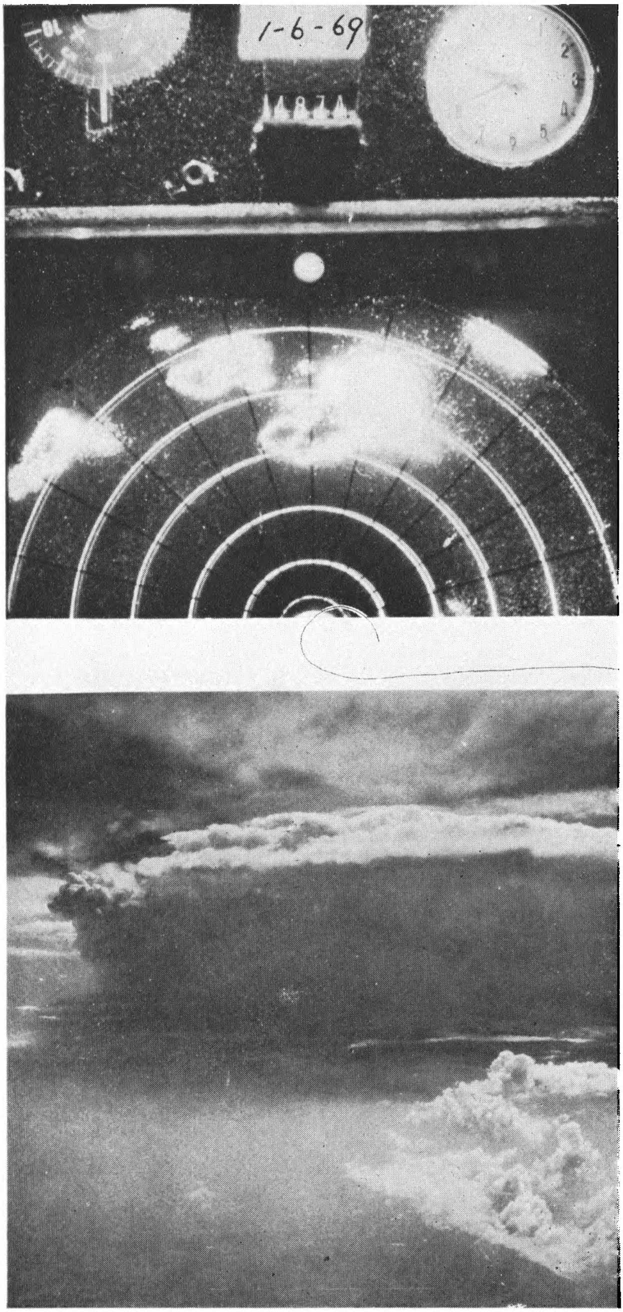

PLATE III—SIMULTANEOUS CLOUD AND RADAR PHOTOGRAPHS OF STORM S_2 AT THE END OF RUN 5, FLIGHT 17

Note also the velum at the storm top. Time is GMT (=IST $-5\frac{1}{2}$ hours).

APPENDIX II—METHOD FOR DETERMINING THE HEIGHTS OF STORM TOPS

(a) The height h_2 of the top of a visible cloud was derived from :

$$h_2 = h_1 + \nu + \frac{Dh}{fe} + C_\theta + C_\varphi + C_R,$$

where h_1 = height indicated by the aircraft's ICAO-atmosphere calibrated pressure altimeter set to 1013·2 mb;

ν = a correction calculated from the afternoon radio-sounding from Dum Dum ($h_1 + \nu$ represents the geometrical height of the aircraft above MSL);

D = radar range of the centre of the radar return from below the cloud top, when the radar scanner was horizontal. (D represents the distance between the camera lens and the vertical through the cloud top, measured along the horizontal axis through the camera);

f = focal length of the camera;

e = a factor to allow for enlargement of the photographs ($\times 2$ was used);

h = distance measured on the cloud photograph from the horizontal centre line to the top of the cloud;

C_θ = a term to correct for the aircraft's (strictly the camera's) pitch attitude, θ, ($C_\theta = D \tan \theta$);

C_φ = a term to correct for the aircraft's (strictly the camera's) roll attitude, φ. ($C_\varphi = \frac{D}{fe} (d \tan \varphi + h [\sec \varphi - 1])$. As φ was always small the term $h [\sec \varphi - 1]$ was neglected;

d = distance measured on the photograph from the vertical centre line of the photograph to the vertical through the cloud top;

C_R = a term to correct for effects of the earth's curvature. ($C_R = R (\sec \alpha - 1) + D \sin \beta (\sec [\alpha + \beta] - \sec \beta)$;

R = vertical distance between the camera and the centre of the earth. (R was taken as 6381 km);

α = $\tan^{-1} \frac{D}{R}$;

β = $\tan^{-1} \frac{h}{f}$.

(b) In principle the height h_2' of the top of the precipitation returning a radar signal was derived from

$$h_2' = h_1 + \nu + D_c' \sin \beta_c + C_R',$$

where D_c' = slant range of the radar return from the top of the storm;

β_c = tilt angle of the radar scanner when pointing at the top of the storm;

C_R' = a term to correct for effects of the earth's curvature; ($C_R' = R [\sec \alpha - 1] + D \sin \beta [\sec (\alpha + \beta_c) - \sec \beta_c]$);

As the radar scanner was gyroscopically stabilized no corrections were needed for aircraft attitude. Because of the large errors in β_c discussed in Appendix III and also because it was found that the corrections ν and C_R' tended to cancel neither of the latter corrections was applied.

(c) The photographs and records of pitch and roll were measured twice by different analysts and two independent sets of results were obtained for

$$\left(\frac{Dh}{fe} + C_\theta + C_\varphi\right) \text{ and for } D_c' \sin \beta_c.$$

The terms $(h_1 + \nu)$ and C_R were evaluated only once for each run. The heights given in columns 4, 5 and 6 of Table I are means of the two assessments.

APPENDIX III—THE ERRORS IN MEASURING STORM TOP HEIGHTS

In this appendix the notation is that used in Appendix II.

The likely standard error of a measurement of indicated height on a pressure altimeter, h_1, is about 100 ft (30 m) and of ν about the same. The combined error in the aircraft's geometric height $(h_1 + \nu)$ is therefore about 150 ft (45 m).

The random error in the major term (Dh/fe) may be gauged from the standard deviation of the differences between values found by the first two analysts. The range D and the distance h were each measured twice. Together they contribute almost all the standard error of 2100 ft in (Dh/fe) shown in Table III. A systematic error in D will have arisen from attenuation of the 31-mm radar beam. Attenuation will have produced an apparent shift of the centre of strong echoes towards the radar. The effect cannot be assessed quantitatively but may perhaps amount to a mile or two. If it does (Dh/fe) is underestimated by 5 to 10 per cent. For some of the highest tops this could be equivalent to a systematic underestimate of 2000 to 4000 feet. This has not been allowed for. In particular cases it could be cancelled out by the random leaning of the cloud towers. The focal length f was measured precisely at RAE Farnborough and may be taken as effectively exact. The enlargement factor, e, is known to within 0·2 per cent. Its contribution to the error is therefore about 80 ft.

TABLE III—ERRORS ARISING FROM DIFFERENT TERMS USED IN EVALUATING VISIBLE STORM TOPS

Term (see Appendix II)	Systematic error *feet*	Random error *feet*
h_1	0	±100
ν	0	±100
Dh/fe	−2000 to −4000 (say −3000)	±2100
C_θ	±300	±315
C_φ	±50	±220
C_R	0	±30

The likely standard error of a visible top in Columns 4 and 5 of Table I is −3000 ±1500 feet (−900 m ±450 m). Each entry in columns 4 and 5 is the mean of two assessments. This error excludes cases where there is a gross difference in interpretation between columns 4 and 5 and Ludlam's values in columns 7 and 8.

The pitch attitude, θ, was also always measured twice.

Table III gives the error in reading θ from the recorder film. The unknown systematic error in the instrumental system for determining θ is considered to be less than 1/10 degree and the random instrumental error is about the same.

Similarly, the roll angle φ and displacement d were measured twice. The reading error due to roll is 220 ft while the unknown systematic instrumental error is thought to be less than 1/5 degree, equivalent to about 50 ft in most cases. Random instrumental effects have been assessed as giving an additional error which is less than half that due to reading errors.

The correction for the earth's curvature C_R was tabulated to the nearest foot but interpolation may have led to errors of about 30 ft. The correction ranged from + 225 to + 1700 ft with a mean value of 870 ft.

Refraction of the radar beam in a spherically curved atmosphere causes the higher radar tops to be systematically underestimated by about 200 ft. In deriving this figure, a temperature and humidity variation with height was used, which was the mean for the days on which flights took place. The day-to-day differences in the effects of refraction were not examined but are likely to be less than this, equivalent, say, to a random error of 100 ft.

The effects of errors in R are entirely negligible.

The slant range D_c' was always measured twice (see Table III). The attenuation, which introduced errors in D, does not do so here.

The highest scanner angle at which a radar return was recorded β_c was effectively decided by the instrumentation operator in the aircraft. It has two main sources of error. The first concerns the glow left after each sweep of the radar and the second the width of the radar beam. At times the operator took 15 to 20 photographs in about 100 seconds, raising the radar scanner by one degree between photographs. It seems likely that he was not always able to follow his instruction to allow the afterglow from one elevation angle to die before taking the photograph of the return obtained at the next higher angle. The afterglow would then be interpreted as echo obtained at the higher angle. Probably the afterglow would not have persisted after two photographs, i.e. two degrees. Secondly, no correction was made to allow for a return being received when the cloud top was in the main lobe of the radar beam but below its axis. In some circumstances a half-beam-width correction is used to allow for this. These two effects mean that some elevation angles β_c may be up to $3\frac{1}{2}$ degrees too high. In comparison, the likely standard error due to errors in the stabilization system ($\pm 0{\cdot}1°$) is trivial. If β_c is reduced by $3\frac{1}{2}$ degrees, all the radar tops come below the visible tops.

None of these effects is so important as the interpretation of the photographs themselves. This may lead to large yet unassessable errors. The analyst must associate each cloud tower with a corresponding radar echo. Referring to the analyst's most common difficulty Professor F. H. Ludlam (private communication) has written 'When cloud tops have become surrounded by a shelf of anvil cloud it is difficult to be certain whether knobbly detail seen at the highest elevation in a photograph is the peak or nearer protuberances from the upper part of the anvil cloud. If such protuberances conceal the peak the calculated height may be an overestimate of several thousand feet. This kind of difficulty arises even at the up-shear side of the storm, where the horizontal extension of the anvil cloud away from the peak is a minimum, but still reaches several miles in storms with very high tops'. He has termed this 'anvil interference' or AI. The effect of differences in interpretation is best seen by comparing Ludlam's re-assessment with the original measurements (see Table I).

Overall, 2000 to 4000 ft should probably be added to measured visible tops to allow for systematic errors. The combined random error for visible tops listed in columns 4 and 5 is $\pm$ 1500 ft.

The error in the measurements of radar tops because of errors in β_c is sometimes 10 000 ft, masking all other errors whether systematic or random.

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A SIMPLIFIED SNOW PREDICTOR

By B. J. BOOTH
(Meteorological Office, Upavon)

Summary. An earlier analysis of snow observations made at Upavon is reconsidered and a simplified snow index is suggested. A test of an American snow forecasting method is also briefly discussed.

Introduction. Some three years ago the present writer examined Upavon precipitation data to test the effectiveness of dew-point temperature as a snow predictor.[1] The *Air Weather Service Technical Report* No. 233[2] describes a snow forecasting method applicable to the area just east of the Rocky Mountains. Wet-bulb temperatures at the surface, T_W, and at 850 mb, T_{W850}, are estimated from the relevant surface and upper-air observations. These are entered on Figure 1 and the type of precipitation to be expected is obtained. (Figure 1 is a modified version of the diagram described in the original article, in that it has only 4 areas as against 6 originally.)

The 00 and 12 GMT surface and 850-mb wet-bulb temperatures were estimated from the dry-bulb and dew-point temperatures (T, T_d) measured at Crawley/Gatwick, Stornoway and Gorleston/Hemsby, when precipitation was occurring during the five winters 1966/67–1970/71, winter being defined as the period from 1 November to 30 April. The data were extracted from the *Daily Weather Report*[3] and the *Daily Aerological Record*.[4] These observations were then entered on Figure 1 and the expected type of precipitation compared with that actually experienced. Table I summarizes the results obtained.

TABLE I—PERCENTAGE FREQUENCY OF CORRECT PRECIPITATION FORECASTS

	Freezing rain (A)	Snow (B)	Rain (D)
Non-showery precipitation	No occurrences	98 [44]	93 [124]
Showery precipitation	No occurrences	96 [73]	78 [108]

[ ] = Total number of precipitation occurrences in each area. Area C is not included since one would expect mixed types of precipitation in this area.

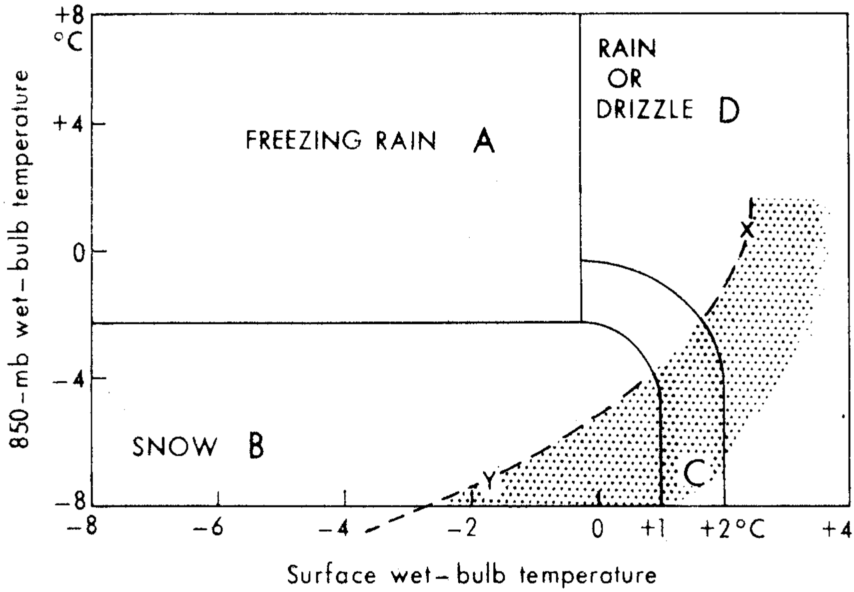

FIGURE 1—TYPE OF PRECIPITATION RELATED TO THE SURFACE AND 850-mb WET-BULB TEMPERATURES

C represents the occurrence of precipitation of mixed types.

While at first the method appears to give a high percentage of correct forecasts, further study of Figure 1 showed that over 98 per cent of all observations (461) fell within the shaded area. The line bounding this area, XY, intersects the boundary line of areas B and C at $T_W = 1\,°C$, i.e. nearly all precipitation observations were of snow when $T_W < 1\,°C$ and of rain when $T_W \geqslant 1\,°C$. There is no similar value for $T_{W_{850}}$. In other words equally good results could have been obtained by referring to the surface wet-bulb temperature alone (at least over the British Isles).

This T_W value of 1 °C appears to be the critical temperature at which precipitation may or may not be in the form of snow and is in good agreement with an idea described by Booth.[1]

Discussion. In an earlier article Booth[1] suggested that if precipitation was occurring and the dew-point depression $\leqslant((-2 \times T_d) + 1)$ degC, then there was a good chance that the precipitation would be in the form of snow. This is rather a cumbersome equation to remember, especially since the original idea was to obtain a simple, readily calculated index which could be plotted and followed on synoptic charts.

