Meteorological Office

Annual Report 1987

HMSO

Meteorological Office
Annual Report 1987

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The front cover shows the areas of present and proposed weather radar coverage, in and around the British Isles. The data from the radars at Shannon and Jersey are made available by the Irish Met Service and States of Jersey respectively. The four photographs are a sequence of FRONTIERS quality-controlled radar rainfall intensity maps at hourly intervals from 1200 (top left) to 1500 GMT on 11 November 1987. Widespread precipitation over England and Wales is associated with an active, partly occluded, frontal system. The surface cold front is marked by a narrow band of heavier rain stretching north-east to south-west. This cold front was intensively observed during its progress across the south-west peninsula and Brittany as part of the Mesoscale Frontal Dynamics Project.

Contents

Foreword by the Director-General

The past year saw some extreme weather in the United Kingdom. January, cold and dry over the United Kingdom as a whole, and very cold in southern England, will be remembered for the arctic spell at mid month with some very heavy falls of snow. The most memorable meteorological event of the year occurred in the early hours of 16 October when exceptionally strong winds hit regions in the south and east of England causing devastation, particularly to trees, on a scale which has not been seen for many generations. Although giving out good forecasts of that storm some days ahead, on the day itself the forecasters expected the most severe winds to miss the inland areas of England. Warnings only 3 or 4 hours ahead, therefore, were given to the emergency authorities and the general public at the time when most people were in bed. After the storm I immediately set up an enquiry into the events that preceded it and the forecasts that were issued. Because of the intense media interest, the Secretary of State for Defence asked Sir Peter Swinnerton-Dyer and Professor Robert Pearce to review the Meteorological Office report and report independently to him with their own conclusions and recommendations. Both reports will be published early in 1988.

The accuracy and useful range of forecasts has continued to improve. In particular, 3-day forecasts are now as accurate as were 24-hour forecasts about 12 years ago. A demonstration of the accuracy and usefulness that medium-range forecasts can now achieve was given in January when the public was given 5 days' notice of both the onset of the severe winter weather and of the thaw that followed.

For short-range forecasting, information from the combined radar network over England and Wales is invaluable. This network has now been extended to cover Ireland through the Shannon radar, which has been set up jointly with the Irish Meteorological Service, and through a new radar at Castor Bay near Belfast, partly funded by the Department of the Environment (Northern Ireland) and which was opened on 30 June. Plans are now well advanced for extending the network to cover Scotland during the next 3 years.

Modernization and automation of the various components of the observing system is a high priority for the Office. During the year a new lightning detection system was set up. Signals from stations at Cyprus, Gibraltar and five sites in the United Kingdom are received at Bracknell. Measurements of the time delays of these signals make it possible for flashes anywhere in Europe and over much of the eastern North Atlantic to be accurately located.

In a drive for greater effectiveness and efficiency at the outstations, high priority is being given to the installation of computing and display equipment. Eight more Defence stations were equipped during the year with terminals which enable a substantial amount of current weather information to be called up for immediate display in graphical or textual form.

Forecasting and support staff continue to support the armed services at various stations. During the year I visited the meteorological offices at Ascension Island, and Mount Pleasant in the Falkland Islands and was impressed with the high level of competence and dedication shown by those manning these stations where facilities are substantially more limited than in the United Kingdom.

Fine details in the temperature and humidity structure of the atmosphere sometimes provide conditions for anomalous propagation of radar which have important military implications. The possibility of forecasting such situations is under investigation. Similar fine detail in the thermal and salinity structure of the ocean markedly affects the propagation of sound waves. The Office is working jointly with the Navy and the Admiralty Research Establishment in the development of numerical models which can be used to predict the oceans' acoustic properties.

Substantial development has taken place in automated telephone services. Of particular importance is Airmet, a tailored service for general aviation customers which, in an efficient manner, provides the information required by most aviators flying within the United Kingdom. Individual contact with forecasters by telephone remains available from four of our Weather Centres for those aviators who require such information.

'Open Road', a service for local authorities, is now provided from all Weather Centres. Forecast information and up-to-the minute radar information are provided and combined in some instances with observations from temperature sensors located in road surfaces to provide guidance for the gritting and salting of roads. Large savings have been realized by those authorities which take this comprehensive service.

Services to the media and the Press have also been extended. Short reports on world weather are broadcast twice a day on the BBC World Service. General forecasts covering Europe are broadcast in English several times a day on the BBC's 'Superchannel'. Improved graphics weather presentations prepared at Weather Centres are now published in most national newspapers.

The Office's Research and Development Programme, although it only accounts for just over 10% of overall resources, continues to make a major contribution towards improving the efficiency, accuracy and quality of the Office's products and services.

The Office has participated in two major international field programs aimed at elucidating the processes which lead to the formation and dispersal of stratocumulus (the FIRE project) and the detailed structure of fronts (the Mesoscale Frontal Dynamics Project). In both programs the Hercules aircraft of the Meteorological Research Flight played a key role.

In the aftermath of the Chernobyl incident the Office has been designated a lead agency by the Department of the Environment in deriving a model to

Functions of the Meteorological Office

The Meteorological Office is the State Meteorological Service. It forms part of the Ministry of Defence and is administered by the Air Force Department. The Director-General is responsible to the Secretary of State for Defence through the Parliamentary Under Secretary of State for Defence Procurement.

The general functions of the Meteorological Office are:

(a) The provision of meteorological services for the Army, Royal Air Force, civil aviation, the merchant navy and fishing fleets; provision of basic meteorological information for use by the Royal Navy; and liaison with the Director of Naval Oceanography and Meteorology.
(b) The provision of meteorological services to other government departments, public corporations, local authorities, the Press, television, radio, industry and the general public.
(c) The organization of meteorological observations, including observations of radiation and ozone, in the United Kingdom and at certain stations overseas.
(d) The collection, distribution and publication of meteorological information from all parts of the world.
(e) The maintenance of the observatory at Lerwick.
(f) The provision of professional training in meteorology.
(g) Research in meteorology and geophysics.

The Meteorological Office also takes a leading part in international co-operation in meteorology. The Director-General is the Permanent Representative of the United Kingdom with the World Meteorological Organization, and acts in concert with the national Directors of the other Meteorological Services in western Europe in the co-ordination of their programs.

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forecast the atmospheric dispersion and deposition following any future nuclear accident.

The Office has also been involved in investigations of the 'ozone hole' over Antarctica. Two forecasters and one scientist were seconded to a location in Chile to support a US team who were to use aircraft to make a wide variety of meteorological and chemical measurements within the region of ozone reductions. A significant contributory factor to the success of the experimental campaign was the quality of the forecasts based on output from numerical forecast models run at Bracknell which were provided to both pilots and scientists.

Finally, I should mention the Meteorological Office's international connections which are of course vital to our whole operation. These were further strengthened by my being elected a Vice-President at the World Meteorological Organization (WMO) Congress last May. The United Kingdom is seen as leading not only in the quality of its meteorological service but also in its development of meteorological applications. In this connection a WMO Symposium concerned with education in the applications of meteorology was held in July at Shinfield Park, Reading and was pronounced a particular success.

Meteorological Committee

Terms of reference:

(a) To keep under review the progress and efficiency of the meteorological service and the broad lines of its current and future policy.

(b) To keep under review the general scale of effort and expenditure devoted to meteorological services and research.

(c) To ensure the maintenance of adequate contact between the Meteorological Office and those who use its services.

Membership as at 31 December 1987:

Chairman:
Sir Peter Swinnerton-Dyer, KBE, FRS

Members:
Mr G.C. Band
Professor A.H. Bunting, CMG
Professor H. Charnock, FRS
Mr D.A. Davis
Professor P.H. Fowler, DSc, FRS
Mr J. Miller, FIOB
Mr R.A. Smith
Mr J. Wilson
*Mr M.A. Gamester (Representative, Civil Aviation Authority)
*Dr J.T. Houghton, CBE, FRS (Director-General, Meteorological Office)
*Captain A. Morrice, RN (Director of Naval Oceanography and Meteorology)
*Air Vice-Marshal M.G. Simmons, AFC, (Assistant Chief of the Air Staff (Operations)); alternate, Group Captain A.M. Bowman
*Mr J.M. Stewart (Deputy Under-Secretary of State (Personnel and Logistics))

Secretary:
*Mr P. Fraser (Secretary, Meteorological Office)

**ex officio*

The Committee met four times in 1987.

Meteorological Committee — research subcommittee

Terms of reference:
To advise the Meteorological Committee on the general scientific lines along which meteorological and geophysical research should be developed within the Meteorological Office and encouraged externally. It shall review progress and report to the Committee annually at their meeting devoted to consideration of the research program.

Chairman:
Professor H. Charnock, FRS

Members:
Professor Sir Robert Boyd, FRS
Professor B. Hoskins
Dr J. Woods
*Dr D.N. Axford (Director of Services, Meteorological Office)
*Mr D. Barber (Chief Scientist, Civil Aviation Authority)
*Group Captain A.M. Bowman (Deputy Director (Navigation))
*Dr D.J. Fisk (Representative, Department of the Environment)
*Mr A. Gilchrist (Director of Research, Meteorological Office)
*Dr J.T. Houghton, CBE, FRS (Director-General, Meteorological Office)
*Mr I. Mackintosh, (Head of Electro-optics and Microwave Group, Royal Signals and Radar Establishment)
*Captain A. Morrice, RN (Director of Naval Oceanography and Meteorology)

Secretary:
*Mr C. Kilsby (Meteorological Office)

**ex officio*

The Committee met three times in 1987.

Introduction

The Meteorological Office is the State Meteorological Service of the United Kingdom. As such it is a source of weather and climate data; it provides weather forecast information and advice for various sectors of government (in particular for Defence), for civil aviation, industry and commerce, and the general public. Forecast weather patterns at several levels in the atmosphere and for the whole globe are generated twice daily using numerical models of the atmosphere and its circulation. Other models are used to predict the weather patterns closer to home. Experienced weather forecasters then assess the models' output and, armed with the latest information from weather radars, satellites and observations from manned and unmanned sites both at sea and on land, they interpret the models' output in the form required by the customer.

For the general public, forecasts are available through the media and are also disseminated by Weather Centres situated in the major cities of the United Kingdom.

For Defence, forecasts and other weather information are provided by Office staff who are to be found working on RAF stations and at some Army Air Corps bases and trials establishments; forecasts are also supplied to the Naval Headquarters at Northwood.

Civil and general aviation receive forecasts of weather and winds tailored to suit their needs. Bracknell as a World Area Forecast Centre has responsibilities for civil aviation that cover the world.

Industry and commerce are supplied with information, which may be either historical climatological data or forecasts, on a repayment basis. More effort is being made through the Weather Centres and through the various enquiry bureaux to increase the awareness of potential customers to the influence of weather on their operations.

Farmers are especially catered for with Office personnel working alongside the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food.

This year the report, in addition to the administration and financial information to be found at the beginning and at the end, has sections on the central forecasting operation and the necessary computing and communications required to make the maximum use of the large and varied range of world-wide observations which are also described. The section on the services provided to our customers is followed by sections on the developments in and research undertaken during the year on forecasting methods. The total central forecasting operation takes up rather more than half the resources of the Office; in comparison the research necessary to maintain the quality and effectiveness of these services represents about a tenth of these resources.

The restyled Headquarters entrance hall at Bracknell

Meteorological Office organization

DIRECTOR-GENERAL
DG MET O
J T Houghton CBE D Phil FRS

- **Director of Research**
  DR Met O
  A Gilchrist MA
  - **Deputy Director Physical Research**
    DD Met O(P)
    K A Browning PhD FRS
    - **Met O 14** Boundary Layer Research — **AD Met O(BL)** P J Mason PhD — F B Smith PhD*
    - **Met Research Flight** — **AD Met O(MRF)** W T Roach PhD DIC
    - **Met O 15** Cloud Physics — **AD Met O(CP)** P R Jonas PhD DIC — S Nicholls PhD*
    - **Met O 19** Satellite Meteorology — **AD Met O(SM)** C G Collier BSc ARCS — D R Pick PhD†
    - **Met O 21** Geophysical Fluid Dynamics — **Head of Met O 21** R Hide ScD FRS*
  - **Deputy Director Dynamical Research**
    DD Met O(D)
    P W White PhD
    - **Met O 9** Special Investigations — **AD Met O(SI)** N Thompson PhD
    - **Met O 11** Forecasting Research — **AD Met O(FR)** A C Lorenc BA — M J P Cullen PhD*
    - **Met O 13** Synoptic Climatology — **AD Met O(SC)** D E Jones MSc DIC ARCS
    - **Met O 18** Professional Training and Publications — **AD Met O(PTP)** D B Shaw BSc (Principal, Met Office College)
    - **Met O 20** Dynamical Climatology — **AD Met O(DC)** H Cattle PhD DIC — **Climate Modelling** P R Rowntree PhD
- **Secretary**
  Sec Met O
  P Fraser
  - **Met O 4** Finance and Supply — **AD Met O(F&S)** R Chapman
  - **Met O 10** Personnel Management — **AD Met O(PM)** A I Johnson BSc ARCS
- **Director of Services**
  DS Met O
  D N Axford PhD C Eng FIEE
  - **Deputy Director Observational Services**
    DD Met O(O)
    P Ryder PhD
    - **Met O 1** Observational Requirements and Practices — **AD Met O(OP)** J M Nicholls BSc
    - Marine Superintendent — Capt G V Mackie MRIN FNI
    - **Met O 3** Advisory Services — **AD Met O(AS)** F Singleton BSc DIC
    - **Met O 16** Operational Instrumentation — **AD Met O(OI)** D J Painting BSc
  - **Deputy Director Forecasting Services**
    DD Met O(F)
    D H Johnson MSc DIC ARCS
    - **Met O 2** Central Forecasting — **AD Met O (CF)** R M Morris BSc — **Head of Met O 2b** A J Gadd PhD; A Woodroffe BSc†
    - **Met O 6** Defence Services — **AD Met O(DS)** S J Caughey PhD — **C Met O HQSTC** J F Keers
    - **Met O 7** Public Services — **AD Met O(PS)** C R Flood MA — **C Met O LAP** D Forsdyke BSc
  - **Deputy Director Communications & Computing**
    DD Met O(C)
    R L Wiley PhD
    - **Met O 5** Telecommunications — **AD Met O(TC)** R J Sowden
    - **Met O 12** Data Processing — **AD Met O(DP)** A P Cluley PhD
    - **Met O 22** Systems Development — **AD Met O(SD)** W A McIlveen PhD
  - **Met O 17** International and Planning — **AD Met O(IP)** S G Cornford MSc
  - **Met O 23** Marketing Services — **AD Met O(MS)** D M Houghton MSc DIC

*Individual merit †Special appointment

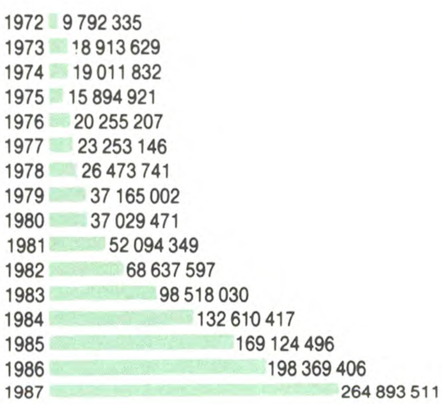
Telecommunications and computing

The collection, storage, processing and dissemination of data, by using the technologies of telecommunication and computing, are functions vital to the successful operation of a modern Meteorological Service. Previous Annual Reports contained sections that dealt separately with communications and computing aspects, but this year a unified section reflects the strong convergence of these disciplines. The term Information Technology (IT) is now often used to span both disciplines. Computer-based techniques dominate the world of high-volume message switching, and the problems of moving data from one machine to another confront the data-processing specialist regularly. Users are also much more aware of the benefits which IT can confer, fostered by personal experience and the rapid growth in the number of small, inexpensive systems found both at Headquarters (HQ) and at outstations. Thus there is considerable pressure on specialized manpower, generated by the rate of change of technology, rising expectations and growing diversity of applications. The Office, in common with many other organizations that are critically dependent on IT, has to bear this pressure at a time of national shortage in IT skills. Although there have been some disappointing delays in bringing forward new projects, much has still been achieved throughout the year.

The Meteorological Telecommunication Centre

Rapid transmission of data is essential to operational meteorology. The Meteorological Telecommunication Centre (Met TC) at Bracknell ensures that data and products flow quickly and reliably between suppliers and users, both within the United Kingdom and internationally. The Global Telecommunication System (GTS), which links almost all countries, was set up as a result of agreements reached by the World Meteorological Organization (WMO) and is a remarkably successful example of international co-operation. The Met TC is an important regional node of the GTS. Observations are collected from fixed and mobile sources in parts of Europe and the North Atlantic for insertion on the GTS. These data, and observations from the rest of the world, are made available for use by forecasters and also form the raw material for computer-based Numerical Weather Prediction (NWP) procedures. Results from NWP models run by the Office are also routed to other Meteorological Services through the Met TC. Bracknell is also one of two World Area Forecast Centres for civil aviation (the other being Washington). Forecast products are distributed twice daily via the Met TC to Regional Area Forecast Centres, and exchanged with Washington to guard against the consequences of either World Centre suffering a major systems failure.

The traffic handled by the Met TC continues to grow, as shown in the figure. A large part of the growth is due to an increasing volume of NWP data for which there is considerable demand.



Number of characters handled in the Met TC on one (November) day

Thanks to continuing effort in developing automated procedures, throughput has doubled whilst the number of operations staff has been halved over the last 5 years. The principal message-switching system is based on a highly resilient configuration of seven Tandem TXP computers. Other functions and facilities are steadily being transferred from older equipment to this modern system. As one consequence of the pressure for growth, it was necessary to increase capacity on the international circuits. This provided an opportunity of converting from communication protocols specific to meteorological message formats to internationally standardized communication protocols capable of handling binary data streams. Further gains in efficiency can be made using compact binary representation in place of character representation to encode data; experiments have been conducted by a small group of countries including the United Kingdom.

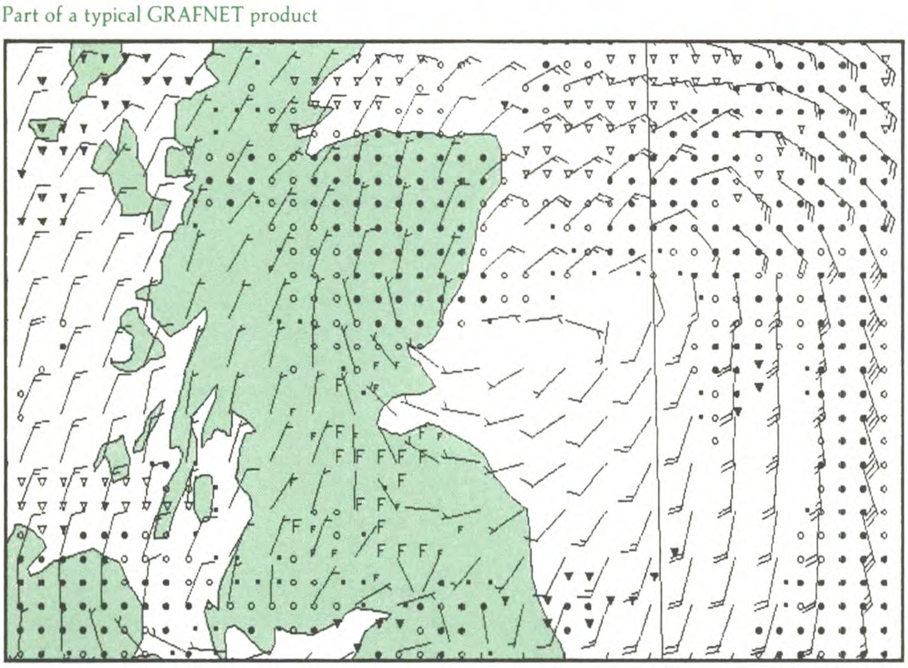
Thanks to this wide experience of international meteorological communications, staff from the communications section at Bracknell play an important role in the future development of the GTS. During the year they were involved in a number of projects including the planning of a new venture in international co-operation using satellites. Communication links in many parts of the world are inadequate, making it difficult to exchange observations and to disseminate forecasts. From mid-1988 a scheme which will exploit communication channels provided by the Meteosat series of meteorological satellites will bring great benefit to many nations in Africa and the Mediterranean area. Alphanumeric data and pictorial products will be transmitted from the Met TC (and by the Italian Meteorological Service) for retransmission via Meteosat to satellite-receiving equipment in the countries concerned.

The Weather Information System

Within the United Kingdom, telecommunication networks are needed to collect observations and disseminate data and forecasts to outstations. This activity still depends on channels which carry character data at telegraph speeds, and charts by analogue facsimile. The first major step in the complete replacement of this old technology was taken during the year. Meteorological offices at eight key RAF stations were equipped with Outstation Display Systems (ODSs), small but powerful computer systems which receive data from Bracknell and then make the information available to the on-duty forecaster as both alphanumeric and graphical displays. Even though the initial version of the ODS is limited (it only receives character data broadcast from the Met TC over an interim digital communication network), the benefits compared to the paper-based system are considerable: the forecaster has rapid access to a much enlarged data base, and the information is presented in useful formats. The ODS also alerts the forecaster to the arrival of important messages; this is necessary now that the hard-copy teleprinter output is no longer scanned. The new system has been well received by its users, and plans to install ODSs at a further 11 sites by early 1988 are well advanced.

The communication network which supports ODS is shared by GRAFNET, a logically distinct facility that comprises a matrix printer at each site driven from AUTOFAX, a computer system in the Met TC which receives and transmits charts in digital form. This technique broadcasts charts about four times faster than is possible by analogue facsimile. GRAFNET was installed at ten locations during the year; a further four will be added soon. AUTOFAX also supports analogue facsimile broadcasts; its capacity has been increased from 4 to 12 such channels, thereby automating tasks previously associated with the operation and scheduling of facsimile broadcasts.

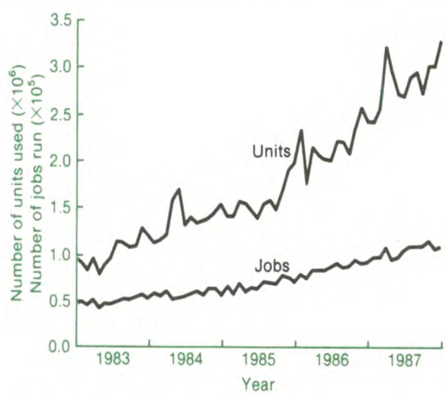
Part of a typical GRAFNET product



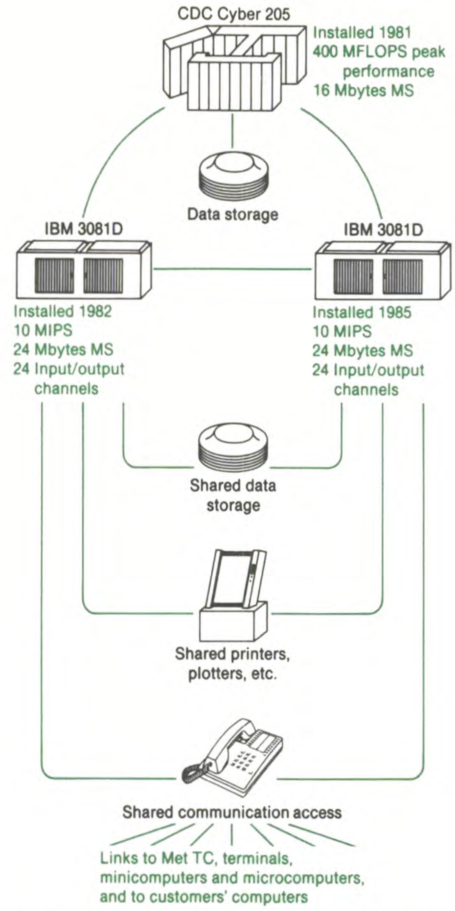
The initial version of the ODS, GRAFNET, and the interim digital communication network are the forerunners of the planned Weather Information System (WIS). Planning for the WIS has suffered some delay but is now going ahead. It will use the latest digital communication techniques to link sources of information to the outstations. Conceptually, the WIS comprises communication nodes and an interconnecting network (together known as the Weather Information Network, WIN) that transmits data to and from the ODS at each site. The WIN will be capable of delivering all classes of meteorological data to the ODS, including charts and satellite and radar imagery; it will also provide a means of collecting observations from outstations and will be connected to public information channels in order to deliver products to users in aviation, industry, local authorities, etc. Auxiliary observers (e.g. coastguards) will not be equipped with an ODS. The basis of a system which will enable them to enter, check and transmit their observations to the Met TC will be a handheld microcomputer that is currently being developed.

The COSMOS computing centre

The processing of meteorological observations, received via the Met TC, to produce weather forecasts out to 6 days ahead requires massive computing power. This is provided by the COSMOS computing centre. In addition to routine NWP, COSMOS also provides facilities for research based on numerical models of the atmosphere, data-processing of climatological records and a host of other activities related to revenue-earning services, investigations, development and administration. Its work-load continues to grow steadily, as shown in the figure below.



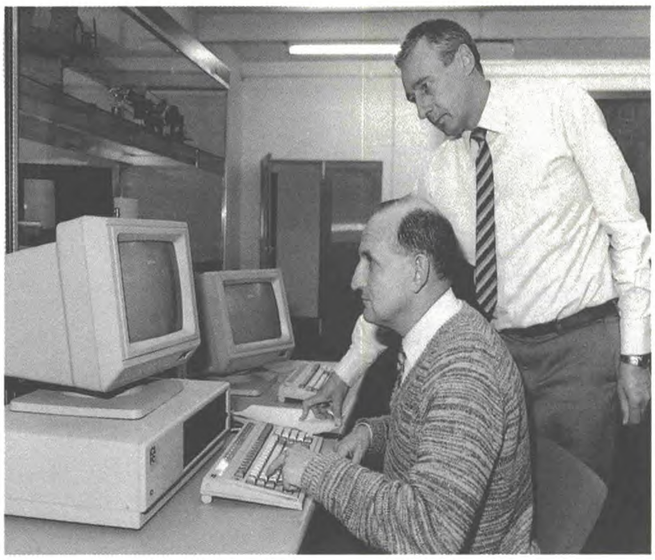
Units used and jobs run monthly on the COSMOS computer, 1983–87



COSMOS — the central computing facility (MS — main storage, MIPS — millions of instructions per second, MFLOPS — millions of floating-point operations per second)

Like the Met TC, COSMOS runs continuously 24 hours each day, every day of the year. By contrast, it has a much more heterogeneous work-load. The key objective of the senior operations staff is to ensure that, if at all possible, critical tasks continue to run to schedule even if problems occur; their background in meteorology complements their technical knowledge when making decisions in a complex real-time environment. The work of the junior operations staff is, however, essentially similar to that at any large computer centre; their tasks have been contracted to a facilities-management company since October. Software aspects are supported by small teams of data-processing specialists responsible for systems programming, data-base design and implementation, and development and maintenance of common user services. The great bulk of application programming is performed by staff in other parts of the Office, to whom COSMOS provides either the primary computing service or large-scale computation services to complement the work performed on local minicomputers.

The presentation of meteorological data to the forecaster in graphical form has gained prominence in recent years. The growing complexity of software to support an increasing number of display devices, that possess varying characteristics, has led to the introduction of a co-ordinated approach based on the Graphical Kernel System (GKS), an established international standard. GKS software is available for various computers used by the Office, including IBM mainframes and DEC VAXs, and allows programmers to



A forecaster being trained at the Meteorological Office College in the operation of a microcomputer to generate and transmit his textual forecasts

An operator controlling the production of a plotted chart in COSMOS

concentrate on the data and their presentation rather than on the details of programming the operation of each different item of display hardware. Interactive graphics displays based on COSMOS are used increasingly in the Central Forecasting Office (CFO), and give the forecasters there access to observational data (including imagery) and the results of numerical forecasts.

The automation of chart plotting has been a major success in the application of computers to save labour in Meteorological Services and the Meteorological Office is no exception. Greater flexibility has been achieved this year by connecting replacement plotters to COSMOS via a microcomputer, thereby allowing forecasters to request plotted charts at times additional to the scheduled production.The same arrangements for plotting are also being made available to other COSMOS users, for example staff who answer climatological enquiries.

In a system as large and complex as COSMOS, the procurement of equipment, that will replace and extend the existing configuration, is a continual process. The major effort in 1987 was to plan the replacement of the Cyber 205 in order to meet the demands of a new generation of numerical models of the atmosphere. A specialized computer capable of performing at least eight times the computational throughput of the Cyber is required. A contract was awarded to Control Data Corporation for supply of an ETA 10 system, to be installed early in 1988. It is planned that the new computer will be operational later that year.

Other developments in Information Technology

Satellite imagery needed by the CFO and outstations is provided by a system known as AUTOSAT which receives analogue signals over a land-line from the ground station at Lasham, Hampshire. After digitization and computer processing, image products are distributed to outstations by analogue facsimile and to users at Bracknell by means of visual displays linked directly to AUTOSAT or indirectly via COSMOS. A second-generation system (AUTOSAT-2), capable of handling the full digital data streams from both polar-orbiting and geostationary satellites, has been designed and procurement has begun. The new system will be installed at Lasham, thus avoiding the problem of carrying the full data stream to Bracknell. Its products will be distributed to each ODS via the WIN and to COSMOS via a high-speed telecommunication link. The latter will connect to a local area network (called the Central Data Network), installation of which has already begun in order to link, at higher speeds, a number of existing computer systems used for both operational and research purposes. The image data will be stored in COSMOS and then retrieved for display in the CFO, for use in association with NWP, and to meet customer requirements such as the graphical presentation of weather information on television.

An investigation into the wider application of IT to help office workers, so-called Office Automation (OA), was undertaken. This involved extensive interviewing of staff, a study of systems available in the market place and consideration of the experience of OA gained in the Civil Service over recent years. A user requirement, technical strategy and cost justification have been evolved as a basis for the first stage of implementation. Another important development, to be implemented late in 1988, is the replacement of the existing HQ telephone exchange. Planning is well advanced for an exchange that is based on the latest digital-switching technology, capable of switching data traffic in addition to providing advanced voice-telephony features.