The original Upavon data have now been reanalysed and a simpler form of a snow index, I_s, obtained by adding together the surface dew-point and dry-bulb temperatures on occasions when precipitation was occurring. Table II shows the frequency of non-showery snow for various values of I_s. ($I_s = T + T_d$.)

TABLE II—PERCENTAGE FREQUENCY OF NON-SHOWERY SNOW AT UPAVON

I_s	*percentage frequency*	*number of observations*
−3	100	24
−2	96	46
−1	91	65
0	79	82
1	47	34
2	17	59

This suggests that a value of I_s between 0 and 1 is the critical value which separates precipitation in the form of rain from that in the form of snow. This is supported by Table III which uses data from Gatwick, Gorleston and Stornoway. If one considers showery precipitation then the critical value of I_s lies between 2 and 3 (Tables IV and V).

This index is a function of the wet-bulb temperature since for dry-bulb and dew-point temperature between + 7°C and − 7°C

$$T_W \approx \frac{T + T_d}{2}.$$

In using the index to forecast the probability of snow, it is necessary to take into account the cooling effect of melting snowflakes. Rain may turn to rain and snow mixed (sleet), then to snow, even though the value of I_s is somewhat greater than 1 before precipitation starts. Lumb[5,6] has shown that the highest wet-bulb temperature at which instability rain can turn to snow is 3·5°C, whilst for prolonged frontal precipitation the value is 2·5°C. The sums of the dry-bulb and dew-point temperatures, as plotted on a synoptic chart, which give wet-bulb temperatures of this magnitude are 6 or 7 and 5 or 6 respectively. Thus if $I_s \leqslant 7$ and precipitation commences as rain then there is a possibility that the rain could turn to snow.

TABLE III—PERCENTAGE FREQUENCY OF NON-SHOWERY SNOW AT GATWICK, GORLESTON AND STORNOWAY

I_s	*percentage frequency*	*number of observations*
−3	100	4
−2	100	6
−1	88	8
0	65	17
1	30	10
2	32	19

TABLE IV—PERCENTAGE FREQUENCY OF SHOWERY SNOW AT UPAVON

I_s	*percentage frequency*	*number of observations*
−3	100	1
−2	100	4
−1	100	2
0	80	5
1	88	8
2	67	3
3	25	8
4	33	9

Although the height of the 0°C wet-bulb level above ground level is of great importance in snow forecasting, as Lumb[7] has demonstrated, its use has one major drawback — namely that of trying to decide which upper-air sounding is representative of a station or area, and how it will change in the future. On most occasions of rain changing to sleet or snow it is reasonable to expect that the downward penetration of colder air will produce a lapse rate from the surface up to 600 m (the greatest depth through which snow can be expected to penetrate downwards), which is near to the saturated adiabatic. This has been confirmed by a study of 90 occasions of rain or sleet with surface temperatures near 0°C during February 1972. Figure 2 shows the relationship obtained between the height of the wet-bulb freezing level, H, and I_s. A similar relationship was obtained when 12 GMT values of I_s and H were calculated for 111 occasions when no precipitation was occurring. It follows that the use of the index I_s will give an indication of the area where the height of the 0°C wet-bulb temperature is lowest and movements of the isopleths of I_s will reflect temperature changes due to advection or vertical penetration of colder air.

TABLE V—PERCENTAGE FREQUENCY OF SHOWERY SNOW AT GATWICK, GORLESTON AND STORNOWAY

I_s	*percentage frequency*	*number of observations*
−3	100	6
−2	83	6
−1	86	14
0	100	24
1	85	13
2	73	26
3	44	18
4	43	23

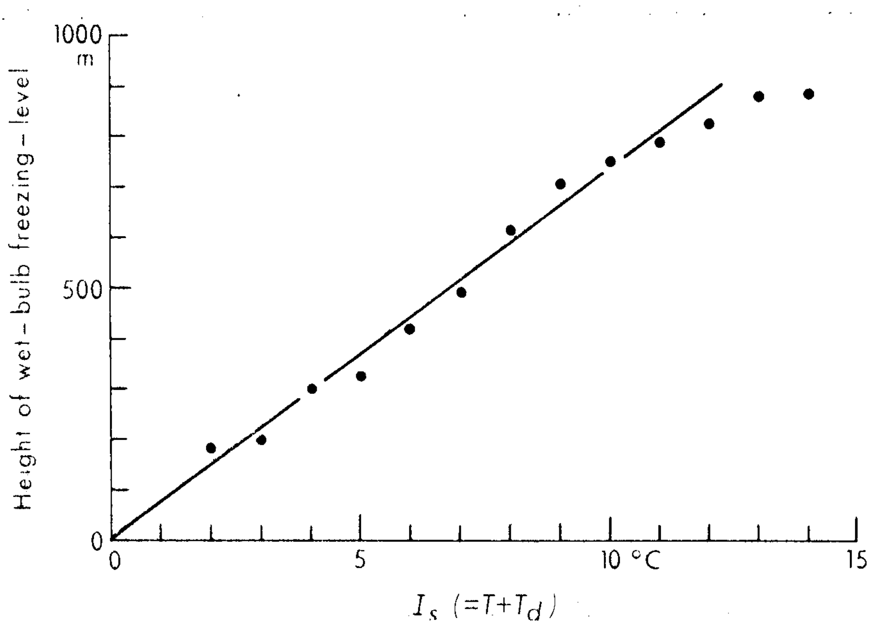

FIGURE 2—RELATIONSHIP BETWEEN SNOW INDEX I_s AND HEIGHT OF THE WET-BULB FREEZING LEVEL

Examples of the use of I_8. The following three examples illustrate the use of the isopleths of I_8 in assessing the probability of snow or rain changing to snow.

Snowfall over England on 11–12 *February* 1970. Figure 3 shows the synoptic situation at 12 GMT on 11 February 1970 and the track of the depression during the next 24 hours. Precipitation in the form of rain reached south-western counties during the late afternoon of 11 February and spread quickly east and north. Most southern counties east of Cornwall and Devon experienced a short period of rain or sleet which quickly turned to snow. Farther north precipitation was solely of snow. Precipitation amounts of 15 mm were recorded at many places in southern England and at Plymouth a total in excess of 30 mm was noted.

The I_8 pattern at 12 GMT on 11 February is shown in Figure 4. The low values in the London area are partly due to overnight stratus, the late clearance of which delayed the normal diurnal temperature rise. An I_8 value nearer 3 or 4 would probably be more representative. As the depression deepened and moved along the English Channel the winds over Cornwall and Devon backed from south through east then north. With the onset of northerly winds cold air was advected over these counties and even here sleet was experienced. Prior to the advection of the colder air over the south-west peninsula all the sleet or snow reported fell over an area where the initial I_8 was less than 7°C.

Figure 5 shows the boundary of the rain and snow ahead of the depression, together with the $I_8 = 7$ isopleth at 12 GMT on 11 February 1970. By 12 GMT on 12 February all the south-western counties had an I_8 value of 5 or less.

The polar air depressions of 25–26 *April* 1950 *and* 13–14 *December* 1958. These depressions have already been discussed in detail by Lumb[6] in terms of the

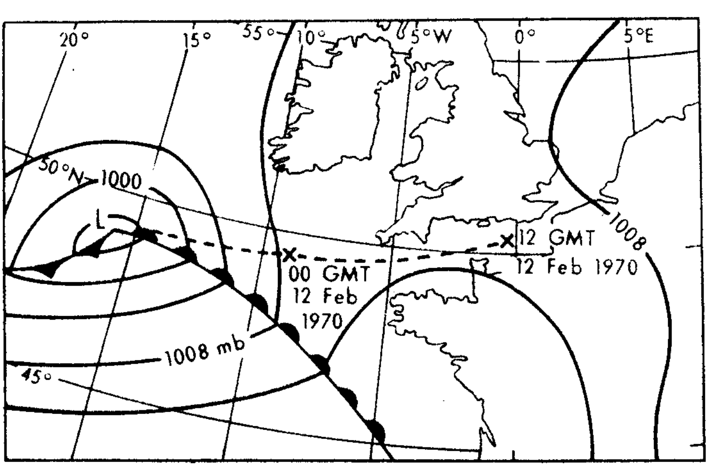

FIGURE 3—SYNOPTIC SITUATION AT 12 GMT, 11 FEBRUARY 1970

The track of the depression during the next 24 hours is also shown.

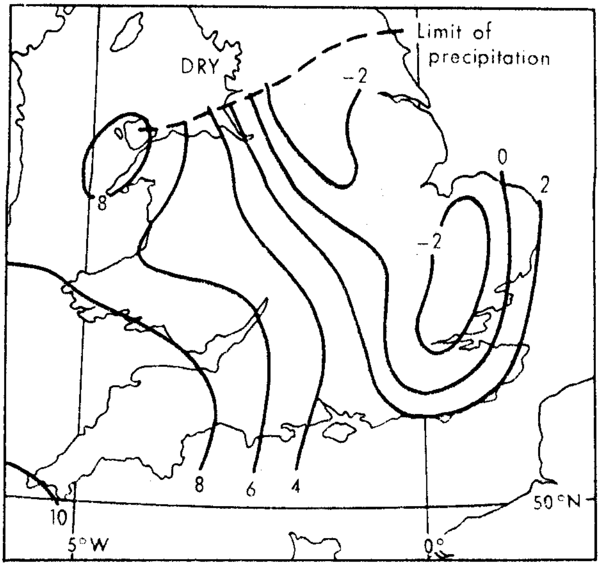

FIGURE 4—PATTERN OF SNOW INDEX I_s AT 12 GMT, 11 FEBRUARY 1970

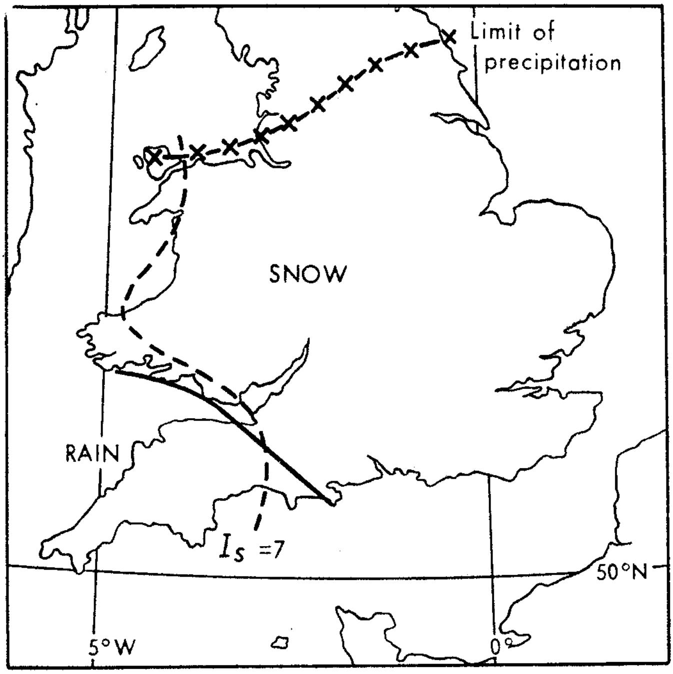

FIGURE 5—AREAS OF RAIN AND SNOW AHEAD OF THE DEPRESSION OF 11–12 FEBRUARY 1970

The I_s isopleth refers to 12 GMT, 11 February.

wet-bulb lapse rate and surface wet-bulb temperature. The purpose of these notes is to show in terms of I_s why rain turned to snow on the first occasion, but not on the second occasion.

The tracks of the two polar lows are shown in Figure 6. Figure 7 shows the isopleths of I_s for 12 GMT on 25 April 1950 and also the northern limit of the precipitation associated with the polar low; other than Cornwall and Devon most of England and Wales had an I_s value of less than 7. Within the area shown there was extensive moderate or heavy precipitation with up to 25 mm of precipitation being recorded.

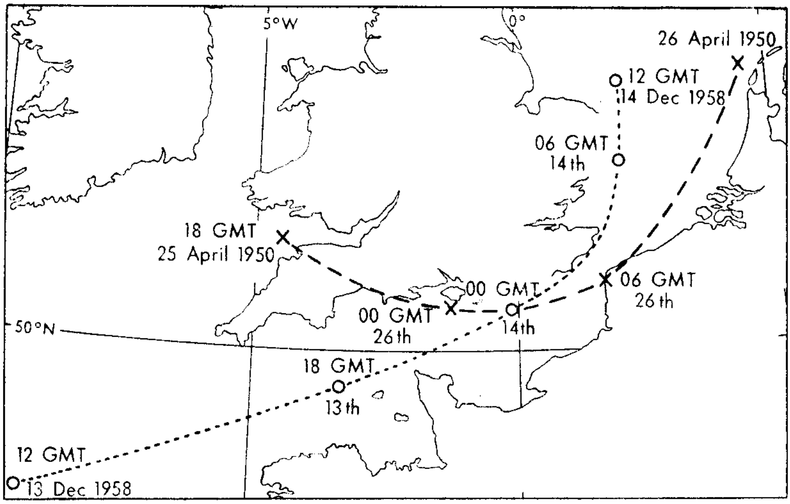

FIGURE 6—TRACKS OF TWO POLAR LOWS

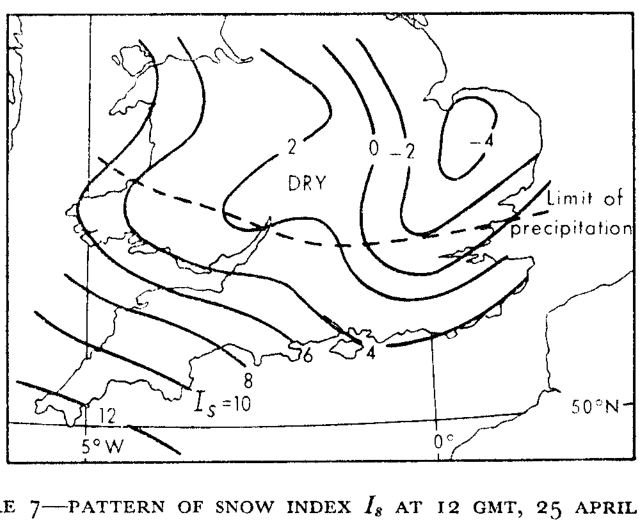

FIGURE 7—PATTERN OF SNOW INDEX I_s AT 12 GMT, 25 APRIL 1950

Precipitation commenced along the Welsh coast during the early afternoon and quickly spread east. Over Devon and Cornwall precipitation was in the form of rain, but elsewhere rain quickly turned to snow. Figure 8 shows the areas in which rain and sleet or snow was reported. It will be noted that the boundary between the rain and snow lies close to the $I_s = 7$ isopleth.

Figure 9 shows the I_s pattern at 12 GMT on 13 December 1958, together with the precipitation area associated with the polar low which moved north-eastwards along the English Channel. On this occasion precipitations fell into a régime in which the I_s value during the previous afternoon was in excess of 7, and hence only rain was reported. Had the air over the Midlands been colder and drier the rain would probably have turned to sleet as the surface winds backed through north behind the depression and advected cold air southwards. In fact, sleet was reported for a short while at London/Heathrow Airport as the surface wind backed to north-west. Heathrow lay on the northern edge of the rain belt.

Conclusion. An important element in trying to determine the form precipitation will take is T_W. Since T_W is not included in the synoptic code a simple function of T_W in the form I_s can be calculated from the reported T and T_d. If values of I_s are then plotted on surface charts the most likely areas of rain, snow or rain turning to snow will be indicated.