The demand for computing support, both at HQ and at outstations, continues to grow apace. COSMOS is the central facility but many applications and research tasks now run on minicomputers (notably the PDP and VAX series) and an ever-increasing population of microcomputers (micros). At HQ the micros are often connected to the larger machines, offering both terminal facilities and local personal computer (PC) applications such as word-processing and spreadsheet. The CFO and all the Weather Centres are now equipped with message-preparation systems, each based on a network of micros which run word-processing (and other applications) and are linked to British Telecom's telex service. These message-preparation systems have eliminated the need for operators to key and transmit messages written by the forecasters, thus leading to large manpower savings. The Weather Centres are also equipped with PCs which run a program to predict road surface temperature; this is part of the forecasting service to highway authorities. Defence outstations are each equipped with a word-processor to help with administration and the same device has proved popular at HQ for use by scientists in drafting reports and papers. The use of desk-top publishing systems is being investigated, both for operational use (e.g. graphics for Press forecasts) and by the Graphics Office at HQ. Communication has always been a problem for scientific staff working on collaborative projects. This difficulty has been mitigated by the increasing use of PCs as terminals to national and international electronic mail services.

Central forecasting

The central forecasting carried out at the Meteorological Office Headquarters in Bracknell has two closely coupled components. There is the Central Forecasting Office (CFO), manned continuously by eight forecasters and their support staff, and there is the numerical weather prediction (NWP) system, capable of running in a fully automated manner on the Office's COSMOS computing facilities.

The man–machine interface

The coupling of the CFO with NWP has two aspects. Firstly, CFO forecasters provide important inputs to the data-assimilation part of the NWP system. They do this by making quality-control decisions on observational data, and also by adjusting the numerically analysed fields to make them consistent with satellite imagery and other information. Secondly, forecasters assess, amend and interpret the numerical forecasts, evaluating them alongside results received from other NWP centres and checking them continuously as relevant observations and imagery become available.

Central forecasting products come either directly from the NWP system, in digital or graphical form, or from the CFO, as charts or texts. In both cases, however, the products are the result of the man– machine mix outlined above.

The technology of the man–machine interface is an important consideration. Increasing use is being made of graphical display facilities linked to the COSMOS computers which allow forecasters to monitor the latest NWP results, to inspect additional NWP information without the costly production of hard copy, and to overlay NWP fields, observations and imagery. Message preparation is also an automated activity, with forecasters entering text at local work stations in the CFO for direct transfer to the Meteorological Telecommunication Centre.

Roles and responsibilities

Several formal roles are fulfilled by the CFO in conjunction with the NWP system. Firstly, it is the National Meteorological Centre for the United Kingdom, and provides authoritative guidance to regional and specialized meteorological offices around the country for defence, public service and commercial purposes. Then, Bracknell is designated a Regional Meteorological Centre by the World Meteorological Organization (WMO). This designation implies a responsibility to make available specified products to other National Meteorological Services throughout Europe, though in fact Bracknell has gained a wider recognition for the provision of numerical products on a global basis. The central forecasting activities at Bracknell also fulfil the two roles of the World Area Forecast Centre (WAFC) London and the Regional Area Forecast Centre (RAFC) London as established by the International Civil Aviation Organization (ICAO). In the context of NATO, the CFO is a Weather Analysis Centre.

The organization of the CFO

The work of the CFO is overseen by the Senior Forecaster on duty, who also has direct personal responsibility for forecasts up to 24 hours ahead, issued at 6-hourly intervals, and for the issue of special warnings of hazardous weather conditions. Forecasts for longer periods, out to 5 days or sometimes a week ahead, are prepared by the Medium-range Forecaster. Other staff on duty specialize in the weather conditions over the British Isles, the weather conditions over surrounding sea areas, the quality control and interpretation of radar and satellite imagery (using an interactive display system known as FRONTIERS), and in operating the Storm Tide Warning Service (established for coastal flood protection purposes).

An Intervention Team of two forecasters is responsible for monitoring the observations and analyses for NWP, and for taking action as necessary to reject or correct observations and to modify analyses. Another is dedicated to the RAFC function for civil aviation, and prepares forecast charts that depict significant weather (e.g. clear air turbulence, deep convective cloud) likely to be encountered by aircraft *en route*.

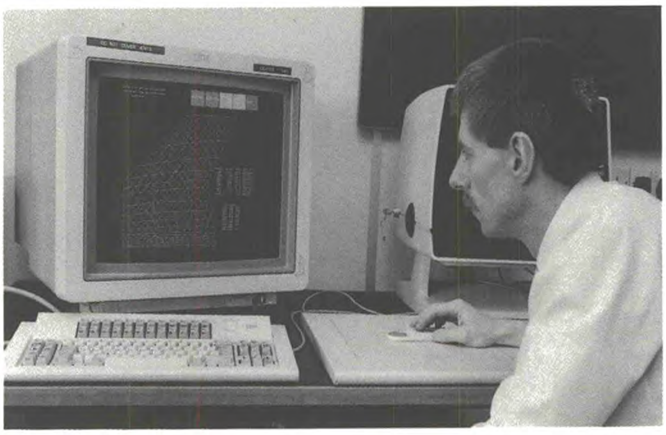
CFO forecasters also undertake various international and commercial services. These include broadcasts on the BBC World Service and frost forecasting for coffee-growing regions of Brazil. A ship routeing service (Metroute) is operated by specialist staff who work closely with the CFO forecasters.

During 1987 work has been in progress that will lead to a reorganization of the CFO during 1988. The reorganization will include the transfer to Bracknell of civil aviation work currently carried out in the meteorological office at Heathrow Airport.

The NWP system

The operational NWP system is based on two versions of a 15-level numerical model of the atmosphere that has been operational on the Cyber 205 computer since 1982. These are expected to be replaced late in 1988 or early in 1989 by higher-resolution versions of a 20-level model that will run on a new ETA 10 supercomputer, but the basic techniques used will remain similar until research results indicate otherwise.

The global NWP model currently has its grid points spaced at intervals of 1.5° in latitude and 1.875° in longitude. Forecasts to 6 days ahead are computed twice daily, from 0000 and 1200 GMT starting conditions derived using observations arriving at Bracknell by 0320 and 1520 GMT. Results up to 36 hours ahead are available by 0415 and 1615 GMT, and the complete 6-day forecasts by 0500 and 1700 GMT. In contrast to the global models favoured at other NWP centres, the Bracknell



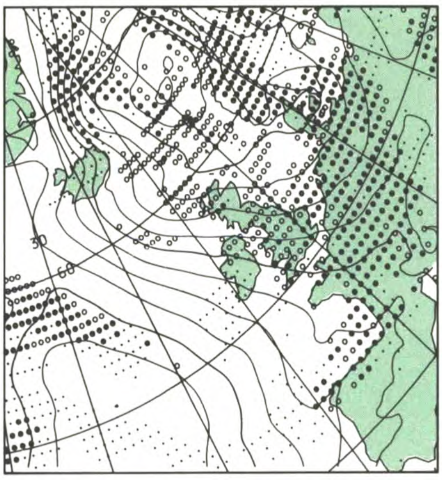
Forecasters use visual display units to inspect the detailed temperature and humidity profiles at selected model grid points when carrying out quality control for the analyses and when interpreting the numerical forecasts in terms of specific weather elements model uses finite-difference techniques, rather than spectral methods, to approximate the governing partial differential equations. The techniques have been used operationally for more than 10 years, and have proved difficult to better for efficiency and accuracy.

The regional, fine-mesh, NWP model currently has its grid points spaced at intervals of 0.75° in latitude and 0.9375° in longitude. This is made possible within the capacity of the Cyber 205 computer by restricting the area of coverage to the region 30–80°N, 80°W–40°E. At the lateral boundaries of this region the calculations make use of information from integrations on the coarser grid. Forecasts to 36 hours ahead are computed twice daily, from 0000 and 1200 GMT starting conditions derived using observations arriving at Bracknell by 0200 and 1400 GMT, with results available in the CFO before 0300 and 1500 GMT. One advantage of the use of finite-difference techniques in the global model is that the same scientific formulation, indeed many of the same computer codes, can be used for the fine-mesh model.

The fine-mesh model, then, is an application of the same techniques that are used in the global model but at higher horizontal resolution in the limited region of special interest. The benefits of the higher horizontal resolution have been recognized for precipitation forecasts generally, and have also been demonstrated for pressure patterns and wind flows in certain cases of rapidly developing low pressure systems. Because of these advantages, the fine-mesh model enjoys a considerable reputation in the National Meteorological Services throughout Europe that receive its products.

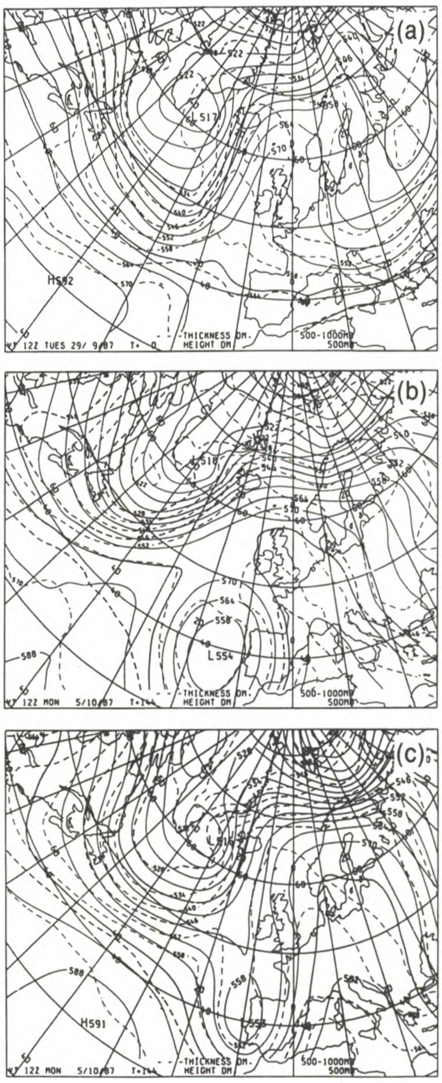
Being limited to a regional coverage, the fine-mesh model can be run with a very early cut-off time for observations. This in turn means that the products are available early and are thereby of increased value to forecasters. There is of course the risk that on rare occasions observations that miss the fine-mesh run will be used by the global model and have a significant beneficial impact. Forecasters have to weigh these factors carefully on occasions when the fine-mesh and global forecasts differ.

Associated with both the global and the fine-mesh models are data-assimilation cycles for the analysis of observations that determine the required initial values at the models' grid points. All relevant observations are used, whether from land stations, ships, buoys,



Additional information available from the numerical models includes cloud cover at each grid point. Such charts are compared with satellite imagery as it becomes available to detect analysis or forecast errors at the earliest possible stage.

balloons, aircraft or satellites. After quality control, the selected observations are assimilated into the numerical model by relaxing the grid-point variables towards interpolated values, derived from the observations, after each time step of integration. For the global model, the assimilation proceeds in a continuous 6-hour cycle, taking account of all observations made within 3 hours of each analysis time. For the fine-mesh model, observations are assimilated in a 3-hour cycle during the 12 hours leading



up to the start of the forecast, each sequence beginning with an interpolation from global model fields.

A third NWP model is undergoing a continuous trial in real time. This is the mesoscale model (grid spacing 15 km) that is expected to become operational, after its area of coverage has been enlarged and its number of levels increased, on the new ETA 10 supercomputer. At present, forecasts up to 18 hours are computed from 0000 and 1200 GMT starting conditions.

Surface wind fields forecast by the global and fine-mesh NWP models are used to drive two numerical wave models for the prediction of sea state. The global sea-state model employs exactly the same set of grid points as the global NWP model. The regional sea-state model employs grid points spaced at intervals of 0.25° in latitude and 0.4° in longitude; it covers the European continental shelf, the Baltic and the Mediterranean; and its formulation includes shallow water effects. Both of the sea-state models resolve the wave energy spectrum with 13 discrete frequencies and 16 discrete directions.

Surface wind and sea-level pressure fields from the fine-mesh NWP model are also used to drive a tidal surge model that is an important tool for the Storm Tide Warning Service. The scientific formulation of this model is the responsibility of the Proudman Oceanographic Laboratory at Bidston, Merseyside.

Medium-range forecasting

As recently as 15 years ago, 72-hour numerical forecasts were virtually useless, with the correlation coefficient between forecast and actual changes of sea-level pressure in the UK region as low as 0.3. After the introduction of the 10-level NWP model in 1972, this figure rose to 0.65, and the possibility of making useful numerical forecasts into the medium range (defined by WMO as more than 72 hours and up to 10 days ahead) began to be accepted. In 1975 the European Centre for Medium-range Weather Forecasts (ECMWF) was established, with the United Kingdom as one of the 17 Member States, and in 1979, by then located in Reading, began

In this typical example of medium-range forecasts the significant change from the initial flow pattern (a), with the formation of the cut-off low near Iberia, is forecast very similarly 6 days ahead by the Bracknell (b) and ECMWF (c) global models. However, there are important differences in the details of the predicted flow pattern, and these have to be weighed by the Medium-range Forecaster.

operational numerical forecasting to 10 days ahead.

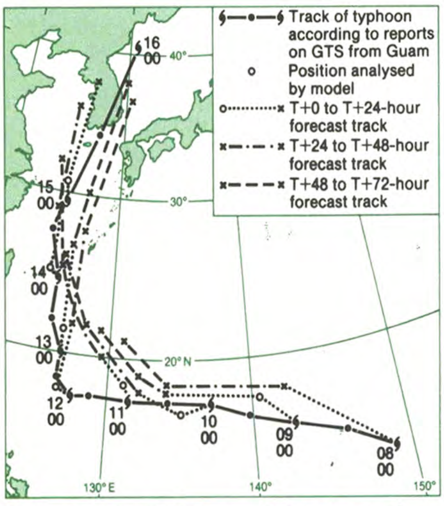
The NWP system at ECMWF is designed specifically for medium-range forecasting. Hence there need be only one forecast each day, and a late data cut-off (1930 GMT for the 1200 GMT starting conditions) ensures that important observations are not missed. A similar specially designed medium-range forecast run is performed at the US National Meteorological Centre near Washington, DC. By contrast, the Bracknell global NWP system is organized primarily for short-range forecasting (up to 72 hours) so that there are two runs each day from early data cut-off times. However, the Bracknell forecasts are extended to 6 days ahead to provide additional guidance for the early medium range.

The ECMWF and US numerical forecasts are provided routinely to the Medium-range Forecaster in the CFO along with the Bracknell results. When the models agree, as is frequently the case, increased confidence is placed in their guidance. When the models disagree, perceived strengths and weaknesses for different types of weather pattern are taken into account. A major requirement placed on ECMWF for the future is the provision of a priori guidance on the skill of each medium-range numerical forecast.