If the precipitation is expected to be of light intensity it will most likely be of rain if $I_s \geqslant 2$ and of snow if $I_s \leqslant 0$, but if continuous moderate or heavy precipitation is expected then rain could turn to snow over ground where the initial $I_s \leqslant 7$, provided that there is no warm advection at or near the surface. Rain may also turn to snow over areas into which colder air with $I_s \leqslant 7$ is advected.

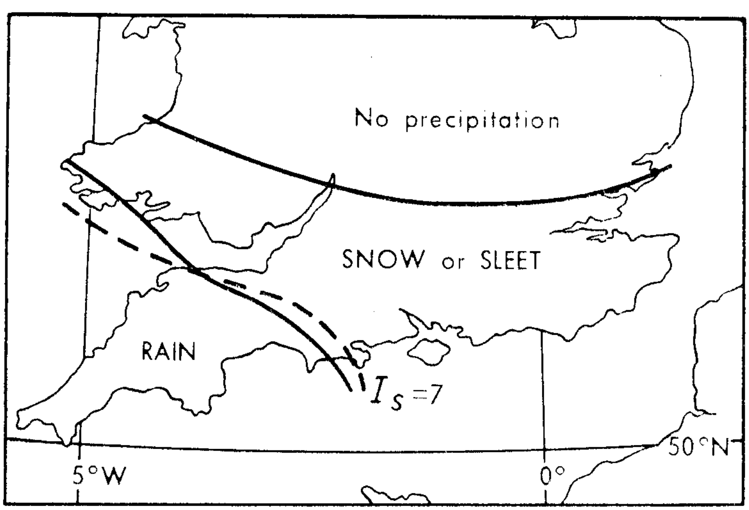

FIGURE 8—AREAS OF RAIN OR SNOW 25–26 APRIL 1950

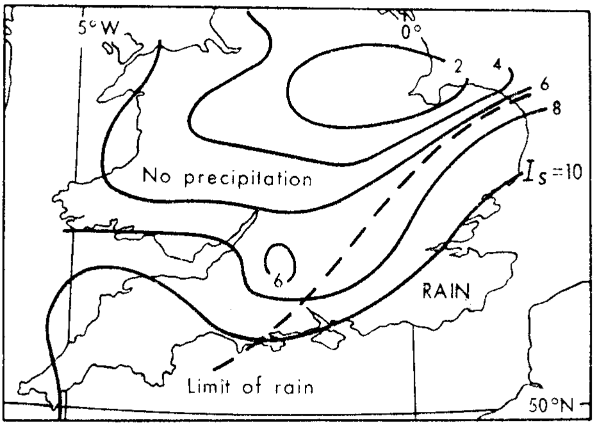

FIGURE 9—PATTERN OF SNOW INDEX I_s AT 12 GMT, 13 DECEMBER 1958

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REVIEWS

Weather forecasting as a problem in physics, by Andrei S. Monin (translated by Paul Superak). 230 mm × 160 mm, pp. x + 199, *illus.*, The M.I.T. Press, 126 Buckingham Palace Road, London SW1, 1972. Price: £5·65.

Forecasting the weather for a day or two ahead is one of the main tasks of all meteorological services, and forecasting for longer periods is a recognizable task which may have even more importance. It is generally agreed that the method of forecasting with the greatest promise of improvement through research is that loosely described as numerical weather prediction. It has been in operational use for more than a decade and is slowly acquiring its own pedagogical literature, in which the presentation is ordered and polished. The difficulties that held up the early investigators are smoothed away and in the mathematization, which is inevitable since the practical problems are finally arithmetic, much of the physics of atmospheric motions gets lost; the grid scales adopted in practice described the dynamical motions tolerably well but are too large for adequate description of the physics, of which current knowledge is essentially small-scale. Professor Monin has written a book which surveys the problems associated with numerical weather prediction, both short- and long-range, from the practical point of view of a physicist. In doing so he has restored some of the physical processes to their rightful eminence and shown some of the rents in the apparently respectable cloak of numerical modelling. Few writers have the qualifications of Professor Monin for doing this for he was an early investigator and has maintained his interest for the better part of two decades.

The four chapters which make up the book of less than 200 pages cover a wide variety of topics so that the treatment necessarily is broad rather than detailed and will not appeal to those who need to know the engineering details of models. However, Professor Monin has given nearly 400 references, showing an enviable familiarity with world-wide literature, which indicate where further details may be found. The first short chapter gathers information not easily found on the observed scales of atmospheric motions. The second chapter deals with short-range weather forecasting and is novel in its development and perhaps in its stress on the use of filtered models. Once again it is the background, such as the way in which the various scales of motion react to sudden changes in pressure and wind, that is brought out rather than the structure of any particular model. The third chapter is concerned with global circulation and long-term weather changes and ranges over the observational problem, the physics of the ways in which heat is put into and taken out of the atmosphere, the results from global modelling, the role of the oceans, predictability and extraterrestrial influences. Much of this is not yet textbook material and is certainly open to discussion so that not everyone will agree with the weight that the author attaches to the roles of the physical processes in determining the large-scale developments over long periods; but whether the reader agrees or not a positive starting point for argument is provided. The fourth chapter deals briefly with modelling the planetary circulation and the atmospheres of other planets.

The book is really a substantial review article without pedagogical pretensions and if it is not quite clear at what audience it is aimed, almost all meteorologists are now well enough aware of dynamical methods to be able to profit by reading it. It brings to our notice a great deal of work carried out in the U.S.S.R. which has not been well known in the west, and indeed this is one of the main values of the book.

In translation Professor Monin has a firm, trenchant style and readers will not only profit from but will enjoy reading this book.

E. KNIGHTING

Some environmental problems of livestock housing, WMO *Technical Note* No. 122, by C. V. Smith. 270 mm × 210 mm, pp. xii + 71, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972. Price: Sw. Fr. 15.

Here is a publication worthy of careful study by all concerned with the housing of livestock. The author, true to the discipline of meteorology, maintains a complete overview of the environmental situation, whilst contemplating in greater detail some of the more specific requirements of livestock housing.

Unfortunately, some material has had to be condensed, and as a result, oversimplification inevitably occurs, particularly in the introductory chapter concerned with establishing the economic and biological motives for housing. Unavoidably too, perhaps, some confusion exists in the frequent use of the term 'environment' when at times it embraces even the unquantifiable elements of stockmanship, and at others only the more specific properties of the aerial environment.

The author, however, leaves no doubt that his real concern is with the latter — the quality, movement and distribution of air in and around livestock buildings. Though there are chapters briefly discussing the thermal and airborne pollutants, e.g. particulates, bacteria, gases, etc. and ventilation systems in general, these are mere precursors to the main sections on air movement.

The effects and patterns of airflow around buildings are discussed with authority but it is unfortunate that some of the data must lose their impact through poor illustration. The data on comparative air patterns resulting from constant-velocity and boundary-layer winds are however gratifying for such information is not readily available to the non-specialist. The movement of air inside the building as a result of air jets, isothermal and non-isothermal motions is neatly packaged in descriptive and mathematical terminology, the latter being perhaps a trifle discouraging to the more casual but interested reader. A short chapter on ventilation rate emphasizes the danger of misinterpreting the concept of air change rate and introduces the more useful quantity — transfer index. This, together with subsequent information on instruments and experimental techniques, provides the research worker at least with some hope for the field measurement of ventilation rate.

The author concludes with a short philosophical note on organizational problems — aimed primarily at the meteorologist, and an extremely useful chapter specifying those technical problems still to be solved. A useful general bibliography finally helps to wrap up a worthwhile contribution to a sadly neglected field.

S. H. BAXTER

NOTES AND NEWS

Meteorological Centenary

The 136-member World Meteorological Organization met in Geneva on 10 September 1973 to celebrate the 100th anniversary of organized international meteorological co-operation. A congratulatory message was received from Dr Kurt Waldheim, Secretary-General, United Nations.

Measurement of the geoid

A new technique for more rapid measurement of the geoid, or mean-sea-level surface, is being evaluated as part of the current SKYLAB mission.

The experiment, which involves the use of a radio-altimeter sensor system, is being conducted by Battelle Columbus Laboratories for NASA's Johnson Space Center (formerly the Manned Spacecraft Center).

According to Zack H. Byrns, technical monitor of the study for NASA, determination of mean sea level is basic to understanding of the ocean and its environment, particularly for modelling ocean currents, tides, circulation patterns, and air–sea interaction. Improved numerical weather predictions require knowledge of these dynamic ocean parameters, he observes. Navigation, waste disposal and pollution control depend on accurate knowledge of ocean dynamics, as does the understanding of climate.

A. George Mourad, who heads the research team at Battelle Columbus, states that to compute the geoid over the oceans by conventional methods would involve the use of many specially instrumented ships and aircraft over several years — an expensive and time-consuming procedure. Should the radar-altimeter technique prove feasible, the global geoid could be computed much more economically and in a much shorter time.

The altimeter in the SKYLAB experiment is a microwave radar that measures the time for pulsed signals to travel from the space station to the sea surface immediately below it and back to the station. This time is then converted into distances. Knowing the orbit of the SKYLAB accurately over a test area, Mourad comments, it will be possible to compute the geoid.

During the SKYLAB missions the geoid will be determined over selected test areas where the mean sea level has already been determined by the best available conventional techniques. These areas are (a) the North Atlantic bounded by Wallops Island, Bermuda and Florida, (b) the Gulf of Mexico, and (c) the Puerto Rico Trench (north of Puerto Rico).

The Battelle study team will make a comparative analysis and evaluation against the existing geoidal profiles determined by conventional techniques to verify those computed from the SKYLAB altimeter.

Earth Resources SKYLARK Scandinavian survey

A British developed Earth Resources (ER) SKYLARK rocket is standing by for launching from Kiruna, Sweden for a survey of the northern regions of Sweden, Finland and Norway. The launch will take place when there are reasonably cloud-free conditions for clear photography of the area.

The SKYLARK survey is part of a research programme sponsored by the Governments of the United Kingdom, West Germany and Sweden to assess the usefulness of remote sensing of the earth's resources by rocket.

The number of SKYLARK rockets launched to date is 314, and they have had a cumulative success rate of 98 per cent. SKYLARK was originally developed by the Royal Aircraft Establishment in 1957, and since that time it has been continually developed and has been used to carry scientific experiments into the earth's upper atmosphere and beyond. The British Aircraft Corporation co-operated with the Royal Aircraft Establishment in adapting SKYLARK as a camera-carrying platform for Earth Resources survey, and the present system is unique in having particular advantages over other survey methods. It can obtain instantaneous large-area coverage at a fraction of the cost of using an orbiting satellite. The payload is designed and built to the local user's requirements and it can be launched at short notice to coincide with favourable cloud-free conditions.

The Remote Sensing Society — a major new scientific society to be formed

Following a series of meetings in the United Kingdom, the Remote Sensing Society is to be formed. The initiative for this has come from a body of scientists, technologists and administrators deeply interested in methods of measuring and managing the earth's resources and environment.

Remote sensing stems from aerial photography and has been given enormous impetus in recent years by the release of information on previously classified military reconnaissance equipment. Particular interest has been shown in devices which operate at 'invisible wavelengths'. Recent reports on SKYLAB and the Earth Resource Technology Satellite (ERTS) have drawn attention to remote-sensing techniques for monitoring features and phenomena on earth.

A new society is needed because so many branches of science and technology are involved. Inquiries should be directed to Mr R. W. Laing, Public Relations Officer, Remote Sensing Council, at 37 Jessop Road, Stevenage, Hertfordshire.

THE METEOROLOGICAL MAGAZINE

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DECEMBER 1973 No 1217 Vol 102
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SCIENTIFIC PAPERS

No. 31 The three-dimensional analysis of meteorological data

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

37½p (40p by post)

No. 32 The Bushby-Timpson 10-level model on a fine mesh

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

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THE METEOROLOGICAL MAGAZINE

Vol. 102, No. 1217, December 1973

RETIREMENT OF MR V. R. COLES

Mr V. R. Coles, Deputy Director of the Meteorological Office responsible for forecasting services, retired on 9 September 1973 after 36 years' service. He graduated in mathematics and physics at Reading University in 1934 and was then awarded a Henry Fellowship for a year's study and research at Yale University in the U.S.A. On returning to England he continued his research at Reading University, taking the Master of Science degree, and accepted an appointment in the Meteorological Office in April 1937. His career was to be spent almost entirely in synoptic meteorology — weather forecasting, the organization of forecasting services and research into the problems of synoptic meteorology.

During the first decade of his career in the Office Roy Coles served with the Royal Air Force in a variety of posts, at the headquarters of Bomber Command, at flying stations, at the School of Air Navigation and on an overseas tour in Iraq. In 1947 he was posted to the Central Forecasting Office, then in Dunstable, and he spent the next eight years on the Senior Forecasters' roster. He then went to Cyprus on promotion to Senior Principal Scientific Officer for a tour of duty as Chief Meteorological Officer to the Royal Air Force in the Near East.

On returning home towards the end of 1957 Mr Coles was appointed Assistant Director responsible for research in synoptic meteorology, a post he held for four years, and then became the Assistant Director in charge of the Central Forecasting Office. In 1966 he was promoted to Deputy Chief Scientific Officer and, as a Deputy Director of the Office, assumed responsibility for all its forecasting services, not only in the Central Forecasting Office but also at the outstations serving the defence forces and civil aviation and at the weather centres serving the general public, industry and commerce. His period as Deputy Director marked the transition to a highly centralized forecasting organization based on computerized techniques using a very powerful computer as well as modern communications facilities.

With all this experience in weather forecasting and with his ever-widening responsibilities, Roy Coles naturally became prominent in international affairs and on several occasions was leader of the British delegation to meetings of WMO's Technical Commission for Synoptic Meteorology, now called the Commission for Basic Systems. He also played a leading role in the intergovernmental meetings on the North Atlantic Ocean Station scheme.

In a career devoted to synoptic meteorology and its applications to weather forecasting, it was very plain that Roy's talents were being used to the best advantage and this conferred on him a degree of leadership and influence that were to be of wide extent and of great value. His enthusiasm burned brightly throughout his career, showing no diminution in later years but rather a greater insight into the problems that still have to be faced. Roy was a fine sportsman in his day, particularly at cricket, and subsequently a mine of information on a variety of sporting topics. Always relaxed and approachable, he will be greatly missed. We wish him and Mrs Coles many years of happiness and good health in their retirement.

P. J. MEADE

AWARD OF IMO PRIZE TO MR J. S. SAWYER

The World Meteorological Organization has awarded the International Meteorological Organization Prize, its highest honour, to Mr J. S. Sawyer, F.R.S., Director of Research in the Meteorological Office for his outstanding researches in dynamical meteorology and for his important contributions to international collaboration in meteorological research. A similar award has been made to Dr C. H. B. Priestley, F.R.S., of the Commonwealth Scientific and Industrial Research Organization, Australia, who worked as a research scientist in the Meteorological Office from 1939 to 1946.

Mr Sawyer's researches, mainly devoted to analytical and theoretical investigations of the structure and dynamics of weather systems, ranging in scale from lee waves to the global circulation of the atmosphere, have always been motivated by a strong desire to improve the standards of weather forecasting. He played a key role as a research scientist in pioneering numerical weather prediction in the Meteorological Office and it was under his direction that the current 10-level hemispheric models were developed and brought into operational service.

He has done a great deal of work over the years for international relations in meteorology, on behalf of both the World Meteorological Organization and the International Council of Scientific Unions. In particular, he has been a member of the Joint Organizing Committee for the joint WMO/ICSU Atmospheric Research Programme since its inception, and is currently President of the WMO Commission for Atmospheric Sciences.

Of the 18 IMO Prizes awarded since their inception in 1956, no fewer than four have been awarded to members of the Meteorological Office and Mr Sawyer joins the distinguished company of Mr E. Gold (1958), Dr R. C. Sutcliffe (1963) and Sir Graham Sutton (1968). It is hoped that the presentation of the medal, certificate and prize will be made at a ceremony in Bracknell early next year.

This high and well-deserved honour will give widespread pleasure to Mr Sawyer's colleagues within the Office and in the meteorological community at large.

B. J. MASON

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NEW INDICES TO LOCATE CLEAR-AIR TURBULENCE

By R. BROWN

Summary. A test of the effectiveness of two indices for locating areas of clear-air turbulence on 12 days of widespread aircraft reports is presented. These indices were suggested by Roach as a modification of an earlier index derived by him on theoretical grounds, but which has proved to be impracticable for direct use in locating clear-air turbulence. The tests suggest that the indices are better than the Richardson number in locating clear-air turbulence and are promising enough to warrant further development. One of the days tested is presented as a case study.

Introduction. Although during the last few years there has been considerable progress in understanding the physical mechanism of clear-air turbulence (CAT) there has been little corresponding improvement in its routine forecasting. Forecasts are usually produced by associating certain upper-air patterns with the occurrence of CAT and by empirical associations between wind shears (both horizontal and vertical) and CAT occurrence. The turbulent areas forecast by these methods are large and it is an important problem to try to reduce the areas in which CAT is forecast without sacrificing accuracy. Roach[1] derived an index to locate areas where CAT is likely from a theoretical consideration of the synoptic processes involved in the production of CAT. Unfortunately it proved impossible to evaluate fields of this index by using synoptic upper-air data because of the poor spatial resolution of these data. This led Roach (unpublished note) to propose two modified forms of his original index which could be more easily evaluated from conventional synoptic data. This paper examines the effectiveness of these modified indices in locating areas of CAT on 12 days when moderate or severe turbulence was reported. A detailed case study is presented of one of these days when an exceptional number of turbulence reports was received.

Theoretical considerations. It is now generally accepted that Kelvin–Helmholtz instability (KHI) occurring in regions of large vertical wind shear is a major cause of CAT. When a large shear exists between two layers of a fluid with a stable density configuration the boundary can become distorted into an amplifying wave or billow which finally breaks down into turbulence. This process has been observed in the laboratory (Thorpe[2]), in the ocean (Woods[3]) and, by using a sensitive radar, in the atmosphere (Browning;[4] Browning, Watkins, Starr and McPherson[5]). A large static stability can inhibit the onset of KHI unless the shearing stress associated with the wind shear is sufficient to predominate. The Richardson number (*Ri*) is a measure of the relative size of these two opposing effects. This may be written in pressure co-ordinates :

$$Ri = -\frac{1}{\rho\theta}\,\frac{(\partial\theta/\partial p)}{(\partial \mathbf{V}/\partial p)^2}, \qquad \ldots (1)$$

where

ρ = density,

θ = potential temperature, and

$\dfrac{\partial \mathbf{V}}{\partial p}$ = vertical shear of horizontal wind.

It has been shown from theoretical considerations (Howard[6]) that $Ri < \frac{1}{4}$ is a necessary but not sufficient condition for the onset of KHI. Attempts have been made to locate areas of CAT using *Ri* fields produced from routine upper-air soundings. The correlation between *Ri* produced in this way and reports of CAT is rather poor mainly because of the poor vertical resolution of the upper-air data. Typically, upper winds are averaged over a vertical depth of about 750 m, yielding *Ri* over 1·5 km to 2 km, whilst 95 per cent of turbulent patches are less than 500 metres thick (Anderson[7]). When *Ri* is calculated from data of a finer vertical resolution, for example, data from a specially instrumented aircraft (Roach and Axford — submitted to the *Quarterly Journal of the Royal Meteorological Society*), there is a closer correlation, suggesting that the association of CAT with KHI is basically correct.

Roach attempted to avoid the problem of evaluating *Ri* from synoptic data by identifying areas where *Ri* was being reduced by the large-scale flow. Assuming hydrostatic, adiabatic, inviscid flow he obtained an expression for the rate of change of the logarithm of *Ri* (Reference 1, equation 10) which can be written in the following form :

$$\Phi \equiv -\frac{D}{Dt} \ln Ri$$

$$= (2\,Ri - 1) \left|\frac{\partial \mathbf{V}}{\partial p}\right| \left|\nabla_\theta p\right| \cos \beta$$

$$+ \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right) \cos 2\alpha - \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \sin 2\alpha \qquad \ldots (2)$$

where $\mathbf{V}$ = horizontal wind vector

$\nabla_\theta p$ = the horizontal pressure gradient in an isentropic surface

u = orthogonal component of $\mathbf{V}$ directed east

v = orthogonal component of $\mathbf{V}$ directed north

α = angle between $\dfrac{\partial \mathbf{V}}{\partial p}$ and north measured in a clockwise direction

β = angle between $\dfrac{\partial \mathbf{V}}{\partial p}$ and $\nabla_\theta p$ (which is 90° in geostrophic flow).

It was hoped that synoptic evaluation of Φ would delineate areas in which *Ri* was being rapidly reduced (Φ large and positive) until it fell below some small critical value and turbulence was initiated by KHI. Roach compared fields of Φ evaluated by hand from synoptic data with aircraft reports of severe turbulence and found little correlation between them, Φ sometimes being negative in the vicinity of the turbulence. He observed that the magnitudes of the multipliers $(\partial u/\partial x - \partial v/\partial y)$ and $(\partial u/\partial y + \partial v/\partial x)$ tended to be large in CAT areas. Roach also discussed the energetics of CAT production based on the principle that if the synoptic-scale deformation processes reduce *Ri* across a layer below its critical value the resultant turbulence tends to increase Ri across that layer. The turbulence will decay unless Ri can be maintained below its critical value by the deformation processes. An expression for the energy dissipation ε was derived by assuming that the turbulence (increasing Ri across the layer) works against the deformation processes (reducing Ri across the layer), the net result being that Ri across the layer is held to a small limiting value.

The resulting expression was :

$$\varepsilon = \Phi \frac{(\Delta \mathbf{V})^2}{24} \text{ for all positive } \Phi , \qquad \ldots (3)$$

where $\Delta \mathbf{V}$ denotes the velocity difference across the turbulent layer. The performance of ε as a locator of CAT was not examined by Roach and equal emphasis is placed in this paper on evaluating ε and a modified version of Φ.

Modified turbulence indices. It can be seen from equation (2) that the value of the index Φ is sensitive to the orientation of the vertical wind shear vector which can change rapidly with height, especially near the tropopause. Examples of this are shown as looped hodographs in References 4 and 8. Fields of the angles α and β cannot be derived from synoptic data with any degree of accuracy because of the poor spatial resolution of these data. It is believed that this is the cause of the rather random pattern of the Φ-fields obtained in the original tests. The index Φ has been modified to remove the effects of fluctuations in the orientation of the vertical wind-shear vector. The modified index Φ_m is derived in the Appendix and takes the form :

$$\Phi_m = (0{\cdot}3\ \zeta_a{}^2 + D_S{}^2 + D_T{}^2)^{\frac{1}{2}} \qquad \ldots (4)$$

where $\zeta_a = \partial v/\partial x - \partial u/\partial y + f$, the vertical component of absolute vorticity,

$D_S = \partial u/\partial y + \partial v/\partial x$, the shearing deformation, and

$D_T = \partial u/\partial x - \partial v/\partial y$, the stretching deformation.

A modified version of the index ε can be evaluated from equation (3) with Φ replaced by Φ_m. A difficulty arises in evaluating ε synoptically in that CAT is usually distributed as an ensemble of patches of various thickness throughout a region of the atmosphere of synoptic dimensions. $\Delta \mathbf{V}$, which should be evaluated across a turbulent layer, will depend strongly on the layer thickness. In this paper $\Delta \mathbf{V}$ has been evaluated between standard pressure levels appropriate to the heights of the turbulence reports. Thus the depth of the layer across which $\Delta \mathbf{V}$ is evaluated varies from 1400 m to 4200 m. To make comparison of the results possible it is necessary to normalize $\Delta \mathbf{V}$ to some standard thickness which in this paper is taken to be 500 m. As previously noted 95 per cent of turbulence patches are less than 500 metres thick. The resultant ε is designated ε_{500}.

Comparison of indices with turbulence reports on 24 November 1971. A special request for CAT reports near the British Isles resulted in 45 reports of moderate or severe turbulence being received on this day for times between 10 and 22 GMT. The high-power Defford radar was operational from 10 to 18 GMT and a large billow event was observed at 1113 GMT.

(a) *Synoptic situation.* The midday surface chart for the British Isles and immediate vicinity is shown in Figure 1. A ridge from a stationary high over the Atlantic covered the British Isles. As a deep low near Jan Mayen moved south-eastwards towards western Norway an associated warm front moved steadily south-eastwards across the British Isles. A north-north-easterly jet between 250 mb and 300 mb lay along the line Aughton–Camborne at midday. A ridge from an upper high to the west of the British Isles extended over the British Isles during the day as the jet weakened and moved away south-eastwards. A cross-section for midday from Long Kesh to De Bilt is shown in Figure 2. A notable feature of the midday ascents is a shear of 90 knots between 400 mb and 300 mb at Hemsby. This is associated with an upper frontal zone.

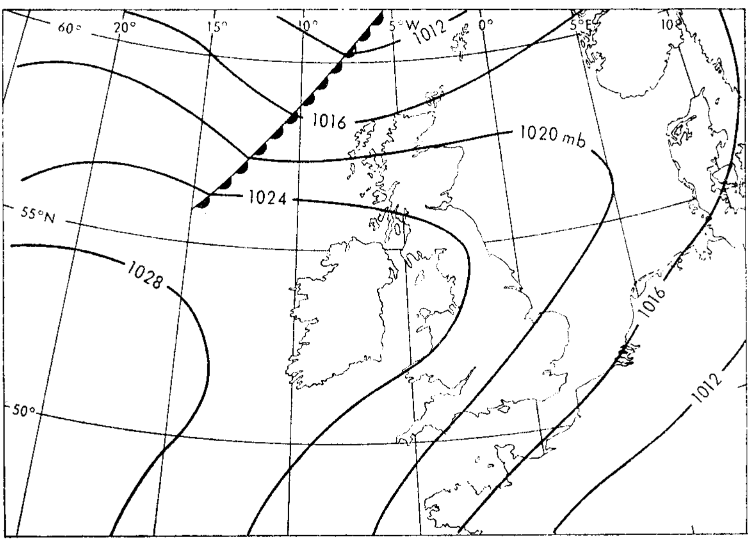

FIGURE 1—SURFACE CHART FOR 12 GMT, 24 NOVEMBER 1971

(b) *Indices and turbulence reports.* Fields of the indices Φ_m and ε_{500} have been evaluated for 12 GMT and 18 GMT at 400 mb and are reproduced in Figures 3–6. Richardson numbers for 12 GMT have been computed and are shown in Figure 7. The indices have been produced by hand analyses of the wind fields, $\Delta\mathbf{V}$ for ε_{500} being evaluated across the layer 500–300 mb. Many stages are involved in the analyses making it difficult to estimate the accuracy of the final product. Assuming that the winds are accurate to 1 m/s, taking the Coriolis parameter as 10^{-4} s^{-1}, and evaluating the wind gradients over 1000 km, the maximum error for $\Phi_m = 10^{-4}$ s^{-1} has been estimated at approximately 25 per cent. Small values of ε_{500} are very susceptible to errors in the winds because of the factor $(\Delta\mathbf{V})^2$. Using the assumptions made above the maximum error for $\varepsilon_{500} = 0{\cdot}25$ cm^2 s^{-3} has been estimated at 50 per cent, whilst for $\varepsilon_{500} = 2{\cdot}5$ cm^2 s^{-3} this is reduced to 26 per cent. These figures suggest that it is probably unwise to believe the smaller-scale features of the

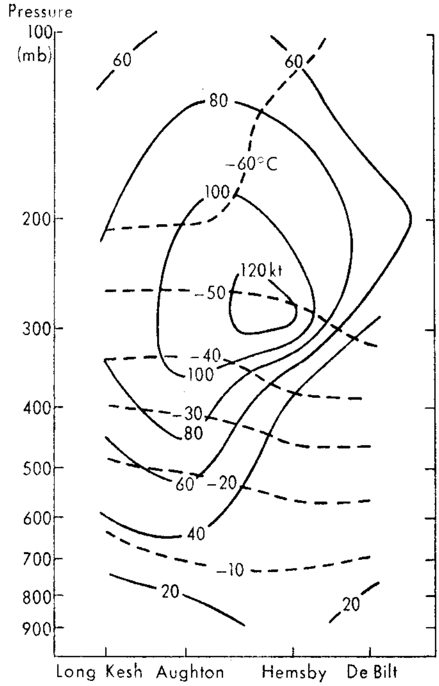

FIGURE 2—VERTICAL CROSS-SECTION OF WIND SPEED AND TEMPERATURE FROM LONG KESH TO DE BILT FOR 12 GMT, 24 NOVEMBER 1971

——— Wind speed perpendicular to section, in knots.
– – – – Temperature in degrees Celsius.

fields. There is a general coherence of shape and position of the fields between 12 GMT and 18 GMT making the gross features of the fields believable. All aircraft turbulence reports between 500 mb and 300 mb for two hours either side of 12 GMT and 18 GMT are superposed on Figures 3–7 to illustrate their positions relative to the fields of the indices and Richardson number. It can be seen that as the maxima of the fields of the indices move south-eastwards between 12 GMT and 18 GMT there is a corresponding displacement of the turbulence reports. It is not possible to observe the movement of the *Ri* field because no temperatures are available for its computation at 18 GMT. Considering the 12 GMT and 18 GMT data together the isopleth $\Phi_m = 10^{-4}\ s^{-1}$ encloses 83 per cent of the turbulence reports and 20 per cent of the chart area. Similarly the isopleth $\varepsilon_{500} = 0{\cdot}5$ encloses 83 per cent of the turbulence reports and 22 per cent of the chart area. At midday the isopleth $Ri = 5$ encloses 73 per cent of the reports and 26 per cent of the chart area. For this day Φ_m and ε_{500} are equally good at locating CAT and both seem slightly better than *Ri*. Time–height sections of the Φ_m and ε_{500} fields have been constructed for Malvern to make a comparison with the billow events observed there. These are shown in Figures 8 and 9. Besides data from the main synoptic hours some additional data have been used from special ascents made at Malvern.

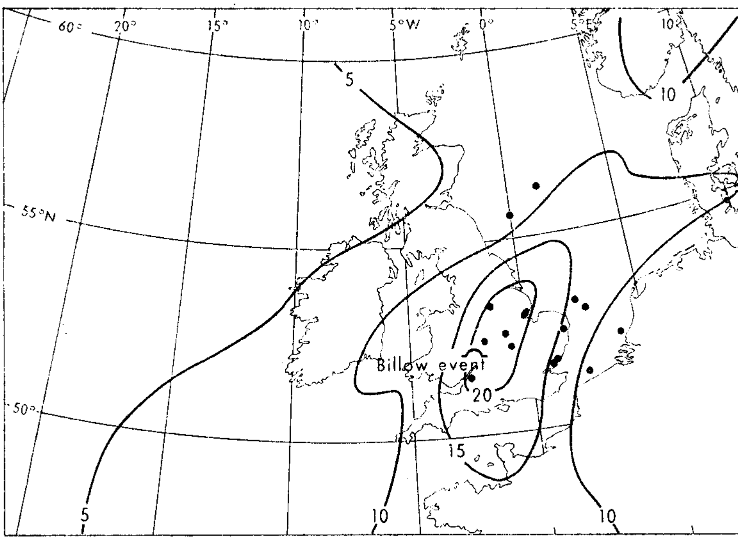

FIGURE 3—FIELD OF Φ_m AT 400 mb FOR 12 GMT, 24 NOVEMBER 1971 IN UNITS OF 10^{-5} s^{-1}

● Aircraft turbulence reports for 10 GMT to 14 GMT between 500 and 300 mb. The billow event was observed at Malvern at a height of 7·9 km at 1113 GMT.