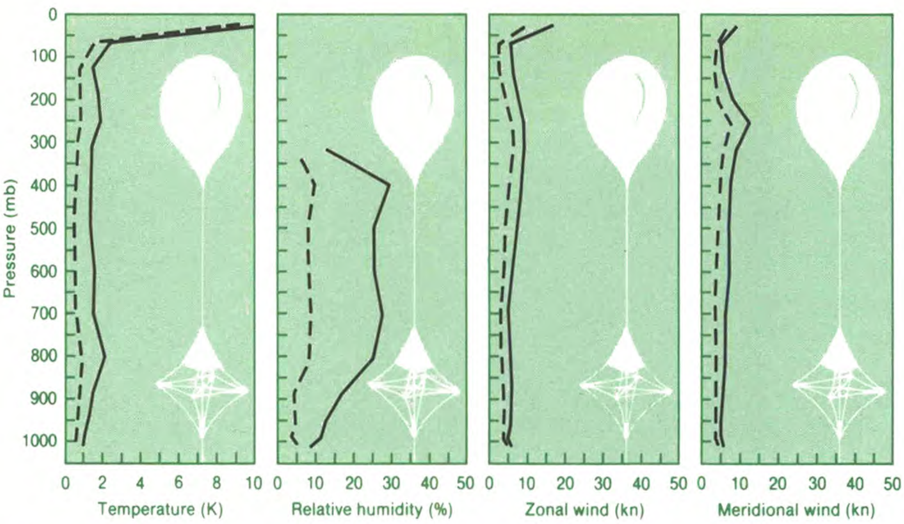
The correlation coefficient between forecast and actual changes in sea-level pressure now exceeds 0.8 for 72-hour forecasts, and 0.7 for 120-hour forecasts; a quality at 120 hours in the latter forecasts similar to that of 72-hour forecasts about 10 years ago.

Tropical cyclones

Since the extension of NWP at Bracknell to global coverage in 1982 there has been the opportunity to assess and improve the quality of numerical forecasts for tropical regions. A pleasing finding has been that the skill of the global model in predicting the tracks of tropical cyclones is a match for any of the specially designed methods that are in use around the world. During 1987 the important role of the Intervention Forecasters in the CFO in correcting the initial locations of tropical cyclones has been demonstrated through case studies.



Forecast tracks of Typhoon Thelma during the period 8–16 July 1987 show a useful skill when compared to the reported track



Root-mean-square differences of radiosonde observations at Ocean Station 'Lima' from background (solid line) and analysis (dashed line) fields for January 1987, from the OPD

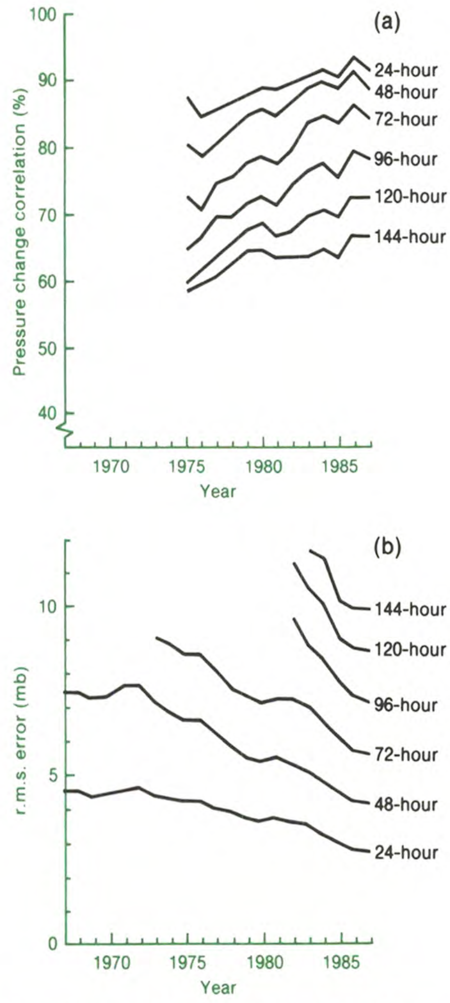
Data-quality studies

Each observation that is used in the NWP system is stored in an Observations Processing Database (OPD) along with its differences from interpolated model fields and with a record of all the quality-control decisions made about it (both during the NWP processing and by the CFO forecasters). After careful study of statistical evidence derived from the OPD, it has been possible to improve the use of certain kinds of observations in the data assimilation. During 1987 the lists of stations used in mountainous regions were revised to eliminate the stations whose reports seem unrepresentative of the models' grid-scale orographic fields. A decision was also made not to use satellite-derived temperatures at model levels near the surface in areas where the sea surface temperature analysis is of reliable quality.

Measures of performance

Statistical measures of NWP skill continue to reveal an upward trend in the accuracy of forecasts. This is despite an absence of major changes in the modelling or data-assimilation techniques in the past few years. The reduced errors are therefore the cumulative effect of smaller changes in the NWP system, including changes in the selection and use of observations that have resulted from data-quality studies. Enhancements of the Global Telecommunication System (GTS) are also likely to have contributed by enabling more observations from around the world to reach Bracknell before the NWP data cut-off times.

For the fine-mesh model, increased emphasis has been given to the objective verification of precipitation forecasts. Statistics for the precipitation forecasts prepared subjectively in the CFO indicate the value added by the human component of the man–machine mix.



Annual average change correlations (a) and root-mean-square (r.m.s.) errors (b) for sea-level pressure forecasts for the North Atlantic area made by the global model

Observations

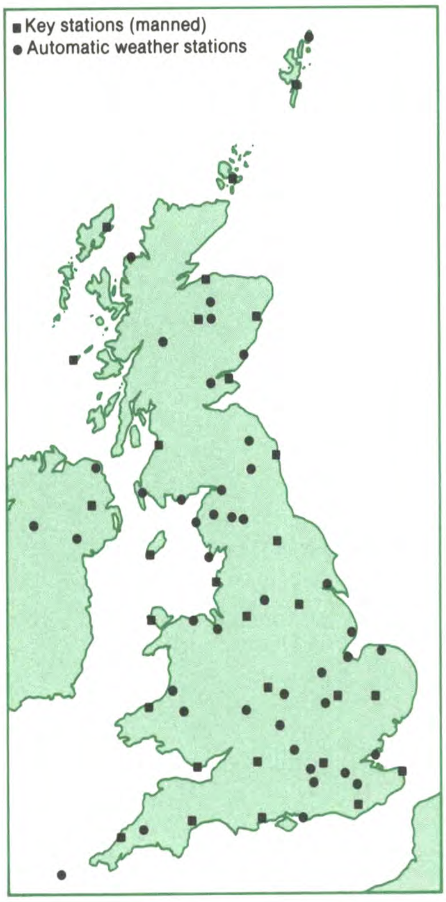
Regular, reliable and accurate measurements of pressure, temperature, wind speed and direction, cloud and precipitation, amongst others, are needed as the basic input to the wide range of forecasts produced by the Meteorological Office. Similar measurements are also essential to the provision of consultancy, advisory, and information services.

To supply these data a series of monitoring networks of different types and applying a variety of techniques has been established. Most stations in these networks are manned, but automatic data-gathering systems are also in use and more are being introduced to provide information from uninhabited regions and to replace the capability lost as manpower is reduced. Not all the necessary data can be obtained automatically, and technology is being developed to narrow the gap between those observations (for example, cloud and precipitation type) best made using human judgement and those measurements made by instrumental methods. Despite this distinction all such measurements are usually referred to as 'observations'.

Many measurements are made *in situ* by placing a sensor at the appropriate place in the atmosphere; platforms such as ships, aircraft, buoys and balloon-borne packages are employed, as well as the more familiar installations at airfields, schools, coastguard stations and the like. However, increasing use is being made of remote-sensing techniques in which properties of interest are inferred at a distance, usually by sensing electromagnetic radiation that has been emitted, scattered or absorbed by the atmosphere.

Surface observations

To define the existing state of the weather over the United Kingdom on a broad scale at or near the surface, a network of 30 'key' observing stations with a spacing of about 150 km is needed. These stations are manned by professional meteorologists who make a wide range of measurements at least every hour. To take account of the effect of topography on current weather and forecasts for a specific locality, regular observations are obtained from a denser network comprising a further 185 stations, 54 of which are manned by the Office, and 43 automatic weather stations (AWSs). The figure shows the current networks of automatic and key observing stations.



Automatic and key observing stations

The AWSs, mainly installed in unpopulated areas, already make and report basic measurements of air temperature, humidity and pressure, and 10-minute average wind speed and direction. Arrangements were made this year to enhance the observing program of most of the automatic stations. By improving the system software and adding further sensors it will soon be possible to add to the basic measurements those of hourly rainfall, surface and soil temperatures, maximum and minimum temperature, winds averaged over 1 hour and hourly gusts, and global radiation. The AWSs will also be capable of accepting data from ceilometers (cloud-base recorders) and visibility sensors; methods of deriving both cloud height and amount from the ceilometer data have been developed and will undergo field testing shortly.

Other surface observing networks satisfy specific needs. Observations alongside major roads and from road-surface sensors assist in the forecasting of conditions hazardous to motorists, especially fog and ice. Mainly to assist in the estimation of evaporation and hence the water balance, measurements of global and diffuse short-wave radiation are made at 14 Office stations, and 23 co-operating stations measure at least the global component.

An extensive data base is required to support climatological services to customers; continuous measurements made at 55 Principal Climatological Stations allow extremes of windiness and rainfall intensity to be derived, whilst daily measurements made at about 450 voluntarily operated Ordinary Climatological Stations help to complete a national picture of the variation of extreme temperatures. Rainfall is measured at about 4800 sites, largely by Water Authorities, river Purification Boards and private individuals, for hydrological and climatological purposes. These voluntary observations make an important contribution by helping to build up a full picture of the climate of the United Kingdom and its variability. The Meteorological Office remains extremely grateful for the dedication and skill shown by those who assist in this way.

Work continued throughout the year in the evaluation of new sensors and observing techniques:

- Analysis of data from the international intercomparison of ceilometers carried out at the Beaufort Park experimental site near Bracknell during 1986 was completed and the final report of the work distributed within the World Meteorological Organization (WMO). The results showed that there has been considerable improvement in the performance of laser ceilometers in recent years but that some deficiencies remain in their performance in fog and precipitation.

- Problems associated with the measurement and reporting of surface wind, particularly gusts, by digital-sampling and processing systems were studied and a performance specification for such wind systems is being developed.

- Soil temperatures down to 100 cm depth were measured by a variety of techniques. An analysis of the field data was completed in the light of a theoretical treatment of thermal diffusion, and the results show that new methods of sensor exposure must be used at automatic stations. Work continues on the definition of a national network of such measurements sufficient to meet the needs of climatology and numerical forecasting.

- Extensive acceptance trials of eight Marconi short baseline visibility sensors were concluded before they were released for installation. Trials commenced at Beaufort Park of two 'forward scatter' visibility sensors for possible addition to AWSs on land and at sea.

Procurement action continued for new systems and some entered operational service:

- Delivery of 28 runway cross-wind resolvers was completed and installation started at RAF stations at home and abroad; the first system went into operational service at RAF Valley, Anglesey.

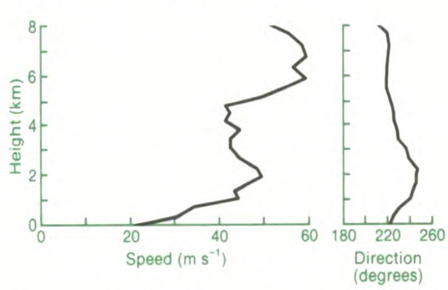
- A contract was placed with the Belfort Instrument Company, USA for the supply of 15 laser ceilometers and factory acceptance testing was underway by the end of the year.

Surface weather observations from the oceans are provided largely by merchant ships. Vessels of many types make up the United Kingdom Voluntary Observing Fleet (VOF) of more than 500 ships. They contribute to a WMO scheme in which 7400 ships of 49 nations provide observations from the oceans of the world. In most cases the observations are reported by radio directly to a coastal station for onward transmission, but the timeliness and regularity of reports are being much improved by the use of direct satellite-based communications. The Meteorological Observing System for Ships (MOSS) is an on-board terminal, developed in the United Kingdom and now fitted to 26 vessels, which accepts manually entered observations, formats the report and transmits it via a meteorological geostationary satellite. The system also allows the ships' officers to enter reports more frequently than at the standard 6-hour intervals.

Ocean Station Vessel (OSV) *Cumulus* continued to man station 'Lima' in the North Atlantic on position 57°N, 20°W — one of the three remaining weather stations operated under the North Atlantic Ocean Stations Agreement. This arrangement is now expected to be maintained until at least the final quarter of 1989. In addition to its normal role of providing regular surface observations and upper-air data, *Cumulus* acted as a platform for a variety of oceanographic experiments conducted by the Admiralty Research Establishment, University College Swansea and the Institute for Marine Environmental Research. Other experiments carried out from the vessel included the measurement of atmospheric turbidity for the United States National Climate Centre, and an assessment of instrumental wind measurements for the Institute of Oceanographic Sciences.

Additional detailed, regular observations are required from the seas around the United Kingdom both to describe the prevailing conditions for shipping and other offshore activities and to provide early warning of weather systems approaching land. Experience and experiment suggest that a network of 9 key stations, reporting a wide range of elements every 3 hours, and about 30 secondary stations, reporting some of these, and less frequently, will meet the need in a cost-effective manner. To date, 5 key stations and 23 secondary stations have been established on fixed buoys and on oil and gas platforms.

- After many delays a data buoy, designated ODAS 452, was deployed on 15 August near 67°N, 13°W by a vessel of the Faeroes Coastguard. This buoy will be maintained for 2 years jointly by the United Kingdom and Iceland.



A profile of the wind speed and direction at Crawley at 0515 GMT on 16 October

- The COST-43 (European Co-operation in Science and Technology) drifting buoy projects in the North Atlantic have continued throughout the year and six buoys supplied by the United Kingdom were launched, including four from vessels plying from the United Kingdom to North America.

- The data buoy, ODAS 20, moored in the southern North Sea at 55°20'N, 02°20'E, was recovered in the spring for repair and battery changes after more than 6 months' successful operation. It was redeployed in the same position in June with an increased battery capacity, sufficient for more than 1 year's operation, and continued in good operational service for the rest of the year.

- The UK/French 'Bosco' buoy was recovered after a mooring failure in January and spent the year undergoing extensive refurbishment in France. A new agreement between France, the United Kingdom and Ireland to deploy and operate the Bosco buoy for a further 2 years starting in spring 1988 was finalized by the end of the year.

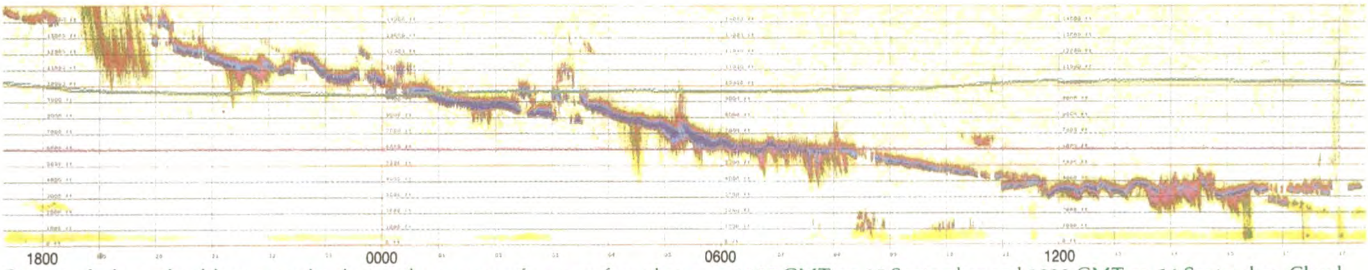
- A contract was placed for the supply and installation of AWSs on two unmanned light-vessels for delivery in 1988 and invitations to tender for the supply of a series of open-ocean meteorological buoys were issued during the last quarter of the year.