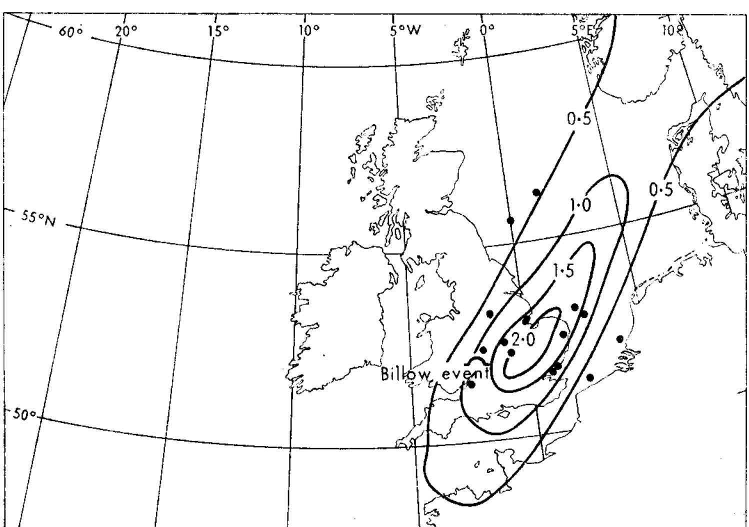

FIGURE 4—FIELD OF ε_{500} AT 400 mb FOR 12 GMT, 24 NOVEMBER 1971 IN UNITS cm^2 s^{-3}

See notes under Figure 3 for explanation of aircraft turbulence reports and billow event.

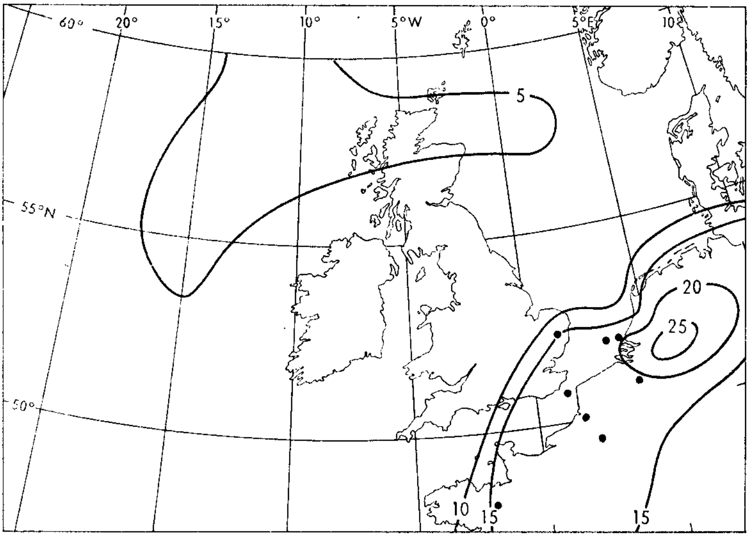

FIGURE 5—FIELD OF Φ_m AT 400 mb FOR 18 GMT, 24 NOVEMBER 1971 IN UNITS OF 10^{-5} s^{-1}

● Aircraft turbulence reports for 16 GMT to 20 GMT, between 500 and 300 mb.

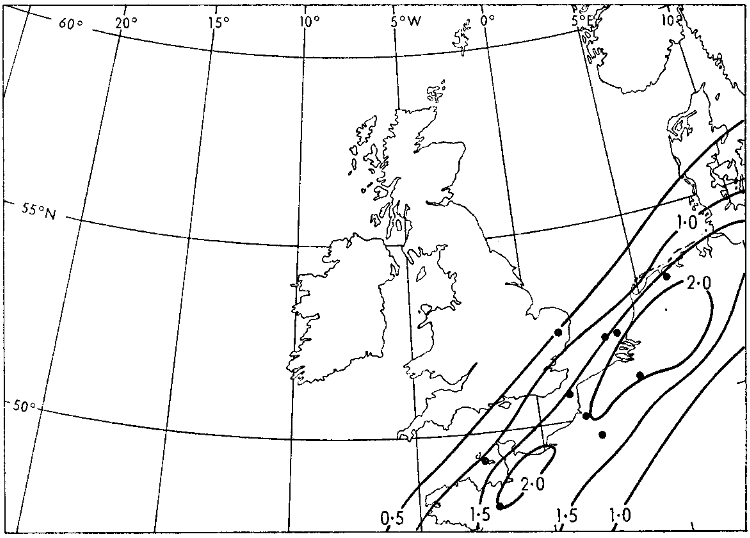

FIGURE 6—FIELD OF ε_{500} AT 400 mb FOR 18 GMT, 24 NOVEMBER 1971 IN UNITS cm^2 s^{-3}

See note under Figure 5 for details of aircraft turbulence reports.

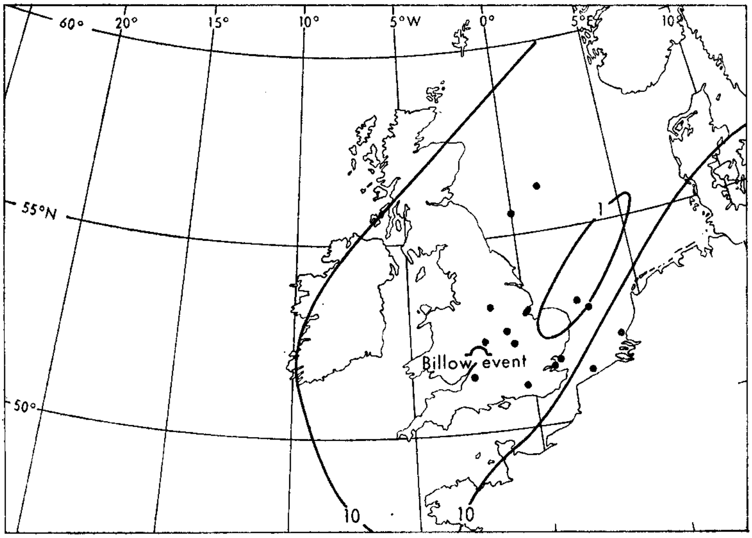

FIGURE 7—FIELD OF RICHARDSON NUMBER *Ri* EVALUATED BETWEEN 500 AND 300 mb FOR 24 NOVEMBER 1971

See notes under Figure 3 for explanation of aircraft turbulence reports and billow event.

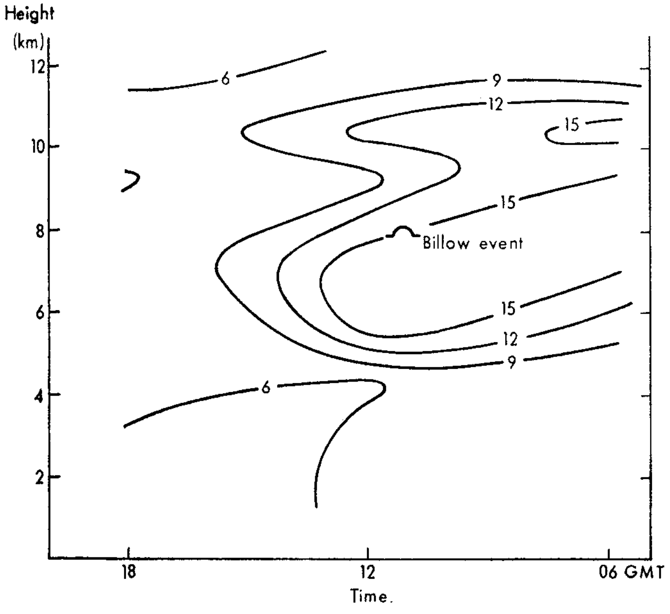

FIGURE 8—TIME–HEIGHT CROSS-SECTION OF Φ_m FOR MALVERN ON 24 NOVEMBER 1971 IN UNITS OF 10^{-5} s^{-1}

See note under Figure 3 for details of billow event.

A word of explanation is needed here concerning a billow event as observed by the Defford high-power radar. The Defford radar receives echoes from optically clear air which are attributed to temperature or humidity inhomogeneities occurring on a scale of half the radar wavelength, i.e. approximately 5 cm. These inhomogeneities are the result of turbulence caused by small-scale KHI. It is possible for KHI billows to occur in the atmosphere simultaneously on several scales, the largest having amplitudes of several hundred metres. The radar has a resolution of 100–200 m and if the larger-scale KHI billows do not exceed this in amplitude the radar echoes are observed to be featureless layers. When billows of a larger amplitude occur a certain degree of their structure is resolved by the radar and their amplitude and wavelength can be measured.

Such an event was observed on 24 November 1971 and its position is marked on the time–height sections. It occurred in a region of above-average Φ_m and ε_{500} values. As the radar was out of use during the earlier part of the day when the largest Φ_m and ε_{500} values occurred other billow events may have taken place unobserved.

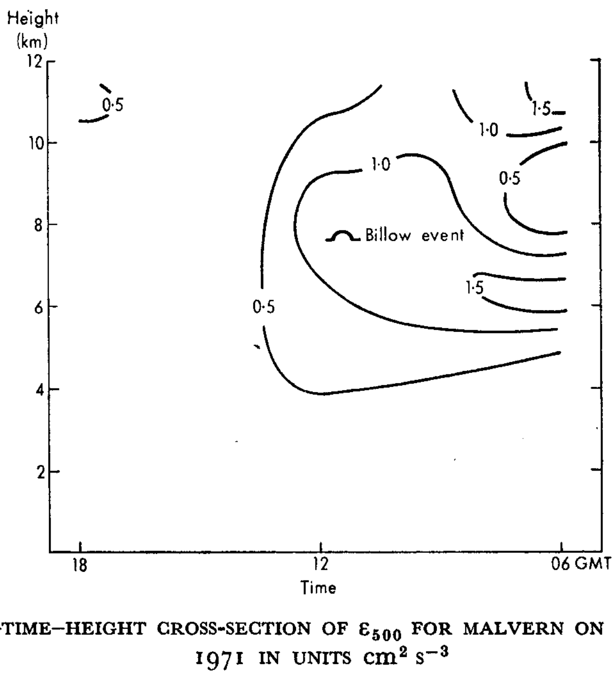

FIGURE 9—TIME–HEIGHT CROSS-SECTION OF ε_{500} FOR MALVERN ON 24 NOVEMBER 1971 IN UNITS $cm^2\ s^{-3}$

See note under Figure 3 for details of billow event.

Further tests of the indices. Fields of the indices have been produced by hand for another 11 days when either aircraft reports of severe CAT were received or billow events were observed using the Defford high-power radar. The indices have been evaluated at the standard levels appropriate to the heights of the turbulence reports and over the same chart area as that used for the 24 November 1971 case study. Typically the number of reports varied from one to five so that no individual day is worth a case study. Considered together they give an indication of the performance of the indices. Tables I, II and III show the number of turbulence reports occurring where Φ_m and ε_{500} are larger than certain values and *Ri* is less than certain values. To see these figures in perspective one must consider the fraction of the chart area covered on average by various values of the indices and this is shown in the second column of the tables. In Figure 10, which summarizes Tables I–III, the number of turbulence reports, converted to a percentage of the total, is plotted against the corresponding percentage chart area. A line bisecting the angle between the axes of this graph represents no skill at locating CAT, i.e. by chance one would expect to find 50 per cent of the reports on average in 50 per cent of the chart area. The significance of the figures in the first two columns of the tables has been examined statistically. There is a small probability of finding any one turbulence report in a given area of the chart and hence it has been assumed that the probability of a certain number of the reports falling by chance in a fraction of the chart area is governed by a

TABLE I—NUMBER OF TURBULENCE REPORTS LOCATED WHERE Φ_m IS LARGER THAN CERTAIN VALUES, THE FRACTIONAL CHART AREA WHERE Φ_m IS LARGER THAN THESE VALUES ON AVERAGE, AND THE SIGNIFICANCE LEVEL OF THESE FIGURES, BASED ON A TOTAL OF 24 TURBULENCE REPORTS

$\Phi_m \times 10^5$	Number of turbulence reports (X)	Fraction of chart area (A)	Significance level
s^{-1}			*per cent*
$\geqslant 10$	17	0·39	1·5
$\geqslant 15$	7	0·10	1·0
$\geqslant 20$	2	0·024	12
$\geqslant 25$	1	0·011	26

TABLE II—NUMBER OF TURBULENCE REPORTS LOCATED WHERE ε_{500} IS LARGER THAN CERTAIN VALUES, THE FRACTIONAL CHART AREA WHERE ε_{500} IS LARGER THAN THESE VALUES ON AVERAGE, AND THE SIGNIFICANCE LEVEL OF THESE FIGURES, BASED ON A TOTAL OF 24 TURBULENCE REPORTS

ε_{500}	Number of turbulence reports (X)	Fraction of chart area (A)	Significance level
$cm^2\ s^{-3}$			*per cent*
$\geqslant 0·1$	17	0·48	5
$\geqslant 0·2$	10	0·36	36
$\geqslant 0·5$	10	0·18	1
$\geqslant 1·0$	9	0·08	0·02
$\geqslant 2·0$	5	0·024	0·04
$\geqslant 3·0$	2	0·006	0·5

TABLE III—NUMBER OF TURBULENCE REPORTS LOCATED WHERE *Ri* IS LESS THAN CERTAIN VALUES, THE FRACTIONAL CHART AREA WHERE *Ri* IS LESS THAN THESE VALUES ON AVERAGE, AND THE SIGNIFICANCE LEVEL OF THESE FIGURES, BASED ON A TOTAL OF 24 TURBULENCE REPORTS

Ri	Number of turbulence reports (X)	Fraction of chart area (A)	Significance level
			per cent
$\leqslant 20$	17	0·55	16
$\leqslant 10$	10	0·35	33
$\leqslant 5$	9	0·23	11
$\leqslant 1$	1	0·02	9

Poisson distribution. If m is the mean number of reports found in a fraction A of the chart area ($m = NA$, where N is the total number of CAT reports) and $P(x)$ the probability that x reports will fall at random in a fraction A of the area then

$$P(x) = \frac{e^{-m}\, m^x}{x!} \qquad \ldots (5)$$

A more meaningful statistic in this case is the probability P that x or more reports will fall at random in a fraction A of the chart area, and this is given by the summation

$$P(x) = \sum_{J=x}^{J=\infty} \frac{e^{-m}\, m^J}{J!} \qquad \ldots (6)$$

The columns headed 'significance level' in Tables I–III show the values of P expressed as a percentage for the corresponding X and A values in the tables. Values of P less than 5 per cent may be taken as showing a significant departure from a random distribution. The most outstanding feature of the results can be seen by referring to Table II. The number of CAT reports found where $\varepsilon_{500} \geqslant 0{\cdot}5$ cm^2 s^{-3} is significantly larger than that expected