Upper-air observations

Upper-air measurements of geopotential, temperature, humidity and winds continued to be made routinely from eight radiosonde stations in the United Kingdom, and from Gibraltar, St Helena, and Mt Pleasant in the Falkland Islands. A profile of wind measured at Crawley radiosonde station in West Sussex on the night of the severe storms in south-east England (15/16 October) is shown in the figure below left; from the surface the mean wind speed increased rapidly with height to approach 100 mph (45 m s^{-1}) at only 3000 ft (1 km).

Considerable progress was made towards the planned replacement of the UK Mk 3 radiosonde system in 1989; detailed requirement specifications were issued during the year and tenders made by three manufacturers were evaluated. For the first time the Office made commercial use of its knowledge and expertise in this field. Thus during May and June the performance of the equipment from two contenders for the Australian Advanced Radiosonde system was evaluated by field trial for the Bureau of Meteorology, Australia. More than 60 comparison flights were made at Crawley where the contending radiosondes were flown with the Mk 3 radiosonde. Additional income was earned from a manufacturer who required detailed information on the performance of his Navaid wind-finding software.

A contract for the production of the ASDAR (Aircraft to Satellite Data Relay) avionics system has now been successfully transferred to Marconi Defence Systems Ltd. Thirteen systems



Output of a laser cloud-base recorder during the passage of a warm front between 1600 GMT on 15 September and 1830 GMT on 16 September. Cloud and other particles in the atmosphere scatter light from a pulsed laser firing vertically upwards, back to a co-located detector. The yellow trace from 1730 GMT on 15 September onwards indicates the presence of low-level haze; the broken trace from 1830 to 2000 GMT provides evidence of ice particles from high-level cirrus seeding cloud around 13 000 ft and inducing precipitation which does not reach the ground. Throughout, cloud lowers as the warm front approaches with virga forming at 0145, 0430 and 0500–0540 GMT. Precipitation begins to fall from a layer of stratocumulus at 1330 GMT but is detected at ground level only from 1506 until 1530 GMT. The low-level cloud begins to disperse from 1700 GMT onwards.

are being manufactured and certified for international use on Boeing 747 and DC 10 aircraft. Most will be exported but the Office is procuring five of these systems for use on UK aircraft. The systems will sample meteorological data measured on the aircraft, quality control and code them and transmit them via meteorological satellites to the ground. In this way both the collection and the communication of AIRcraft REPorts (AIREPs) can be automated.

OSV *Cumulus* continued to provide 6-hourly upper-air observations during her 33-day round voyages out of Greenock. On some occasions measurements were recorded from both the ascent and descent of the radiosonde package; these have demonstrated that the top of moist 'tropospheric' air can be determined much more accurately from humidity measurements made on the descent phase. As part of the international Automated Shipboard Aerological Programme (ASAP), the Office is equipping two merchant ships operating between Felixstowe and Montreal. All the necessary equipment is housed in self-contained containers from which the radiosonde can be launched. A system borrowed from the Atmospheric Environment Service, Canada, has been installed on the MV *Manchester Challenge*. A further unit has been leased and is installed on the MV *Canmar Europe*. Both are operating successfully.

The launch of a drifting buoy

A radiosonde balloon about to be ejected from its container

Lightning detection

It is possible to detect and locate lightning discharges through the electromagnetic emissions which they generate. At radio wavelengths the flashes cause interference known originally as 'atmospherics' because of their origin; this term has since been corrupted to 'sferics'. During the year a new operational sferics-location system was introduced to replace the 40-year old Cathode Ray Detector Finding (CRDF) system. The new system employs an Arrival-Time-Difference (ATD) technique and has five outstations in the United Kingdom at Lerwick, Stornoway, Camborne, Hemsby and Beaufort Park and two in the Mediterranean at Gibraltar and Cyprus, together with a control station also based at Beaufort Park.

One of the outstations acts as a selector station and reports the times at which it detects a sferic event to the control station computer at Beaufort Park. The control station then interrogates the remainder of the outstations for detailed wave forms of sferic events close to this time and extracts the time differences and so calculates possible locations. The figure right illustrates the way in which the ATD system locates the origin of a flash. Up to 400 flashes an hour can be located in this manner. The main features of the resulting distribution are reported in code for distribution on the GTS. A higher-resolution format message suitable for presentation to the FRONTIERS system (see later) or to other users who require location reports to be more precise and more frequent can be made available.

The network underwent pre-operational trials during the summer and early autumn. The results showed that the system fulfils its design requirements for location accuracy and throughput of fixes. For example, thundery activity over Great Britain was located with estimated root-mean-square errors of less than 5 km, compared with an estimated 30 km error for the CRDF system. The derived fix locations also agreed convincingly with regions of heavy rainfall identified on the weather radar network. The figure on page 16 shows an example of the network radar picture for 1400 GMT on 29 July 1987, which combines the two types of data.

The synoptic situation at 1400 GMT had a low pressure centre over the North Sea with a trough extending from The Wash to the Isle of Wight. The trough moved south-eastwards during the afternoon. A small low centre on the trough, that was over the Midlands at 1200 GMT, moved south-east and by 1300 GMT was the focus of the thundery activity over London which produced the heavy rain illustrated in the figure on page 12. The thunderstorms then intensified as they moved eastwards and by 1400 GMT were the cause of serious flooding in Essex; this was widely reported in the Press and on television.

Lightning fix over Libya as located by the new ATD system

The UK weather radar network

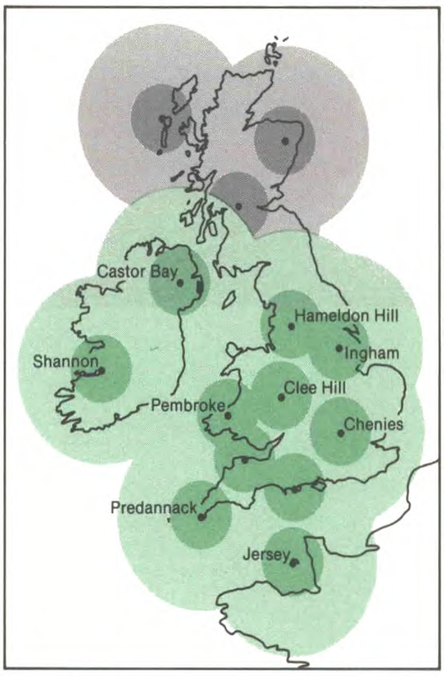
The timely detection and measurement of precipitation is extremely important. Whilst precipitation provides all the water essential for domestic purposes, agriculture and industry, it can also cause flooding and disruption of communications with the associated damage and sometimes risks to life.

Traditionally rainfall has been measured by using funnel rain-gauges but, because of the large spatial and temporal variability of precipitation, a large number of such gauges are required for accurate estimates of the total rainfall over a particular area. For operational uses, such as river-flow forecasting, rainfall readings are required within a few minutes, making automatic measurement and some form of telemetry essential. Radar, however, can measure rainfall and snowfall instantaneously over a large area, thus simplifying the collection and transmission of data.

The current network of weather radars has developed as a result of over 20 years' research and development performed by the Meteorological Office in conjunction with the Royal Signals and Radar Establishment at Malvern. Almost all the systems have been installed as part of co-operative ventures: the partners include nine of the ten Water Authorities in England and Wales, Devon County Council, the Directorate of Naval Oceanography and Meteorology, the Ministry of Agriculture, Fisheries and Food, and the Departments of the Environment and of Agriculture for Northern Ireland.

From the earliest days of radar it was realized that precipitation could be detected, but effective exploitation of the fact awaited the development of computers able to cope automatically with the large volumes of data. An understanding of the factors affecting the relationship between the return signals and rainfall rate was also required. The first attempt to assess the utility of such measurements was made in the *Dee Weather Radar Project* (1968–77). A prototype Plessey weather radar system was installed in North Wales and the output assessed both by the Water Industry and by the Meteorological Office. The Dee Project demonstrated that the operational use of radar was practicable, that precipitation measurements were possible in hilly country as well as over lowland areas, and that the rainfall measurements could in turn be used for river-flow forecasts. It was also clear that radar offered a useful technique for measuring snowfall as it occurred. In parallel with the Dee Project a method was developed for accepting the output from a number of overlapping radars and integrating these into a composite data base.

Developments of technique and understanding continued throughout the *North West Weather Radar Project* (1977–85). The aims of this project were to establish and evaluate an unmanned operational weather radar station at Hameldon Hill (see figure below) that was integrated with Water Authority communications, to utilize the radar data in producing quantitative forecasts of rainfall and river flow, and to assess the costs and benefits of this approach. The system proved to be highly reliable and the project showed that radar data could be used, together with hydrological numerical models developed during the project, to generate forecasts of floods. In some zones at risk from floods, forecasts had not been possible previously and in others the prospect of floods could be detected earlier, thus allowing more warning to be given. During the project, methods of calibrating the radar by the use of a small number of telemetering rain-gauges were devised so that optimum estimates of surface rainfall could be obtained.



Current and planned weather radar network

Thus it was demonstrated that radar could satisfy certain requirements of the water industry but the Meteorological Office was keen to exploit the opportunities presented by the availability of both radar and satellite data for weather forecasting purposes too. The ability of the radar systems to present a 'picture' of the changing distribution and intensity of rainfall over a wide area was considered to be a powerful aid to meteorologists in the preparation of short-period forecasts.

The *Short Period Weather Forecasting Pilot Project* (1978–82) was aimed at developing the observational and processing facilities that were necessary for the Office to improve its forecasts for the period 1 to 6 hours ahead. Radar data were available from old radars installed at Camborne and Upavon and also from new radars on Clee Hill and Hameldon Hill. Visible and infra-red satellite images were available half-hourly from Meteosat. Although there is no simple relationship between cloud imagery from satellites and rainfall measured at the surface it was hoped that the project would identify procedures which would provide some useful information in this respect.

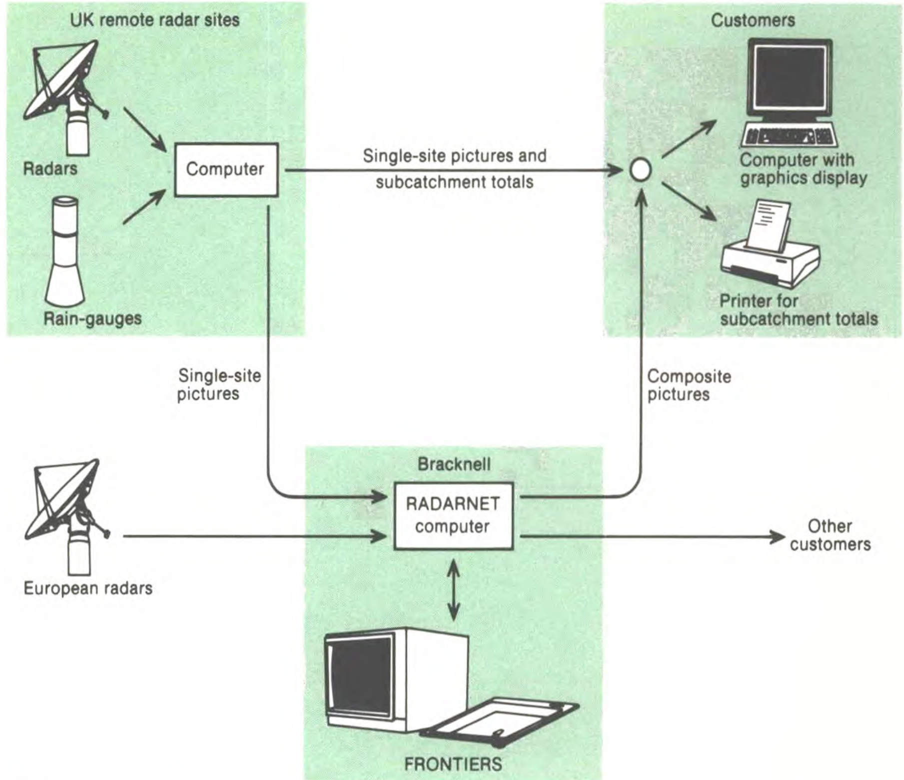
The project showed that the production of short-period forecasts based on radar and satellite data was feasible but that subjective intervention by a forecaster with ready access to conventional meteorological observations (temperature, humidity, etc.) was vital.

During 1981–83 a Meteorological Office/National Water Council Joint Working Group carried out a detailed study of the potential benefits of a national weather radar network, particularly for the Water Authorities. In its final report the group confirmed that operational experience had demonstrated significant advantages in flood prediction and warning, and endorsed the development of a network of unmanned radars. A network of 11 or 12 radars was envisaged to cover catchments in England and Wales that were at risk from short-period flooding and where warnings might be expected to reduce damage. The group identified relevant catchments and calculated the likely benefits as shown in the figure right. They assumed that quantitative precipitation forecasts out to 4 hours ahead would be achieved through the use of network data by FRONTIERS (see later). Overall, a benefit–cost ratio of the order of 3:1 was estimated for the network.

On the basis of this report, which noted the substantial benefits of a radar covering the London area, by 1985 a further radar was established at Chenies. At this stage the network of five weather radars (Camborne, Upavon, Clee Hill, Hameldon Hill and Chenies) was declared operational and data from each site, together with those from a radar located at Shannon, in the Republic of Ireland, were being relayed to a central network computer (RADARNET) where composite images covering most of the southern half of the United Kingdom were formed.

By then it had become clear that it was not economic to purchase and install radars in a piecemeal fashion and the older, technically inferior radars at Camborne and Upavon were demonstrating their limitations. Therefore, in collaboration with the Water Authorities and others, a number of consortia were formed and six new radars were purchased. Those at Castor Bay and Predannack are now operational and by the end of the year their data were being included in the composite image. Information from the Castor Bay radar in particular proved very useful in helping forecasters and others during the heavy flooding experienced in parts of the Province during October. Construction and installation are well advanced at the Ingham site in Lincolnshire and, subject to planning approval, the installations in Devon, Dorset and West Wales will be completed next year. The authorities in Jersey are planning to refurbish, reinstall and digitize a weather radar on the island in 1989. The Meteorological Office is assisting in this, and the data from the radar will be included in the composite in due course. Plans are in hand to extend the network into Scotland. The Meteorological Office and the Scottish Development Department expect to collaborate in installing three radars, in the vicinity of Glasgow or Edinburgh, to the north-west of Aberdeen, and in the Hebrides, during the early 1990s.

Currently the network of radars, their on-site processors, and the RADARNET facility generate a number of products to meet the needs of users both within and



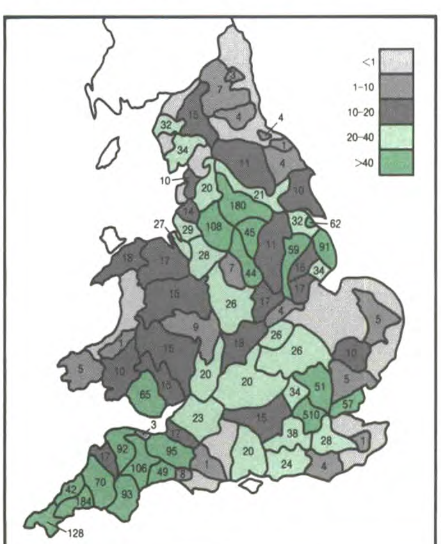
RADARNET — the distribution of radar data to customers

outside the Meteorological Office. Almost all of these are distributed in near real-time over dedicated communication circuits, so capitalizing on the timeliness of the data.

The individual radars in the United Kingdom operate on a cycle which repeats every 5 minutes and data are processed and reduced to measurements of rainfall in both 2 km × 2 km and 5 km × 5 km areas aligned with the National Grid. The data are also used to calculate rainfall accumulations in up to 200 different river subcatchments per radar.

Currently, Water Authorities are the principal external users of such data from single radars. They can and do choose to use them in a number of ways. The simplest method is to display them as coloured images on a television screen. By replaying sequences against a map background the motion and development of areas of precipitation can be inferred.

Quantitative estimates of the total rainfall which has fallen during the last few hours in sensitive catchments can also be extracted and displayed. In the future several Water Authorities expect to use catchment data as one of the inputs to the numerical models of river response which will guide flood forecasting.



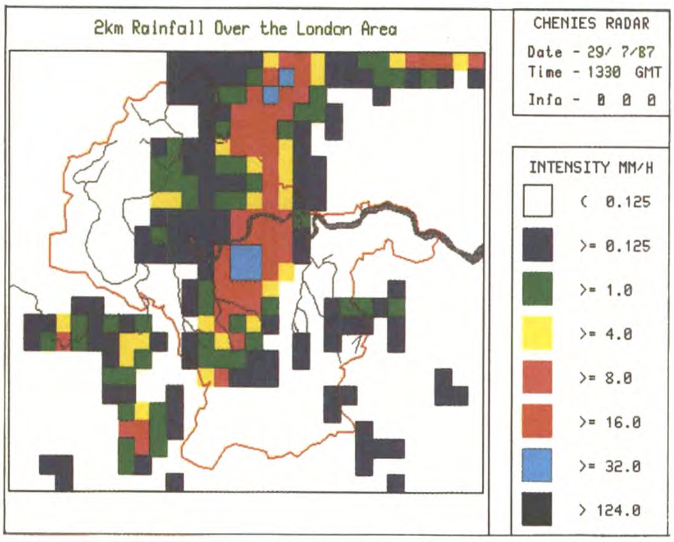
Disposition of benefits (£000) likely to accrue from the installation of a weather radar network and quantitative precipitation forecasts from FRONTIERS

There are many potential beneficiaries whose needs cannot be met by data from a single radar sited primarily to cover flood-risk areas. The composite images generated by RADARNET, and their derivatives, serve those needs. The RADARNET computer receives data from each radar every 15 minutes and generates images of the kind shown on page 12 some 6 minutes after capture. At present these are distributed to over 50 outlets, including Meteorological Office Weather Centres, forecasting offices on military airfields, the water industry, universities, County Councils and Road Authorities. During 1989 it is hoped that such data will be available for use in live presentations on national television by the Meteorological Office Weathermen.

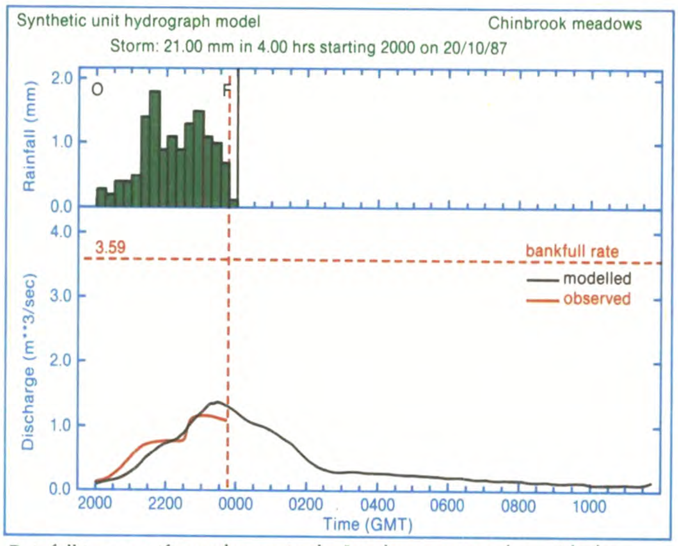
The European dimension

Developments in the United Kingdom have been paralleled to some extent elsewhere in Europe. Happily this has been marked by very effective collaboration, in which the Meteorological Office has played a major role. In 1979 a new project, COST-72, sponsored by the European Economic Community, was established. Over the succeeding 6 years the project assessed the benefits of radar data to users throughout Europe, produced an outline radar system specification, studied the quality of radar data, and demonstrated the feasibility of exchanging information in real time throughout western Europe.

In 1985 a further project, COST-73, began. This is concentrating on the many aspects of international radar data exchange and exploitation. The

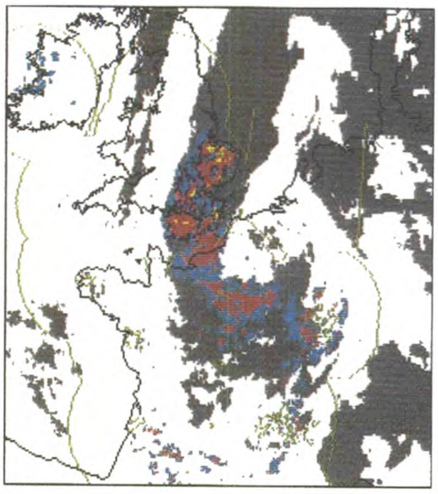


The heavy rainfall in the London area on 29 July as detected by Chenies radar and displayed by Thames Water Authority (courtesy of Thames Water Rivers Division)

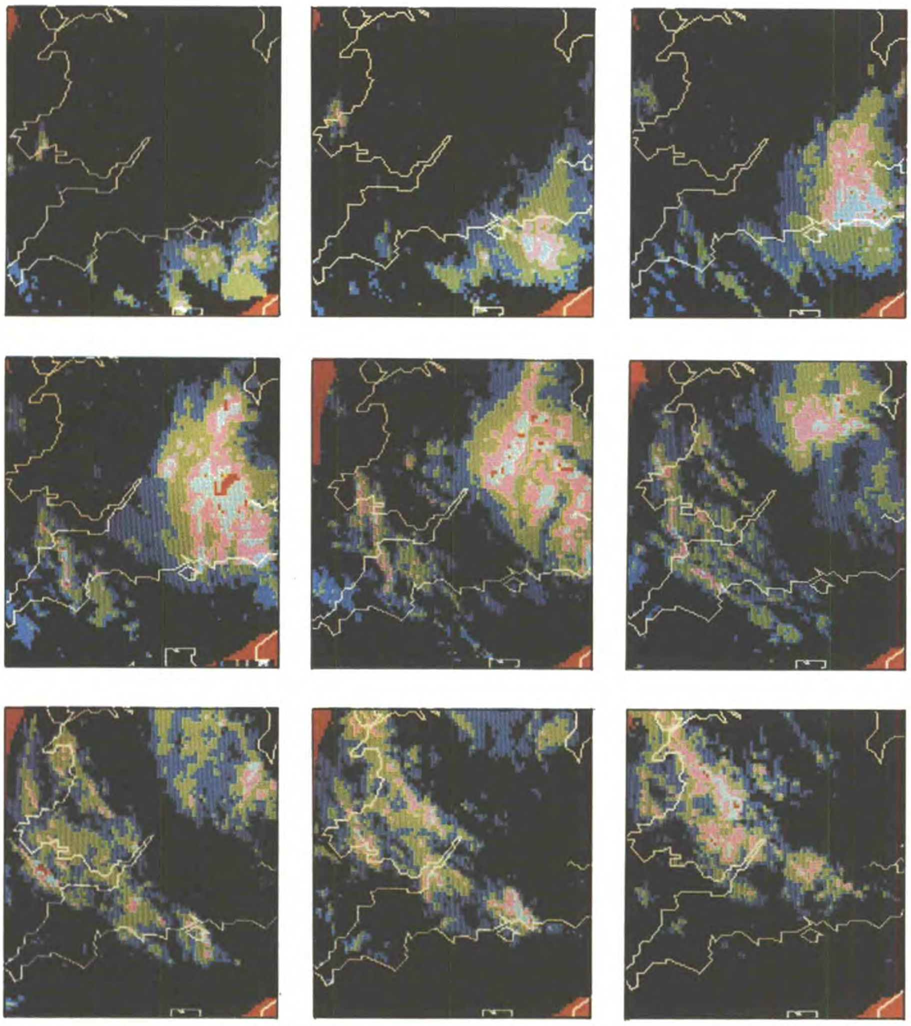


Rainfall in a specific catchment in the London area together with the modelled and observed river flow on 20/21 October (courtesy of Thames Water Rivers Division)

Meteorological Office acts as a hub for this activity, receiving data every hour from Switzerland and the Netherlands and every 15 minutes from France and, as already noted, from the Republic of Ireland. These data are combined hourly with equivalent UK data and with infra-red satellite data, to construct a European composite as shown in the figure right. This is forwarded directly to France, the Republic of Ireland, Switzerland, Sweden and Finland. As further radars are installed and become operational in Denmark, the Federal Republic of Germany, Spain, Austria and Belgium, it is expected that they will contribute to the composite, which will in turn be distributed widely to National Meteorological Services throughout the Continent.



A composite of European radar data and infra-red cloud images. Blue, red and bright yellow areas show different rainfall rates inferred from radar data. Maximum radar ranges and areas where spurious (ground-return) echoes are likely are shown in green. Areas of possible rain-bearing cloud, appear in grey.



A sequence of images from RADARNET illustrating the development and movement of rain over southern England and Wales during the evening and early morning of 20/21 October. Some flooding was caused in parts of south-east England as an area of heavy rain moved northwards from the Channel.

Observations from satellites

Earth-orbiting satellites, able to sense radiation from the atmosphere, provide opportunities for meteorologists to make relevant measurements.

- By detecting the variable solar radiation reflected by clouds and the earth's surface during daylight hours, a conventional image can be formed and transmitted back to earth.

- By monitoring certain infra-red wavelengths, images of cloud can be obtained at all times of the day.

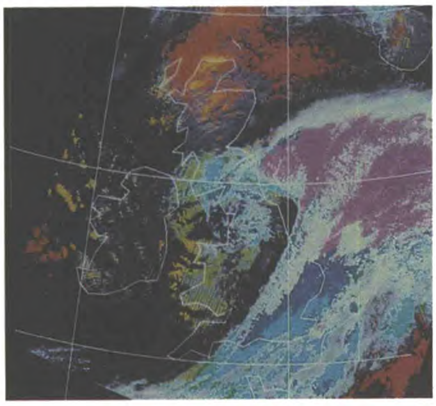
- By measuring infra-red or microwave radiation at a range of wavelengths, some of which are strongly absorbed and some of which are not, it is possible to discern the temperature of the atmosphere as a function of height.

Much effort is being expended to make the most of these techniques on satellites in polar orbit some 1000 km above the earth's surface and on others which rotate with the earth and therefore remain stationary relative to it at about 36 000 km above the equator.

Use of digital data received from the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites, will enable improvements in the quality of available satellite images to be achieved. Therefore a new processing system, named AUTOSAT-2, capable of manipulating these digital measurements is being procured. Supporting research is under way. This has the objective of exploiting the radiances from the five available wavelengths in the visible and infra-red, singly and in combination. Conventional visible and infra-red images will be provided for distribution to the Central Forecasting Office and outstations. It is also planned to produce for distribution a number of other products in image format. These include estimates of land surface temperature for frost and road icing forecasts, 5-day mean sea surface temperatures around the British Isles, and snow-cover maps. Research into methods of improving the images which characterize the distribution of fog, for aviation and motorway warnings, is well advanced. A product which illustrates the disposition of cloud-top temperature and hence height is also under development; an example is shown in the figure below. The product has obvious applications for aviation forecasting. A scheme is also under development to derive parameters from AVHRR data that will help to initialize the mesoscale forecast model described elsewhere.

A Local Area Sounding System (LASS) had been producing atmospheric temperature and humidity profiles in near real-time for several years. The system receives raw radiance data directly from the NOAA polar-orbiting satellites, whenever one is in line of sight from the United Kingdom. LASS uses the measurements of radiance emitted from the atmosphere to estimate temperature and humidity as a function of height. The resulting 'soundings' supplement similar soundings (i.e. SATEMs) received from Washington over the Global Telecommunication System (GTS), but are at a much higher density in the main area of interest — most of the North Atlantic and western Europe — and are available significantly earlier. They are supplied to the Central Forecasting Office in chart form and are assimilated into the fine-mesh model analyses. Although satellite soundings provide a denser network of observations in both time and space than is available from the conventional radiosonde network, there are significant problems to overcome if the desired accuracy is to be achieved. The presence of cloud complicates the analysis of infra-red radiances considerably; microwave frequencies are much better in this respect. More fundamentally, measured radiances are representative of broad vertical layers of the atmosphere, and new methods of incorporating their information content to maximum effect in numerical weather prediction models remains a very active research area.

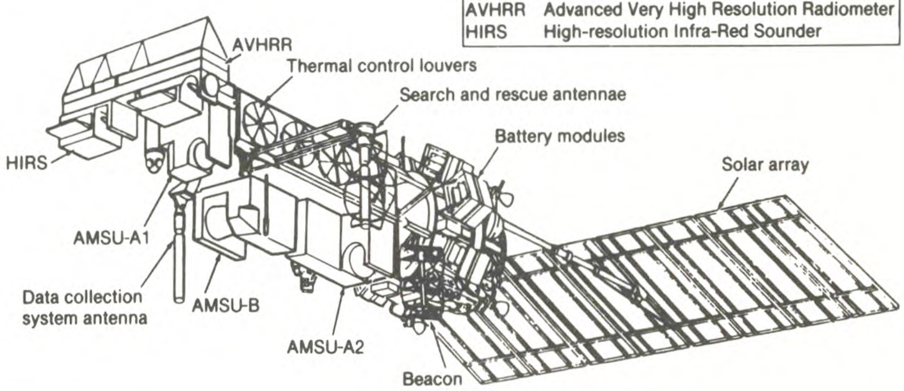
Cloud-top temperature satellite image as inferred from a satellite infra-red image



A development-model microwave receiver for the AMSU-B instrument

The next major contribution which the Office will make to polar-orbiting spacecraft is a five-channel microwave radiometer, designed to provide humidity soundings on a global scale at 15 km horizontal resolution. The instrument is known as the Advanced Microwave Sounding Unit Model B (AMSU-B). The formal processes which lead to a competitive tender and contract placement to build three flight models for NOAA K, L and M have been initiated. Launch of NOAA K is scheduled for late 1992–early 1993.

AMSU	Advanced Microwave Sounding Unit
AVHRR	Advanced Very High Resolution Radiometer
HIRS	High-resolution Infra-Red Sounder



NOAA K, L, M spacecraft configuration showing the position of AMSU-B

The provision of instruments to NOAA, in the form of Stratospheric Sounding Units, for flight on their polar-orbiting satellites continued; the next launch is scheduled for 18 February 1988. Currently a unit is operational on NOAA-9 and is performing within specification. Two further units are being made available for deployment.

The Meteorological Office is contributing the focal plane assembly for an Along Track Scanning Radiometer (ATSR) which will fly on the European Remote-sensing Satellite (ERS-1). The engineering model was assembled and tested successfully during the year. All the components for the flight model unit were delivered and the unit was assembled before environmental and performance testing. The calibration targets, to be used for validations of the ATSR, were constructed.