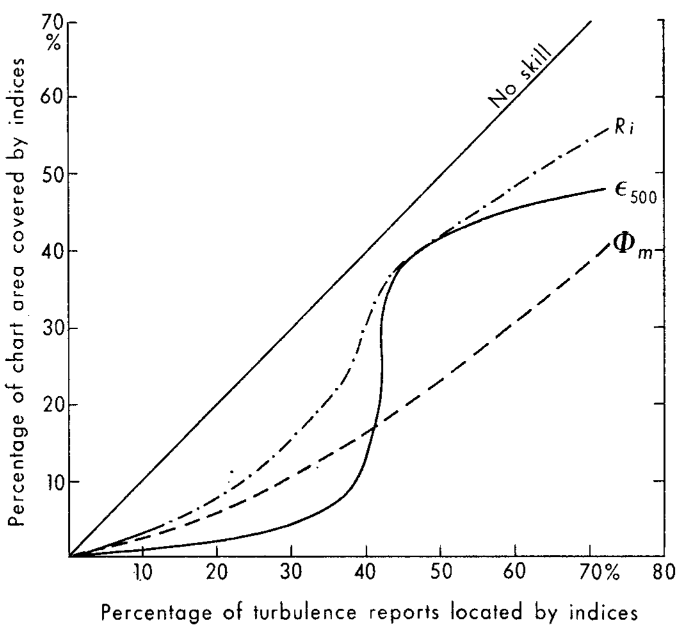

FIGURE 10—SUMMARY OF TABLES I–III

The number of turbulence reports converted to a percentage is plotted against the fractional chart area also converted to a percentage.

by chance. In Table I it can be seen that there is a significant tendency for CAT reports to be located where $\Phi_m \geqslant 10^{-4}$ s^{-1}. The results for $\varepsilon_{500} \leqslant 0{\cdot}2$ cm^2 s^{-3} and those for $\Phi_m \geqslant 2 \times 10^{-4}$ s^{-1} do not differ from those expected purely by chance. Both indices are superior to *Ri* in locating the turbulence reports, and the performance of the latter is not noticeably different from that expected purely on the basis of chance. The areas required by Φ_m and ε_{500} to locate the majority of the turbulence reports are large. The fields of the indices have been evaluated over an area extending from 48°N to 60°N and 20°W to 10°E. If turbulence occurs within this region it is likely to cover approximately a third of the chart area. The indices have only been evaluated when turbulence was reported within this region. It is possible that if the indices had been evaluated over a much larger area the fractional values in Tables I–III would have been reduced.

Conclusion. The tests described in this paper are open to criticism on the grounds that they are only based on positive reports of CAT. To relate the indices to the probability of encountering CAT it is necessary to have a substantial body of nil reports for the days that CAT was not reported. These were not available at the time this work was performed. It is believed that the tests do show a qualitative relationship between the indices and reports of CAT. These reports are not randomly distributed but are preponderant in areas of large ε_{500} values and above-average Φ_m values. The performance of the indices seems sufficiently encouraging to warrant their further development. This will involve the evaluation of the indices by computer from the output of the Bushby–Timpson 10-level model and comparison with a large body of specially commissioned aircraft observations of CAT and its absence.

Acknowledgement. The author is most grateful to Dr W. T. Roach for his helpful suggestions during the course of this work.

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Appendix I — The derivation of the expression (4) **for the index Φ_m.** By referring to equation (4) it can be seen that there are three terms within parentheses in the expression for Φ_m. The first of these terms is derived from the first term on the right-hand side of equation (2). Removing the factor $2Ri$ from within the parentheses, using equation (1) and noting that

$\nabla_p \theta = -\left(\dfrac{\partial \theta}{\partial p}\right) \nabla_\theta p$ one may write

$$(2\,Ri - 1)\,\frac{\partial \mathbf{V}}{\partial p} \cdot \nabla_\theta p = 2(1 - 0\cdot5\,Ri^{-1})\,\frac{(\partial \mathbf{V}/\partial p).\nabla_p \theta}{\rho\theta\,(\partial \mathbf{V}/\partial p)^2}\,. \quad \ldots (1\text{A})$$

Using the gas equation, the equation for hydrostatic equilibrium in the form $\dfrac{\partial p}{\partial \varphi} = -\rho$ (where φ is the geopotential), and noting that $\dfrac{\nabla_p \theta}{\theta} = \dfrac{\nabla_p T}{T}$ one can show that

$$\frac{\nabla_p \theta}{\rho\theta} = -\frac{\partial}{\partial p}\,(\nabla_p \varphi)\,. \quad \ldots (2\text{A})$$

The thermal wind equation may be written in terms of the geopotential in the following way :

$$\frac{\partial}{\partial p}\,(\nabla_p \varphi) = -f\mathbf{k} \times \frac{\partial \mathbf{V}_g}{\partial p} \quad \ldots (3\text{A})$$

where f is the Coriolis parameter, $\mathbf{k}$ the unit vector along the vertical, and $\mathbf{V}_g$ the geostrophic wind.

Eliminating $\dfrac{\partial}{\partial p}\,(\nabla_p \varphi)$ from equations (2A) and (3A) and using the result to eliminate $\dfrac{\nabla_p \theta}{\rho\theta}$ from equation (1A) one may write

$$(2\,Ri - 1)\,\frac{\partial \mathbf{V}}{\partial p} \cdot \nabla_\theta p = 2(1 - 0\cdot5\,Ri^{-1})\,\frac{\partial \mathbf{V}}{\partial p} \cdot \frac{f\mathbf{k} \times \partial \mathbf{V}_g/\partial p}{(\partial \mathbf{V}/\partial p)^2}$$

$$= 2(1 - 0\cdot5\,Ri^{-1})\,\frac{f\,\partial \mathbf{V}_g/\partial p}{\partial \mathbf{V}/\partial p}\,\sin\gamma \quad \ldots (4\text{A})$$

where γ is the angle between $\dfrac{\partial \mathbf{V}}{\partial p}$ and $\dfrac{\partial \mathbf{V}_g}{\partial p}$.

Assume now that the horizontal wind $\mathbf{V}$ is given by the gradient wind equation

$$\mathbf{V}^2 K = f\,(\mathbf{V}_g - \mathbf{V}) \quad \ldots (5\text{A})$$

where K = curvature of trajectory.

Differentiating equation (5A) with respect to pressure,

$$f\frac{\partial \mathbf{V}_g}{\partial p} = \frac{\partial \mathbf{V}}{\partial p}(f + 2K\mathbf{V}) + \mathbf{V}^2\frac{\partial K}{\partial p}. \qquad \ldots (6A)$$

The following assumptions are now made concerning equation (6A) :

(a) $\mathbf{V}^2 \dfrac{\partial K}{\partial p}$ may be neglected in comparison with the other terms.

(b) Noting that the vertical component of absolute vorticity may be written $\zeta_a = f + \dfrac{\partial \mathbf{V}}{\partial r} + K\mathbf{V}$ (where $K = \dfrac{1}{r}$) and assuming that $K\mathbf{V}$ and $\dfrac{\partial \mathbf{V}}{\partial r}$ are of the same sign and roughly the same size then from equation (6A) :

$$f\frac{\partial \mathbf{V}_g}{\partial p} \approx \zeta_a \frac{\partial \mathbf{V}}{\partial p}. \qquad \ldots (7A)$$

Combining equations (7A) and (4A) :

$$(2\,Ri - 1)\frac{\partial \mathbf{V}}{\partial p}\cdot \nabla_\theta p \approx 2(1 - 0{\cdot}5\,Ri^{-1})\,\zeta_a \sin\gamma. \qquad \ldots (8A)$$

The term $(1 - 0{\cdot}5\,Ri^{-1})$ is assumed to be of order unity to avoid a separate evaluation of Ri. The angle γ cannot be evaluated meaningfully synoptically and the factor 2 sin γ is accordingly omitted, leaving ζ_a as an approximation to the first term of Φ. Originally $\zeta_a{}^2$ appeared as the first term within the parentheses in the expression for Φ_m. This dominated the other terms in regions of calm where ζ_a tends to f. In order to reduce this spurious effect the first term was reduced by an arbitrary factor to $0{\cdot}3\,\zeta_a{}^2$. The derivation of the terms $D_S{}^2$, $D_T{}^2$ within parentheses in the expression for Φ_m is now considered. Looking at the right-hand side of equation (2) it can be seen that the value of the second and third terms depends strongly on the angle α.

It became clear during the trials of Φ that the angles change rapidly with height, producing a quasi-periodic oscillation in the magnitude of these terms of an amplitude determined by the multipliers $(\partial u/\partial x - \partial v/\partial y)$ and $(\partial u/\partial y + \partial v/\partial x)$. The multipliers themselves also change with height, but rather less rapidly so that a characteristic profile of the last two terms of equation (2) would appear as in Figure 11 with the dotted curve forming the modulus of the oscillations. Roach, in a private communication, has suggested that it would be more meaningful to estimate this modulus as an indication of the general intensity of the deformation processes in a region of synoptic dimensions. This modulus is given by the expression $(D_S{}^2 + D_T{}^2)^{\frac{1}{2}}$. The square of the total deformation has been used by others, notably Endlich,[9] as a CAT forecasting index. In formulating the modified index Φ_m the first term of Φ has been effectively approximated by $(0{\cdot}3)^{\frac{1}{2}}\,\zeta_a$ and the second and third terms by $(D_S{}^2 + D_T{}^2)^{\frac{1}{2}}$. The approximate terms contain no information about the sign of the equivalent terms in the original index, which even if large may be of the opposite sign. To avoid producing unrealistically large values Φ_m is not formed from the algebraic sum of $(0{\cdot}3)^{\frac{1}{2}}\,\zeta_a$ and $(D_S{}^2 + D_T{}^2)^{\frac{1}{2}}$ but in the following manner :

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$$\Phi_m = (0{\cdot}3\ \zeta_a{}^2 + D_S{}^2 + D_T{}^2)\ . \qquad \ldots (9A)$$

Finally the index ε_{500} is defined by

$$\varepsilon_{500} = \Phi_m \frac{(\Delta \mathbf{V})^2}{24}\,, \qquad \ldots (10A)$$

where $\Delta\mathbf{V}$ is the velocity difference normalized across a 500-metre layer.

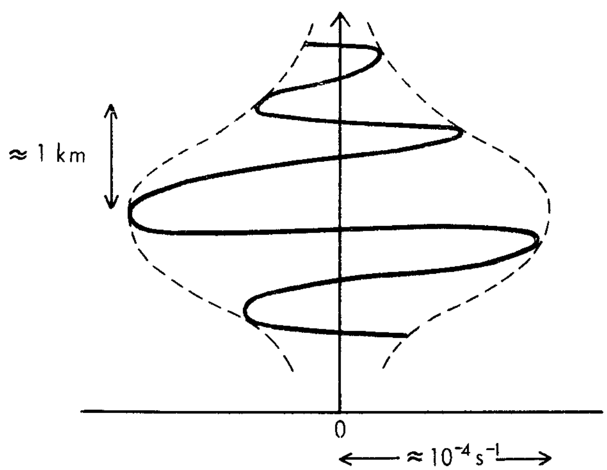

FIGURE 11—IDEALIZED ILLUSTRATION OF RELATIONSHIP BETWEEN $(D_T \cos 2\alpha - D_S \sin 2\alpha)$ AND $(D_T{}^2 + D_S{}^2)^{\frac{1}{2}}$ WHEN VECTOR $\partial\mathbf{V}/\partial p$ IS ROTATING WITH HEIGHT

——— $(D_T \cos 2\alpha - D_S \sin 2\alpha)$
- - - - $(D_T{}^2 + D_S{}^2)^{\frac{1}{2}}$
α is the angle between $\partial\mathbf{V}/\partial p$ and North.

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HIGH VALUES OF DAILY AREAL RAINFALL OVER ENGLAND AND WALES AND SYNOPTIC PATTERNS

By E. N. LAWRENCE

Summary. Seasonal and secular variation of the higher values of daily areal rainfall is examined in relation to synoptic patterns. During recent years, there has been an increase in the number of days with high values of areal rainfall and also an increase in the frequency of days of cyclonic weather type. Seasonal variation suggests that thermal instability is an important factor.

Introduction. Daily values of areal rainfall over England and Wales were calculated for the period 1950–72, mainly for the purpose of obtaining synoptic-type rainfall averages. In this note, the seasonal and secular variation of the higher values of daily areal rainfall is discussed in relation to synoptic patterns.

Method. The method of calculating daily areal rainfall over England and Wales is described elsewhere.[1] For various rainfall thresholds, the annual variation, by month and by quarter, is shown in Table I and the individual quarterly and yearly values are given in Table II. Occasions of daily areal rainfall of 20 mm (0·79 inches) or more are listed in Table III which shows the associated synoptic type[2] and the mean midday surface pressure.

Results. From the number of occurrences of daily values of areal rainfall $\geqslant$10, $\geqslant$15, $\geqslant$20 and $\geqslant$25 mm, presented in Table I, it can be seen that for thresholds up to and including $\geqslant$20 mm, the number of occurrences is highest in November and lowest in April (but zero in May for daily values $\geqslant$20 mm). For daily values of rainfall $\geqslant$25 mm, two occasions occurred in July and the other four in April, September, October and December. Two of the three occasions of daily rainfall $\geqslant$30 mm occurred in July (the other occasion being in October) and the absolute maximum value of daily rainfall also occurred in July.

Days of areal rainfall $\geqslant$10 mm occurred with various synoptic types as follows: 149 cyclonic days, that is, 13·0 per cent of all cyclonic days; 82 days (5·7 per cent) of straight-westerly type; and 20 days (7·0 per cent) of cyclonic-westerly type. These synoptic types refer to the Lamb catalogue of daily synoptic types.[2] For the threshold $\geqslant$20 mm (see Table III), the corresponding percentages are 1·0, 0·3, 0·3; and for the threshold $\geqslant$25 mm, the percentages are 0·3, 0·07 and nil (that is, for cyclonic, straight-westerly, and cyclonic-westerly types, respectively). Clearly, the synoptic type most strongly associated with the higher values of daily areal rainfall is the cyclonic type.

It can be seen from the indication of pressure level (Table III), that high values of daily areal rainfall tend to occur with about average pressures in summer and reflect the effects of thermal convection or thermal lows.[3] In contrast, the cyclonic pressure levels on occasions of high daily rainfall during the winter half-year are generally associated with baroclinic lows of well-below-average pressure.

The yearly values of the number of occurrences of areal rainfall exceeding 20 mm per day (Table II) increased markedly during the period; for example, there are 4 occasions in the 1950s, 12 occasions in the 1960s and 6 in the period 1970–72: again, daily values exceeding 25 mm occurred only in the years 1960, 1967, 1968, 1969, 1971 and 1972, while daily values exceeding 30 mm occurred only in 1967, 1968 and 1969. The results of a variance ratio analysis (F-test) on the three equal periods of seven years in the 21 years ending at 1972 show that the annual frequency of days with 25 mm or more has period differences which are significant at the one per cent level (that is, less than one chance in a hundred of the series occurring by accident). The series for 20 mm or more shows a corresponding significance at the five per cent level.

The yearly frequencies of days with cyclonic type are shown in Figure 1. It can be seen that the period from 1952 onwards indicates a change (which can be best represented by a linear term) which has less than one chance in 50 of arising by accident in the sampling of such data.