A contract with Marconi Defence Systems to design and build prototype receivers for AMSU-B is nearing completion. All the microwave receivers have been assembled and their performances investigated. A supporting scientific and calibration program has begun. An internal microwave reference target has been designed, constructed and tested and a contract placed to build a space-quality version. Detailed laboratory measurements have been made on the microwave properties of water in its three phases and supporting aircraft measurements are planned. The results will be incorporated into the radiative transfer scheme which is necessary for the interpretation of the satellite instrument measurements.

FRONTIERS

The concept of FRONTIERS (Forecasting Rain Optimized using New

Techniques of Interactively Enhanced Radar and Satellite data) arose out of experience gained in the Short Period Weather Forecasting Pilot Project. Development of the system began in 1981 and continues today. Currently FRONTIERS is a computer-based system that receives radar and satellite data in image format and can manipulate them under forecaster control to generate new image-based products. These fall into two categories:

• Improved (i.e. enhanced, extended, quality-controlled) images of the current rainfall patterns.

• Quantitative predictions of future rainfall, extending over the next few hours.

Much effort has been expended in designing and implementing menu-driven software that is easy to use and requires no specialist knowledge of computers. The system is fully integrated into the Central Forecasting Office, and is able to benefit from and contribute to the many other activities which take place there.

Currently FRONTIERS provides quality-controlled radar images, from which occasional false echoes have been removed, some 30 minutes after data capture, via RADARNET to the various outlets described earlier. Forecasts for a few hours ahead are being assessed before operational use begins. An example of such a forecast and its verification is shown on page 16. At present, simple linear extrapolation of past movement is employed to forecast future movement of rain areas, but improvements are now in hand which will use the wind fields derived from numerical weather prediction models.

Through FRONTIERS the marriage of weather radar, high-resolution sferics and satellite data, against a backcloth of conventional *in situ* measurements will offer a number of specific advantages for the preparation of very-short-period forecasts — or nowcasts as they are known.

• The benefits of surface rainfall estimates with high spatial and temporal resolution, available in near real-time, and of quantitative precipitation forecasts for a few hours ahead were recognized by the Meteorological Office/National Water Council Working Group. The United Kingdom now holds a leading world position in the exploitation of weather radar and satellite data for these purposes.

• The ability to see the extent and intensity of rainfall over large areas within a few minutes of data capture and to track the movement of cells of heavy rain using the 'time lapse' replay of a sequence of radar images, gives forecasters a greatly enhanced 'feel' for the weather situation. Every forecaster who has access to the data can benefit in this way. FRONTIERS exploits the data specifically to generate quantitative site-specific forecasts of rainfall a few hours ahead. The data are beginning to be used to initialize the mesoscale model and to verify the detailed rainfall predictions which it generates.

• Aviation activities remain susceptible to weather conditions, particularly when these are severe. Aircraft are mainly at risk during times of take-off and landing. Happily the United Kingdom does not experience violent storms of the type and intensity which have contributed to major aircraft accidents in the USA. However, the regions of strong wind shear which attend thunderstorms are a source of discomfort for passengers and a constraint on air traffic control. They can be alleviated by knowledge of the existence and movement of rain cells inferred from weather radar network and satellite data. Helicopters are susceptible to icing, and poor visibility impairs their search-and-rescue missions. Satellite and weather radar data can assist in identifying breaks in these conditions, which may allow such missions to be completed.

• Both road and rail transport are affected by snow or rain falling onto frozen surfaces. Again radar data provide a unique insight into the location and extent of areas affected, thereby allowing scarce, costly clearance equipment to be deployed efficiently.

• Lightning strikes on the electrical grid network cause disruption to supplies and create hazards for those working on the lines. Weather radar and sferic data indicate the position and movement of thunderstorms while weather radar and satellite data can indicate the areas at risk from future lightning activity.

• Accurate, site-specific, short-period forecasts of rainfall, for which weather radar can be an aid on at least some occasions, can assist farmers to achieve greater efficiency in the application of fertilisers and pesticides.

• Microwave-frequency communication links, which are finding increasing use, are greatly attenuated by precipitation falling through the transmission path. Weather radar data can provide the detail necessary to optimize the design and use of such links.

• Studies have shown that the detailed areal coverage provided by a radar network is vital for the accurate, early estimation of the location and amount of wet deposition (material brought to the surface in rain) which may follow pollution events. Weather radar data were used in studies of the deposition of radionuclides in the United Kingdom following the Chernobyl incident.

Observing system performance

The foregoing explains something of the current technology of observing systems and their disposition to meet the needs of weather forecasters and others for meteorological data. An annual investment of several millions of pounds is required to procure, sustain and operate these systems. It is essential to ensure that this represents value for money by assessing their performance in the field against current needs.

Whenever possible, meteorological instrumentation is tested before it is used operationally, to ensure that manufacturers have met the requirements for system safety, reliability, data quality and other essential characteristics. In some circumstances such testing can take place in the controlled conditions of the Test and Calibration Laboratory but ultimately it is performance in the operational environment that matters. As noted above, the Meteorological Office has hosted international comparisons of radiosonde equipment and ceilometers as a means of establishing such performance. Much has been learned from these and other trials. Next year visibility sensors will be assessed in like manner.

When in operational service, evaluations of the performance of observing systems and their communication interfaces are carried out by a variety of procedures and for several purposes:

• Automated continuous monitoring of the availability, timeliness, integrity, and accuracy of data as received centrally at Bracknell facilitates several quick-response actions: chaser messages are sent to request missing data; maintenance authorities are informed of and respond to instrumental and communication problems; and forecasters are alerted to the impact of poor data on analyses and forecasts. Such monitoring is the main method of checking the performance of systems that operate in remote locations (e.g.

drifting buoys and shipborne radiosondes) and of automatic stations (e.g. on land and aircraft).

- Centralized monitoring of data accuracy, together with periodic field intercomparisons of different designs or types of sensor, provides information on the systematic differences between their measurements, and allows standard corrections to be made to observational data. For example, there are several different designs of radiosonde in use. Each has slightly different characteristics. It is possible to compensate for these before the data are used in numerical weather prediction models.

- Time-series data, statistical analyses of the differences (over several weeks) between observed values and computer-analysed values of a variable, as well as field trial results and maintenance reports, enable basic deficiencies in system software and hardware to be detected, and these often lead to improvements in design by the system operators and manufacturers.

Whilst the procedures described above have been established largely to meet national requirements, their importance for similar purposes has been recognized by the international community.

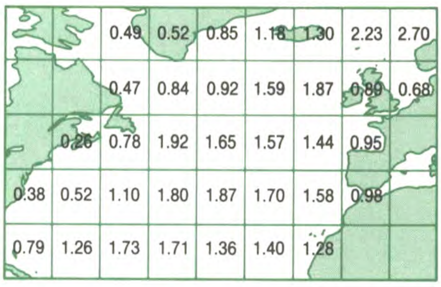
- Analyses of the performance of all the radiosonde designs used in the world are undertaken annually for WMO.

- Quarterly reports on drifting buoys deployed on the North Atlantic are prepared for the COST-43 Secretariat and the international Drifting Buoy Cooperation Panel.

- The stability of satellite radiometer channel frequencies is monitored for satellite authorities in the USA.

A major international project, the Operational World Weather Watch Systems Evaluation — North Atlantic (OWSE–NA), commenced in 1987. Most European and North American countries are joining together to conduct a detailed assessment of the cost and field performance of all land, marine, airborne and space-based observing systems on and over the North Atlantic, and of their communication links to each participant. At the same time numerical forecasting centres in several countries are carrying out studies of the impact of observations reported by various systems on both the analyses of present weather conditions and on forecasts. The storm which caused extensive damage in southern England and northern France during the night of 15/16 October represented one event of particular importance in this respect. The Evaluation will be used in the design of the North Atlantic observing networks for the next decade, and to establish adequate international arrangements to overcome system problems and so increase their efficiency.

The figure below depicts the distribution of surface-based data sources over and around the North Atlantic and illustrates some deficiencies of present-day networks. Over a 1-week sampling period in winter only 15 surface observations were received on average for each midday observation time from merchant ships in the entire Atlantic west of the British Isles (i.e. from 50 to 60°N, 10 to 60°W), since the major shipping lanes lie further south. It would require about 200 such observations together with satellite imagery to achieve an adequate description of the broad features of weather disturbances at the surface. Each midnight even less surface observations are received — only ten from the above area — owing to a lack of communication resources on many vessels at night. Drifting buoys are being deployed in the data-sparse areas labelled SOBA and SCOS in the figure but at present they have limited observational capabilities and are highly susceptible to damage and communication problems. The three Ocean Station Vessels provide essential upper-air data, but cost £4M per annum to operate. Satellites provide a dense network of coarse-resolution temperature soundings over the North Atlantic, and radiosondes launched every 12 hours from ASAP vessels when in transit yield more detailed though sparsely distributed information. It is not yet known if the data from these sources will be an adequate substitute for those from the fixed Ocean Station Network.

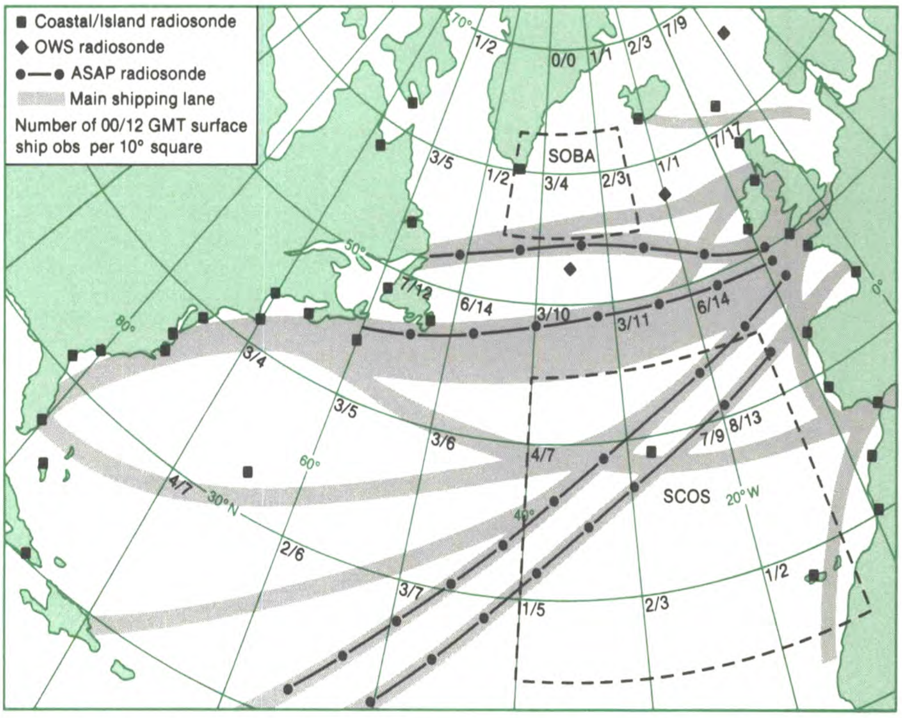


Wind bias data at 250 hPa (see text for details)

Some preliminary results from OWSE–NA impact studies are depicted in the figure above. For each 10° latitude–longitude area, the figure shows the root-mean-square vector differences at 250 hPa between winds analysed with and without upper-air data from ship radiosondes, although the data from Station Charlie (at about 53°N 36°W) are retained in both analyses. Differences (in m s^{-1}) were calculated over a 5-week period, with maximum impact demonstrated to be close to the ship positions and routes. In some individual situations, the impact of the removed ship data has been clearly marked by changes in the subsequent model forecast — changes much more severe than suggested by the statistical data in the figure.

Conclusions

The foregoing reveals several fundamental characteristics of the modern approach to meteorological data capture:

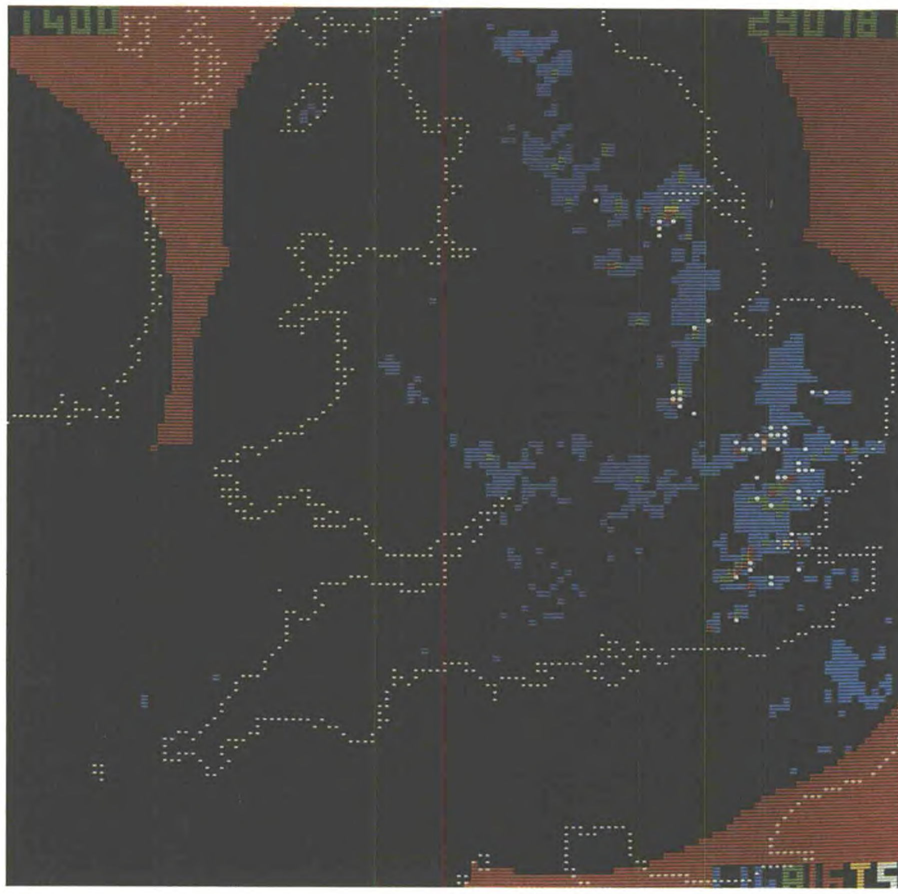


Availability of data for the North Atlantic (SOBA — System of Operational Buoys in the Atlantic, SCOS — South COST-43 Operational buoy System)