Conclusion. There has been an increase in the number of days with high values of areal rainfall ($\geqslant$20 mm) over England and Wales during recent years. During the same period, there has also been an increase in the frequency

TABLE I—MONTHLY AND SEASONAL DISTRIBUTION OF HIGH VALUES OF DAILY AREAL RAINFALL EQUALLING OR EXCEEDING VARIOUS LIMITS, OVER ENGLAND AND WALES DURING THE PERIOD FROM 1950 TO 1972

	Jan.	Feb.	Mar.	Jan.–Mar.	Apr.	May	June	Apr.–June	July	Aug.	Sept.	July–Sept.	Oct.	Nov.	Dec.	Oct.–Dec.
								Number of days								
⩾10 mm (0·39 in)																
1950–59	17	19	9	45	5	8	10	23	16	21	18	55	13	29	16	58
1960–69	16	10	10	36	4	8	13	25	16	16	22	54	20	23	22	65
1970–72	4	0	3	7	3	1	3	7	0	3	1	4	2	16	3	21
1950–72	37	29	22	88	12	17	26	55	32	40	41	113	35	68	41	144
⩾15 mm (0·59 in)																
1950–59	2	2	1	5	1	3	5	9	4	4	4	12	5	8	1	14
1960–69	2	1	2	5	0	2	4	6	4	2	6	12	5	5	5	15
1970–72	0	0	1	1	1	0	2	3	0	2	1	3	0	6	1	7
1950–72	4	3	4	11	2	5	11	18	8	8	11	27	10	19	7	36
⩾20 mm (0·79 in)																
1950–59	0	1	0	1	0	0	0	0	0	0	0	0	1	2	0	3
1960–69	1	1	2	4	0	0	0	0	2	1	1	4	2	1	1	4
1970–72	0	0	0	0	1	0	2	3	0	0	1	1	0	2	0	2
1950–72	1	2	2	5	1	0	2	3	2	1	2	5	3	5	1	9
⩾25 mm (0·98 in)																
1950–59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1960–69	0	0	0	0	0	0	0	0	2*	0	0	2	1†	0	1	2
1970–72	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
1950–72	0	0	0	0	1	0	0	1	2	0	1	3	1	0	1	2

* 32·3 mm (1·27 in) and 39·1 mm (1·54 in).
† 31·2 mm (1·23 in).

TABLE II—NUMBER OF OCCASIONS OF DAILY AREAL RAINFALL OVER ENGLAND AND WALES EQUALLING OR EXCEEDING VARIOUS LIMITS DURING EACH QUARTER AND EACH YEAR FROM 1950 TO 1972

	1950	'51	'52	'53	'54	'55	'56	'57	'58	'59	'60	'61	'62	'63	'64	'65	'66	'67	'68	'69	'70	'71	'72
											Number of days												
$\geqslant$10 mm																							
Jan.–Mar.	7	7	1	3	3	6	3	4	6	5	6	3	4	3	3	2	5	4	2	4	1	4	2
Apr.–June	1	2	0	3	5	6	0	1	3	2	1	4	1	2	2	2	2	5	3	3	1	4	2
July–Sept.	11	7	6	5	5	0	7	6	6	2	8	5	6	7	1	6	4	4	9	4	1	2	1
Oct.–Dec.	3	6	7	3	13	5	4	3	5	9	12	5	3	3	3	9	8	8	7	7	10	4	7
Year	22	22	14	14	26	17	14	14	20	18	27	17	14	15	9	19	19	21	21	18	13	14	12
$\geqslant$15 mm																							
Jan.–Mar.	1	0	1	0	0	0	0	0	1	2	1	0	0	0	1	0	0	1	1	1	0	1	0
Apr.–June	0	1	0	1	3	1	0	0	2	1	1	0	0	0	0	1	1	2	1	0	0	3	0
July–Sept.	2	2	0	0	1	0	3	2	1	1	1	1	3	0	0	3	1	0	2	1	1	1	1
Oct.–Dec.	2	2	1	0	3	0	1	1	2	2	4	1	0	2	1	3	1	2	0	1	4	1	2
Year	5	5	2	1	7	1	4	3	6	6	7	2	3	2	2	7	3	5	4	3	5	6	3
$\geqslant$20 mm																							
Jan.–Mar.	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	0	1	0	0	0
Apr.–June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
July–Sept.	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	1	0	0	1
Oct.–Dec.	0	1	0	0	0	0	0	1	0	1	2	0	0	1	0	0	0	1	0	0	1	0	1
Year	0	1	0	0	0	0	0	1	1	1	3	0	2	1	1	0	0	2	1	2	1	3	2
$\geqslant$25 mm																							
Jan.–Mar.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr.–June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
July–Sept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
Oct.–Dec.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Year	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1*	1*	1*	0	1	1

* Values $\geqslant$30 mm: 31·2 mm (1·23 in); 32·3 mm (1·27 in); 39·1 mm (1·54 in), respectively.

TABLE III—OCCASIONS OF DAILY AREAL RAINFALL OVER ENGLAND AND WALES EQUALLING OR EXCEEDING 20 mm DURING THE PERIOD 1950–72

Year	Month	Day	Rainfall *mm*	Rainfall *in*	Synoptic type*	Surface pressure† *mb*
1951	Nov.	5	23·1	0·91	C	994
1957	Nov.	3	20·3	0·80	W	986
1958	Feb.	24	20·1	0·79	C	994
1959	Oct.	26	22·4	0·88	W	1009
1960	Jan.	23	20·1	0·79	SW	996
1960	Oct.	8	21·6	0·85	C	996
1960	Dec.	3	29·0	1·14	W	1000
1962	Aug.	6	24·1	0·95	C	1006
1962	Sept.	29	20·8	0·82	S	996
1963	Nov.	17	20·8	0·82	C	998
1964	Mar.	14	21·6	0·85	S	998
1967	Feb.	27	20·3	0·80	W	1000
1967	Oct.	16	31·2	1·23	C	1006
1968	July	10	32·3	1·27	CE	1016
1969	Mar.	12	20·1	0·79	U	1003
1969	July	28	39·1	1·54	C	1015
1970	Nov.	1	21·1	0·83	CW	1012
1971	Apr.	23	25·7	1·01	C	1003
1971	June	10	23·6	0·93	CNE	1010
1971	June	18	24·1	0·95	C	1016
1972	Sept.	8	27·7	1·09	U	1014
1972	Nov.	12	20·1	0·79	C	1002

* C = cyclonic, CNE = cyclonic north-easterly, etc., U = unclassified.
† Pressure at 53°N 2°W at midday on *Daily Weather Report* chart.

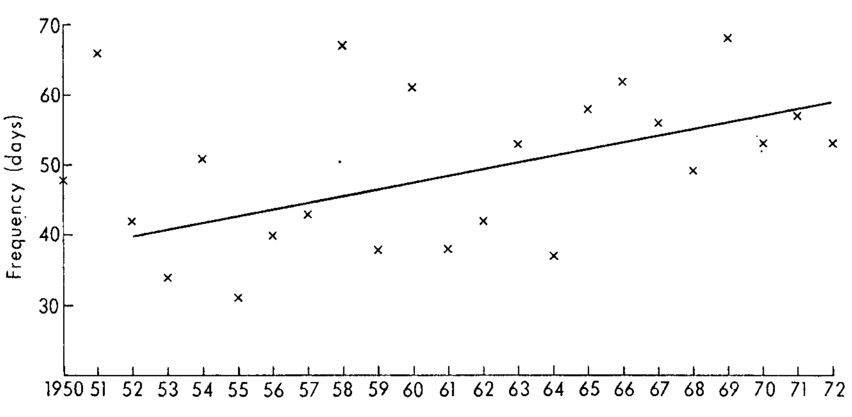

FIGURE 1—YEARLY FREQUENCY OF CYCLONIC TYPES (LAMB CLASSIFICATION) 1950 TO 1972, AND THE LINEAR COMPONENT FOR 1952 TO 1972

of days of cyclonic weather type, thus confirming the association of high areal rainfall with cyclonic weather, though high values of areal rainfall occur with other synoptic weather types and especially when thermal instability is an important factor. This study describes the fluctuations that have occurred in the recent past but does not indicate the changes to be expected in the near future; indeed, it is not possible to say that the indicated 'trends' will continue.

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REVIEWS

Introduction to the nonlinear theory of mesoscale meteorological processes by L. N. Gutman. 240 mm × 175 mm, pp. vi + 224, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), John Wiley & Sons Ltd, Baffins Lane, Chichester, Sussex, 1972. Price: £10·35.

Many aspects of the weather such as fog, showers, sea breezes and frontal phenomena, which affect people and communities, are on a small scale, less than hundreds of kilometres in horizontal extent. The local weather forecasts issued by state meteorological services are often interpretations of the synoptic-scale forecasts in terms of these smaller-scale, or mesometeorological, events and these forecasts are of extreme importance to those who must endure the weather. Mesometeorological research is not new; forecasters have been trying to understand local weather conditions almost since forecasting began and descriptions and theories are to be found in the great meteorological texts of a hundred years ago. Since then the literature has abounded in rules for description and prediction but little of the research has been on a connected basis, concerned with generalities. The substantial progress that has been made with numerical prediction on the synoptic and global scales suggests that the numerical approach to mesometeorological processes may be expected to yield success; at the same time the synoptic numerical forecasts provide the background against which the mesometeorological systems develop. There is little doubt that expression of the physics of mesometeorological phenomena in terms of mathematics for introduction into numerical weather prediction will be a major preoccupation of research in the next decade.

Dr Gutman's book, which was published in the U.S.S.R. in 1969, is therefore very timely. It seeks to provide the mathematical abstractions of some of the main mesometeorological processes and it indicates obliquely how these abstractions might be used to provide numerical forecasts. The author considers six main topics; in each he follows the same pattern — a short introductory history of the problem, the simplified equations with some solutions and then some rather fuller equations which are usually insoluble in analytic terms except in rather special cases. The topics are topographical effects, fronts, thermals, cumulus clouds, whirlwinds and tornadoes, and sea-breezes and other local winds. The longest chapter is that on wave motions produced by topography and though it differs in detail from the well-known WMO *Technical Note* No. 34 the development is rather similar. The problems attacked in the other chapters are, of course, much harder because the heat and energy sources and sinks become much more important than in the mountain wave problem and the non-linear effects are considerably increased. The first simplifications, generally having the effect of linearizing the mathematics, give analytic solutions which are at best illustrative and at worst misleading. The second simplifications which include some of the non-linear effects, usually of the dynamical advective terms rather than the physical terms, lead to computed solutions which must be more realistic and these results are well worth looking at.

Perhaps one of the most welcome features of the book is that it provides a résumé of recent Russian research into mesometeorological problems which may not otherwise be easily available. Dr Gutman is well aware also of the work of western authors, as his text and bibliography show. There is no comparable text published in English and the book is bound to be read with great interest as providing a good theoretical basis for attacking meso-meteorological problems.

The translation reads easily and the odd misprint is not likely to mislead. The book is beautifully produced, but alas its price is high even by today's standards and most people will have to be content with referring to a library copy.

E. KNIGHTING

Atmospheric energetics, by Jacques van Mieghem. 235 mm × 155 mm, pp. ix + 306, *illus.*, Clarendon Press: Oxford University Press, 37 Dover Street, London W1X 4AH, 1973. Price: £7·50.

The outward show of the atmosphere is weather — temperature, cloud cover, rain and so on — and locally this is the most important aspect. Yet weather is a product of the motions resulting from the uneven solar heating of the earth/atmosphere system which presents the system with the problem of transferring energy from the equatorial to polar regions and it is not until it is known how this energy is transferred that one can claim to understand atmospheric processes. The general mechanisms, the Hadley circulation and the large-scale atmospheric vortices are well known from observations but need considerable clarification before they become acceptable explanations of the energy transfer. Professor van Mieghem sets out in this book to provide a systematic account of this transfer of kinetic, potential and thermal energies.

He starts by carefully treating in the first half-dozen chapters the fundamental equations of motion and the idea of resolving motions into a basic and fluctuating part and the application to turbulent flow. Two chapters follow on forced and free convection; they are a concise treatment of turbulence near the ground, very necessary because there are important sources and sinks of energy in the boundary layer. The remainder of the book deals with the energy in the free atmosphere. Following normal practice the flow at any given instant is separated into a zonal period average, obtainable from climatology, and departures from this average, the latter usually being termed eddy motions. Equations can then be developed for the energetics of the system, the rates of change of the mean and eddy kinetic and potential energies and their northward transfer. Because the equations of motion are non-linear there must be considerable interaction between waves of different wavelength, e.g. between the weather-bearing systems and the general circulation, and formal expressions are obtainable for the way in which energy is passed from scale to scale. The study of these equations along with the observations allows one to see the inner working of the atmosphere, the cycle of energy conversions and transfers. The equations are particularly suitable for use with the computed results from atmospheric models of the general circulation and provide insight into the atmospheric behaviour in regions where there are few observations.

Professor van Mieghem leads us through all the difficulties in his impeccably logical style and his reduction of the papers in the literature to a readable concision is quite a *tour de force*. Of course, the book is highly mathematical with a large number of equations because the subject matter is highly numerate; however, it is essentially all the same kind of mathematics and not difficult to follow. It is a particularly opportune moment for publication, since the energetics of the atmosphere will be closely studied over the next few years when the Atlantic Tropical Experiment of the Global Atmospheric Research Programme (GARP) and the First GARP Global Experiment (FGGE) will provide a great deal of extra observational data.

E. KNIGHTING

Turbulent diffusion in the environment, by G. T. Csanady. 240 mm × 160 mm, pp. x + 248, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht, Holland, 1973. Price: Dfl. 40.– –. (hard-cover edition Dfl. 70.– –).

Dr Csanady's book is concerned primarily with the theoretical and mathematical treatment of turbulent diffusion problems and has sprung from courses given to engineering graduate students specializing in environmental fluid mechanics. It consists of seven chapters dealing with the following topics: molecular diffusion and Fick's 'constant diffusivity' law, statistical theory in the context of Brownian motion and random-walk processes, statistical theory applied to turbulent diffusion in laboratory and atmospheric flows, growth of plume elements especially in water, dispersion in shear flow, effects of density stratification and behaviour of buoyant plumes, and the fluctuation in the concentration of dispersed material.

The most novel sections of the book are in the last three chapters, the content of which is drawn substantially from the author's own original papers. His apologies for the preference given to his own contributions are unnecessary, as they are enlightening and stimulating of further thought, as indeed is the book as a whole. Generally speaking, the reader is steered skilfully through the subtleties which abound in the basic concepts. There will be finer points on which specialists in the field will be ready to argue, but on the whole a balanced and realistic view is presented. Obviously, the air pollution meteorologist must not expect the book to provide him with a full background of the observational experience in respect of atmospheric turbulence and dispersion or with detailed working rules. Nevertheless the more mathematically inclined will find it a valuable component of his library and one which will undoubtedly repay selective study.

The style is concise and neat and there are very few misprints. Absence of an index is, however, an important omission and one which will be a disadvantage in sustained use of the book. Editions are available in both limp or hard covers. In both cases the price is high, but judged from the limp-covered version reviewed here the production is of excellent quality as regards paper, printing and general layout.

F. PASQUILL

Earth's voyage through time, by David Dinely. 215 mm × 135 mm, pp. 320, *illus.*, Hart-Davies, MacGibbon, 3 Upper James Street, Golden Square, London W1R 4BP, 1973. Price: £3·95.

This book describes the story of our planet from its formation some 4600 million years ago right up to the present time, with some brief speculations on the next 5000 million years.

It is well written and well illustrated and contains very few errors either of fact or in the production. Almost any scientist will find the book fascinating since the author's knowledge clearly extends over a wide range of scientific disciplines. He considers among other things the origin of the solar system, the nature of the interior of the earth, the composition of the earth's atmosphere and how it has varied over geological time, the possible origin of life on earth, and how it has evolved. However, the book is inevitably mainly about geology in the widest sense including how the structure of the earth's surface has changed throughout its history and is still changing today and how the various forms of life have evolved from their early beginnings.

To the present reviewer the most interesting chapters were those dealing with the continental drift theory originally propounded by Wegener (a meteorologist!). The author produces most convincing evidence that some 100 million years ago all the land masses of the earth were contained in one huge continent which broke up into 'plates' (likened to ice floes) which have subsequently drifted apart. Apparently the mechanism for this, best observed in the Atlantic, is that there is virtually continuous up-motion going on in some areas followed by lateral spreading of the earth's crust. This results in an expansion of the ocean floor which amounts, in the Atlantic, to about 2 cm/year. This must of course be compensated for in some way since the earth as a whole is not getting bigger. What apparently happens is that at the deep ocean trenches (the ultimate in waste disposal?) one section of the ocean floor is sinking under another and becomes reabsorbed in the earth's core so that the whole forms a sort of giant slow convection system. Among the evidence for this sort of mechanism are the facts that the rocks of Brazil and Africa are similar and of similar age in the region where the two continents originally fitted together; the rocks on either side of the ridge on the floor of the North Atlantic Ocean are of similar age, and the age of all rocks on the ocean floor is less than 70 million years. This would represent the time the continents have been drifting apart at about 2 cm/year.

World geography as we now know it has thus developed from a single continent in about 70 million years which is only about 1½ per cent of geological time. It is suggested that the process of formation and break-up of land masses has taken place at least once before in the history of the eart

Against this background it becomes easier to understand many geological puzzles. It is here that the meteorologist may become interested: if there was only one continent, clearly world climate would be different. The author suggests a super monsoon type with outflow from the continent in winter and extreme conditions in the continental interior. In other epochs more like our own, climates would be more equable in many areas and more variable generally. There is scope for thought here and for some original work by meteorologists. It would be interesting for instance to work out what the general circulation would have been like at the time of one world continent and how it would have reacted as North and South America gradually drifted apart from Europe and Africa.

However, apart from a little on the possible causes of ice ages, there is not much in the book of direct interest to meteorologists. Nevertheless I can thoroughly recommend it as a fascinating study of what science has been able to deduce of the earth's history.

R. A. S. RATCLIFFE

Determination of the water equivalent of snow cover, edited by L. K. Vershinina and A. M. Dimaksyan. 245 mm × 172 mm, pp. iv + 142, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem). Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £5·50.

In 1962 the Applied Geophysics Institute of the Main Administration of the Hydrometeorological Service, U.S.S.R., proposed a new method for the determination of the water equivalent of snow by aerial surveying. The method is based on attenuation of the natural gamma radiation of the earth by the snow cover. The first experiments were carried out in January 1963 and showed the method to be feasible. They were followed by further trials during the winter of 1963–64, and then from 1964 to 1968 the scale of the studies was extended to several different regions, over courses and areas of various sizes, and to cover a number of typographical types. The work included investigation of the discrepancies, sometimes large, between the water equivalents obtained by airborne gamma surveying and those from control measurements of high standard on the ground. Measures for minimizing the errors were developed and introduced.

This collection of 11 papers discusses the main results. It is dedicated to the memory of V. A. Uryvaev, Director of the State Hydrological Institute and 'leading organizer of experimental hydrological studies' at the time of his death. It had been his responsibility to direct and develop the work under field conditions; he had written the introductory paper and was co-author of 6 of the 10 following papers. There are seven authors in all. One of them, Vershinina, also an editor, should be specially mentioned. She appears as individual author of two papers, including the second longest, and co-author of five others. With Uryvaev she produced the longest paper, occupying just over one-third of the volume. Any question of quantity against quality does not arise, and there is no doubt that the total could be fairly labelled: Uryvaev, Vershinina *et alii.* The volume contains a large amount of information, but taken as a single whole it is not as easy to read as it might have been.

The difficulty does not arise from any individual paper and certainly not from the translation; the English is quite clear and as simple as it could be for writing of this kind; the style might with advantage be taken as a model by some of our own writers. The weakness is that the papers overlap and link several topics in a way that is neither entirely co-ordinated, nor sufficiently indicated by the titles and abstracts immediately below them. Again, the introductory paper, though a very useful brief summary (little more than four pages), is not a good guide to all the information in the other ten. A second reading, with notes and cross-references prepared during the first, is therefore helpful to get maximum value from the book, at least for a reviewer whose sometime approach to a high-resolution photographic memory is beginning to suffer, with age and in the spate of current scientific literature, from more or less fogged plates.

Nearly every paper deals in some way with errors of assessment and accuracy of results. But there is no compact numerical summary, all on one page, of the main conclusions in this respect. It appears, on widely separated pages, that in the most favourable circumstances the airborne gamma survey provides results with an accuracy well within 10 per cent, slightly better than the usual ground survey methods as at present developed and in regular use; whilst in the least favourable conditions the airborne survey can underestimate by 30 per cent or more, or overestimate by 90 per cent or occasionally much more (unusually bad but not extreme examples from the lengthy comparative tables). The largest percentage discrepancies tend to occur, as one might expect, with the smaller absolute values, whilst apart from this the most important single source of error (for which useful corrective measures have not been devised) is that the gamma survey assesses the water equivalent of snow with, in addition, the water (or some of it?) in the upper soil layer. Thus: 'The method cannot be employed in a swampy locality' though 'during stable thawless winters . . . the error of airborne surveys is . . . close to that of ground surveys, but . . . somewhat lower'.

There is no comparison of costs or effort for airborne and ground surveys (a fairly thorough search suggests that this was not given on one of the fogged plates). 'The (former) method is promising for use in little-populated regions with a steady winter' (page 46), implying perhaps that it might be relatively too expensive for areas where ground survey teams can be recruited. The reader is expected to know about the objects of such work, except for an occasional generalized explanation that snow data are 'widely used in various hydrologic calculations' (page 1) and 'for operational purposes of hydrological forecasts' (page 84). It is to be assumed that, according to circumstances, the information is used both to estimate the potential dangers from snowmelt floods, and to assess future water resources for all purposes, including navigation and hydroelectric power.

Work was continuing at the time of the Russian publication. If the refinements hoped for are achieved, we may perhaps look forward to a correspondingly improved systematic account of the technique; yet this volume, despite its shortcomings as a unified treatment, may then become a classic, and within its field a fitting tribute to V. A. Uryvaev, a man who was deservedly well known, respected and liked at international meetings, as well as in his own country.

A. BLEASDALE

Environment and plant life, by S. A. Searle. 220 mm × 140 mm, pp. 278, *illus.*, Faber and Faber, 3 Queen Square, London WC1N 3AU, 1973. Price: £4·50.

This book is based upon the study of the individual environmental factors of plant growth and development in the hope that their integration may provide 'clues to some of the mysteries that confront us today'. The integration is the difficulty and Mr Searle can hardly expect to succeed where so many have failed; nevertheless there is much of value in his book. For example, the meteorologist has his attention focused on many interesting applications of his subject to the cultivation of plants, while the farmers, growers and gardeners may well gain insight into the effect of weather and climate on their efforts to produce food or provide decoration. One could perhaps complain that there is too much emphasis on the atmospheric environment and too little on the soil. The author concedes that these are equally important but the chapter on the soil occupies less than one-tenth of the book.

The chapters on the aerial environment for plants are arranged in a somewhat unconventional order. In a book dealing with plant life there is much to be said for treating soil temperature before air temperature but still more for starting at the very beginning, with solar radiation. These chapters outline the basic facts concerning the distribution of the individual elements in time and space, linking these where possible with plant response. Also, both the instruments and standard methods of measurement are described.

A number of the following chapters emphasize the ways in which the environment may be modified to the advantage of plant production. These are well known to agricultural meteorologists and include principally the use of various types of windbreaks, irrigation, protection against frost and, more generally, the selection of suitable sites. Although practical details are not given, these form a useful introduction to those unfamiliar with the ideas. In this respect it is interesting that one of the major manipulations of the environment to improve production is unrelated to meteorology, viz., the manipulation of day-length by providing light or shade for chrysanthemums in the greenhouse to produce blooms at any time of the year. Another (but accidental) example of the control of the photoperiodic response of plants occurs just outside Wormwood Scrubs Prison where the floodlights are providing effective long days to parts of the plane trees which line the pavement.

The book is easy to read but in places there is a somewhat uneasy balance between the straightforward presentation of facts and the adjectives used to describe processes. For example, on page 23 Mr Searle refers to the 'tremendous wave of heat' in relation to soil temperature and a little later to the 'far vaster seasonal wave'. Again, on page 51 he talks of water 'falling in a reasonable manner upon the soil surface' and there are many other places where rephrasing would have led to improvements. But these are minor points which may be overlooked when assessing the merits of the book, which will be of interest to many who work in the fields of ecology and plant production.

The publishers are to be congratulated on the attractive appearance of the book. It is extremely clear, the diagrams and plates are of high quality and there are useful appendices with an adequate index.

W. H. HOGG

Meteorology for seamen, by C. R. Burgess. 210 mm × 130 mm, pp vii + 249, *illus.*, Brown, Son and Ferguson, Ltd, Publishers, 52 Darnley Street, Glasgow, 1973. Price: £4.

This is the third edition of a book first issued in 1950. Although many amendments and additions have been made, and the sections on cloud physics and upper-air charts have been rewritten and enlarged, the layout remains essentially the same. There are four parts :

I Factors which go to make up the weather;
II The climates of the oceans;
III Weather forecasting;
and IV Observing and recording the weather.

The primary aim is to provide the seaman with all he needs to know about meteorology, and a little more besides, without using any mathematics. This aim has been substantially achieved, the author having managed to condense a great deal of useful information into a relatively small volume, with the aid of many, albeit rather small, photographs and diagrams and a number of maps and tables. Two subjects of special interest to the mariner, namely cargo ventilation and ship routing might have received more attention however.

The reviewer found the chapters on climates and the one on sea and swell particularly good. For a third edition the number of misprints is rather high and although the writing is generally clear and sound a number of obscurities and errors were noted.

An unfortunate first impression is given in the second sentence of the opening chapter where it is stated that 'These (oxygen and nitrogen) and other, rarer, gases of which the atmosphere mainly consists have no effect on the weather, but some other bodies often present in the air, namely water vapour, salt and certain products of combustion, have a considerable effect . . .'. The important effects of carbon dioxide and of ozone appear to have been overlooked. On page 26 the explanation given for the occurrence of rain from clouds whose tops do not reach the freezing level is difficult to follow and probably incorrect, and on page 144 the opening sentence in a section on the effects of topography on wind reads 'Air, unless unstable, as indeed it usually is (in the lower levels) near the equator, objects to rising over high ground so that much of it escapes round the ends'. Although it is claimed in the preface that apart from horizontal distances which are still given in nautical miles, the metric system has been adopted almost entirely, there are still several examples of the use of mixed units, e.g. metres and feet for heights and °F and °C for temperatures, on the same pages. On page 11 reference is made to p. 224 which is a blank page (p. 236 is probably intended) and on page 209 the reader is referred to Tables 6 and 7 of Appendix I when Tables 7 and 8 are the relevant ones.

Despite these shortcomings this is a book which continues to fill a need, although, at more than five times the price of the first edition published 22 years earlier it seems a little less reasonable than its original version.

H. C. SHELLARD

NOTES AND NEWS

Negative surge warnings*

In September 1973 the Storm Tide Warning Service at Bracknell started to issue warnings of 'negative surges' in the North Sea. The need for this service is clearly indicated by tidal records from coastal tide gauges. For example, measurements at Southend over a period of two years show that the level of the sea was 2 feet or more below predicted levels on 51 occasions — on six of these it was 6 feet or more below them. Such differences resulting from 'negative surges' could be critical when tankers are operating with keel clearances of only a few feet in the eastern part of the English Channel and the southern North Sea.

Initially the new service will be experimental, providing only rudimentary warnings to shipping broadcast from coastal radio stations. The negative surge warnings will be given whenever tide levels are expected to be half a metre or more below the levels predicted in tide tables. The message will simply be that 'abnormally low tidal levels are expected' in a given area.

The service will be experimental until two problems have been solved : the relation between coastal tide-readings and open-sea tide levels, and the forecasting of non-progressive surges. The first requires the installation of an offshore tide gauge. The second arises because 25 per cent of negative surges do not progress predictably southwards down the east coast of England. Instead, they occur simultaneously at all points on the east coast. These rogue surges cannot at present be forecast.

Numerical forecasting for the tropics

The first major experiment of the Global Atmospheric Research Programme (GARP) is the GARP Atlantic Tropical Experiment (GATE) scheduled to take place in the tropical Atlantic during the summer of 1974. The experiment was motivated by the recognition of the crucial part played by the tropics in the global circulation of the atmosphere and of the many unresolved problems regarding the tropical atmosphere. The principal aims of GATE are to observe the tropical atmosphere in detail by using all possible methods (e.g. ships, buoys, aircraft, and meteorological satellites) so as to establish the nature and the behaviour of the various scales of tropical weather systems and the interactions between them. The detailed scientific, operational and logistical planning of the experiment is being undertaken by a group of scientists known as the International Scientific and Management Group (ISMG) located at Bracknell.

In order that the Meteorological Office should be in a position to derive the maximum benefit from the GATE experiment, an additional research group has been established within the Dynamical Climatology Branch

* This news item was originally published in the issue of *New Scientist, London*, dated 20 September 1973.

(Met O 20) specially to work on the problems of applying numerical models of the atmosphere to the tropics. Apart from studying and attempting to improve the tropical performance of the existing models, the group is setting up a high-resolution model (1-degree grid and 11 levels) suitable for short-period forecasting (up to two days) over the GATE area during the period of the experiment in 1974. This objective calls for a system of data processing and tropical analysis which is already the subject of collaborative effort with the Forecasting Research Branch (Met O 11).

OBITUARY

Mr James Paton

It was a great shock to everybody associated with meteorology in Scotland to hear of the death of Mr James Paton on 26 August 1973, only a few weeks before he was due to retire from his post of Reader in Meteorology in Edinburgh University.

Mr Paton graduated M.A. (Honours Mathematics and Natural Philosophy) in 1925 and B.Sc. (Honours Physics) in 1926 at Edinburgh University. After a spell of about a year in the Meteorological Office he accepted an invitation from the Professor of Physics to return to Edinburgh as a lecturer. He maintained his association with meteorology by serving in the Royal Air Force Volunteer Reserve before ill-health forced him to resign. Shortly after the war, under his guidance, Edinburgh became the first university in Britain to introduce courses in meteorology for undergraduates in the Faculties of Arts and Science and in 1954 Mr Paton was appointed Reader in Meteorology. In 1964 he became the head of the newly formed Department of Meteorology.

Throughout his career he had a keen interest in meteorological optics and he was a well-known authority on aurora and noctilucent clouds. For many years he assembled and published reports of these phenomena and since 1957 he had been in charge of the Balfour Stewart Laboratory which was formed in Edinburgh, with financial help from the Royal Society, to carry on this work. He was elected a Fellow of the Royal Society of Edinburgh in 1946, and he was a member of the Meteorological Research Committee and the Advisory Committee on Meteorology for Scotland for many years.

Mr Paton chose to live in Scotland whose hills and mountains were a source of great enjoyment to him and during his life he did much to advance the cause of meteorology in this country. He will be remembered with gratitude by his students not only for his ability as a lecturer but also for his patience and helpfulness in resolving their problems. He will be greatly missed by his countless friends who enjoyed his company and benefited from his advice.

D. R. GRANT

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