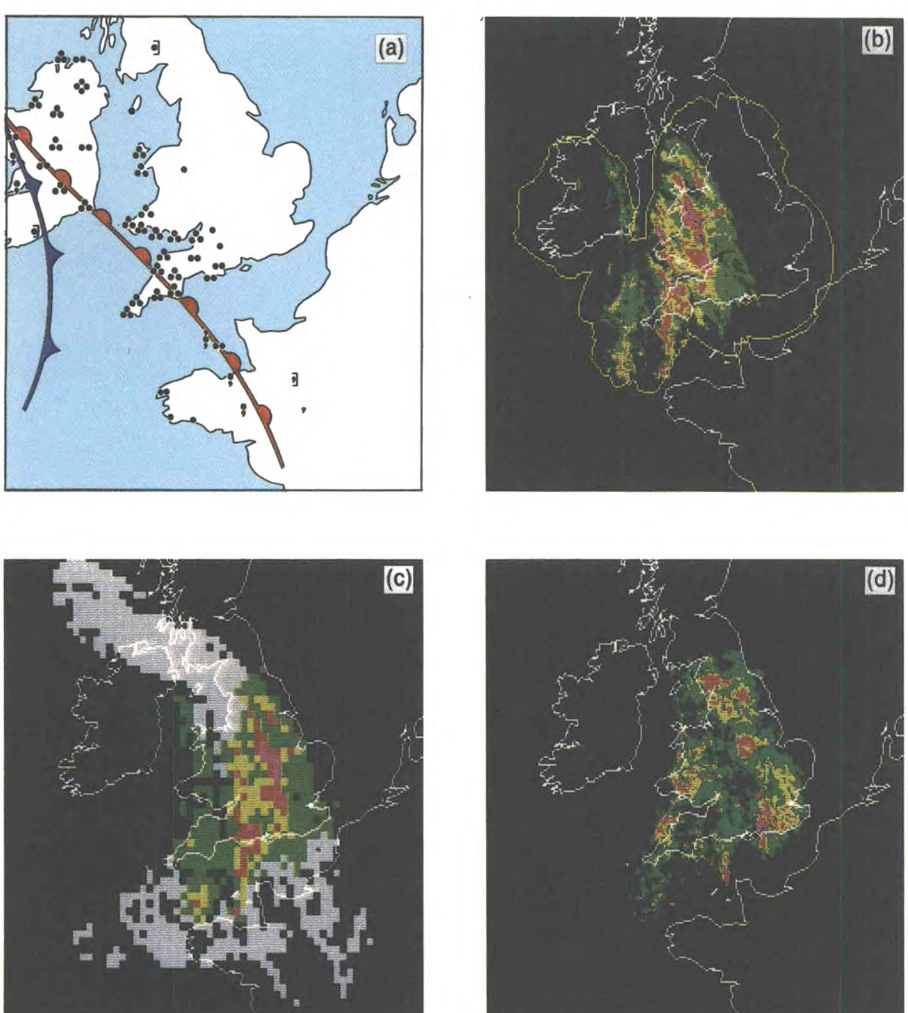
• There is no single, comprehensive measurement technique to be adopted. *In situ* methods can provide direct measurements where they are required, but to keep costs down 'platforms of opportunity' must be exploited to the full. Remote-sensing methods can provide widespread, timely data but often great ingenuity is required to infer the crucial information. Ground-based remote sensing complements that from space. Integration and presentation of different data types in compatible formats can be the key to success.

• Although some observing tasks can and are being automated, human interpretation — whether of a 'chaotic sky' or of data on a FRONTIERS screen — remains a vital ingredient.

• The required quality of data will not be achieved without careful assessment of the operational performance of observing systems, singly and jointly. This must be matched by a willingness and capability to act when deficiencies are perceived.

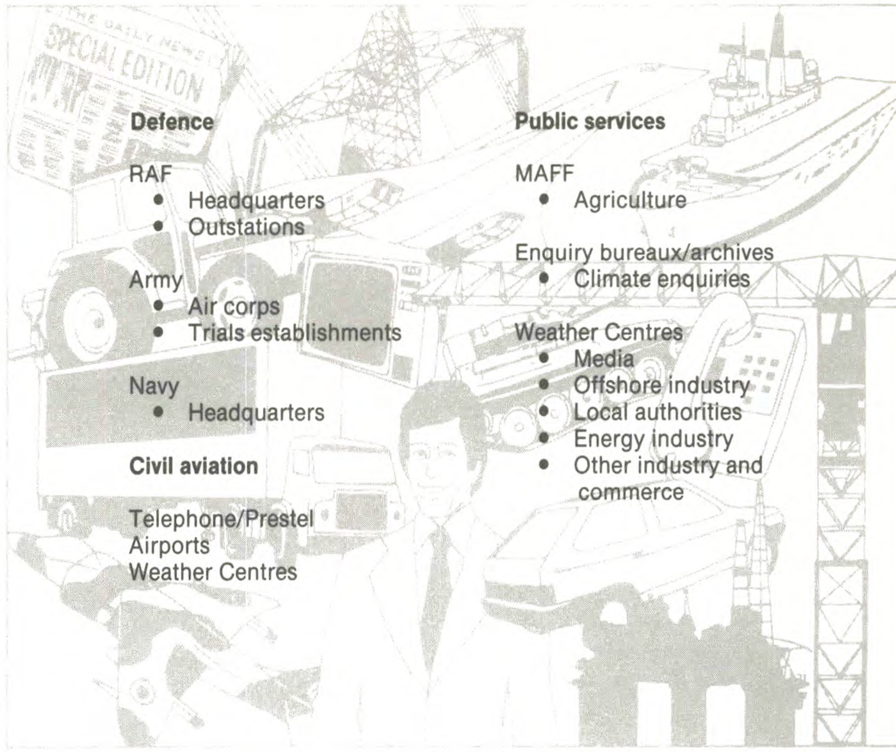


The network display for 1400 GMT on 29 July. The small white dots indicate the lightning strikes detected by the ATD system during the previous 30 minutes. The colours of individual 5 km squares are indicative of the observed rainfall rate.



Short-period rainfall forecasts using FRONTIERS. (a) At 1100 GMT on 26 February an area of rain (indicated by the black dots) is crossing the UK from west to east. (b) The rainfall detected by the radar network at 1130 GMT. A forecaster uses the FRONTIERS interactive display to interpret the radar rainfall data in the light of other observations and his understanding of the meteorological situation. The irregular yellow boundary shows the effective area of radar coverage. (c) The forecaster uses cloud images from Meteosat to estimate the likely distribution of rain beyond the range of the radius. FRONTIERS then computes a sequence of forecasts by moving segments of the rainfall pattern at speeds inferred from past motions. This figure shows the forecast for 1430 GMT, 3 hours ahead, in which rainfall deduced from satellite data (shown in white) and from radar measurements are combined. (d) The rainfall pattern measured at 1430 GMT for comparison with the forecast — only rain within the range of values is shown.

Services



DEFENCE

Services for Defence form a key element of the activities of the Office. The commitment of resources is significant, amounting to approximately 25% of the total manpower and about 40% of the total cost of the Office. The table below summarizes the distribution of Defence services offices and manpower. A wide variety of work is undertaken, ranging from support for high-performance low-flying jet aircraft and long-range transport and maritime reconnaissance aircraft to helicopters operating in search-and-rescue or supporting roles. In meeting these tasks the Office must maintain an efficient and cost-effective organization. To this end statements of user requirements from all three Services have been developed and these form the basis for decisions concerning the deployment of manpower and the nature of the services provided. The meteorological support needed for the new high-technology weapons systems that are being progressively introduced by the Armed Forces is already setting fresh challenges for the forecaster and will form an increasingly important part of his job in the years ahead.

Headquarters activities

The major computer and communications resources at Bracknell, together with the Principal Forecasting Office at Headquarters Strike Command (HQSTC), provide the basis for support to the meteorological offices serving Defence in the outfield. Considerable progress has been made in installing a new communications system that allows meteorological data to be rapidly transferred from Bracknell to computer terminals in airfield forecasting offices. The system, known as the Weather Information System (WIS), is operational at the front-line bases in RAF Strike Command. The speedier service and better presentation of the information provided by the WIS have been welcomed warmly by both staff and aircrew.

A certain amount of applied research is undertaken. Some progress has been made into forecasting the presence and strength of radar ducts (see later) in the atmosphere. A trial to assess the usefulness of numerical forecasts of surface ducts over the sea was carried out in conjunction with the Royal Navy. Analysis of the results of this trial is under way.

Improvements to the support provided for electro-optical ranging and imaging devices are also being sought. These systems are coming into more widespread use in both the Army and Royal Air Force, and offer meteorologists an opportunity to contribute to tactical decision-making.

A numerical model which predicts the paths of sound rays in the atmosphere forms the basis for a noise prediction service at the Ministry of Defence Procurement Executive (MOD(PE)) and Army Ranges. Use of this service has helped to reduce both noise damage and local complaints arising from the testing of artillery shells and explosives. Some encouraging comparisons have been obtained between predicted and directly measured sound levels at various distances from explosive sources. Further improvements in modelling techniques are being investigated.

The Office maintains close international co-operation and liaison with other NATO nations. Of particular note are the close working relationships maintained with the Air Weather Service (AWS) of the United States Air Force and with the German Military Geophysical Office. An exchange program between forecasters at AWS units and meteorological offices in the United Kingdom has commenced and is providing valuable comparisons between the different techniques and approaches used.

Summary of Defence services and staff complements, 31 December 1987

	United Kingdom		Germany and the Netherlands		Mediterranean and South Atlantic	
	Offices	Staff	Offices	Staff	Offices	Staff
HQ Bracknell	1	13				
HQSTC/HQRAFG	1	6	1	6		
PFO HQSTC	1	52				
MMOs[1]	3	56			3	56
AMOs[2]	2	31	2	29		
Subsidiary forecasting and observing offices:						
RAF	29	240	2	18	1	3
Army aviation	2	11	2	10		
MOD (PE) experimental flying	3	19				
MOD (PE)/Army Ranges	6	43				
NATO Allied Meteorological Office			0	2		
Radiosonde units	4	0[3]			2	15[4]

[1] MMO, Main Meteorological Office
[2] AMO, Area Meteorological Office
[3] Function integrated with subsidiary forecasting offices at MOD (PE) establishments
[4] Includes function integrated with MMO in the Falkland Islands

Organization and role of Defence services outstations

The distribution of meteorological offices that serve the Royal Air Force, the Army and the MOD(PE) trials establishments in the United Kingdom is shown right. Meteorological offices overseas are located with the Army Air Corps in the Federal Republic of Germany, and on RAF stations both there and in Gibraltar, in Cyprus, on Ascension Island and in the Falkland Islands.

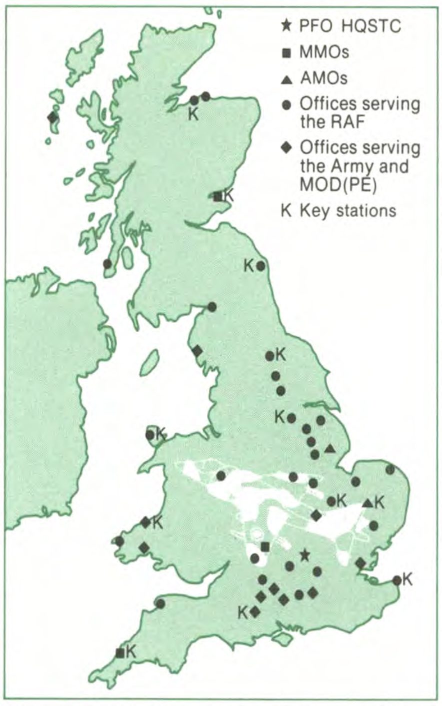
The organization and manning of outstations is kept under continuous review to ensure that the network meets the military requirements in the most efficient manner. In January and March the last two Main Meteorological Offices (MMOs) located on non-operational bases were transferred to operational airfields with subsequent savings in manpower.

Meteorological support to the Royal Navy is provided in the form of observational data, and numerical forecasts prepared at Bracknell. Close liaison is maintained with the Directorate of Naval Oceanography and Meteorology (DNOM) and especially between the forecasting offices at HQSTC and Commander-in-Chief Fleet. This co-operation ensures that meteorological support for Defence activities from the Office and the Royal Navy are properly co-ordinated and effectively provided.

Weather has always been an important factor in the design, development and evaluation of ballistic and missile weapons systems. The Office provides support for such trials at seven Range stations. Trials vary from the routine calibration of new gun barrels to the testing of the latest generation of sea-skimming missiles. During each trial the vertical structure of the atmosphere is monitored frequently; this provides the data which are essential for range safety, trials management and retrospective analysis.

Meteorological services in the Mediterranean

There has been a Meteorological Office presence in the Mediterranean, both in Cyprus and at Gibraltar, since before the Second World War. At both the RAF base in Cyprus, and at the joint military/civil airfield on Gibraltar there are MMOs with UK-based forecasters and locally employed support staff who together provide a continuous service to meet, primarily, the meteorological requirements of the military. UK technical staff maintain a wide range of meteorological and communication equipment. At Gibraltar a radiosonde station provides a full program of upper-air ascents.

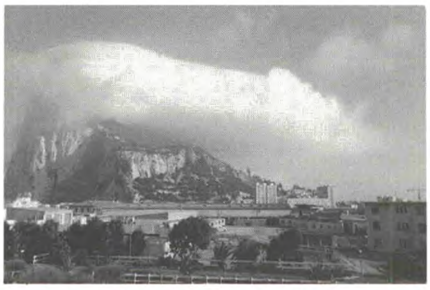


Meteorological offices serving Defence in the United Kingdom

The major roles of the two MMOs are similar. Specialist meteorological advice is given to senior military commanders. Forecasts and other meteorological information are provided for local RAF operations and for Army units, as well as route forecasts for use by long-range RAF transport, and other aircraft departing from the bases. Weather forecasts are also provided for local civilian radio and television stations.

Additionally, in Cyprus, advice is provided for Army Air Corps helicopters operating in support of the United Nations Force in Cyprus, and very close co-operation is maintained with the national Cyprus Meteorological Service (CMS). At Gibraltar, the Office provides all meteorological services for the increasing civil aviation traffic; full support is also given to the Flag Officer Gibraltar and to resident and visiting Royal Navy units, including the provision of ballistic messages for gunnery training.

To enable the MMOs to provide the wide range of services required of them, data from a number of sources are used. At both MMOs there is ground equipment capable of receiving cloud pictures from the routine polar-orbiting weather satellites. These facilities will be replaced early in 1988 by equipment also capable of receiving geostationary weather satellite data. Surface and upper-air observations for the region are received on dedicated telegraph circuits from Bracknell. Both offices are equipped to receive radio facsimile and radio telegraph broadcasts. The MMO in Cyprus, additionally, receives a program of charts, including forecast charts from the Bracknell 15-level global model, on a dedicated digital facsimile link via satellite. These charts are valuable aids to the forecasters and plans are in hand to make them available to the CMS forecasting centre at Larnaca Airport.

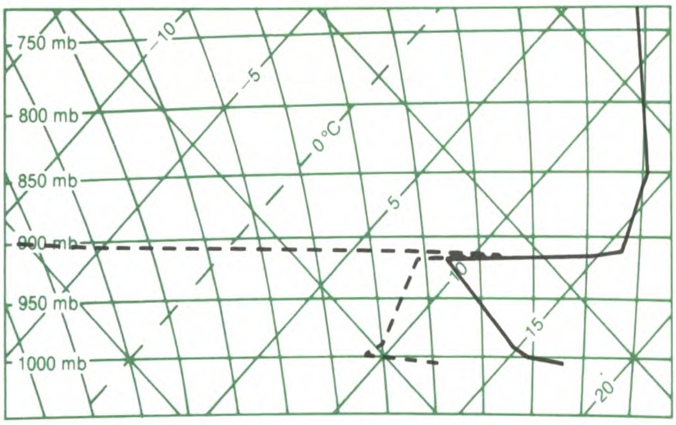


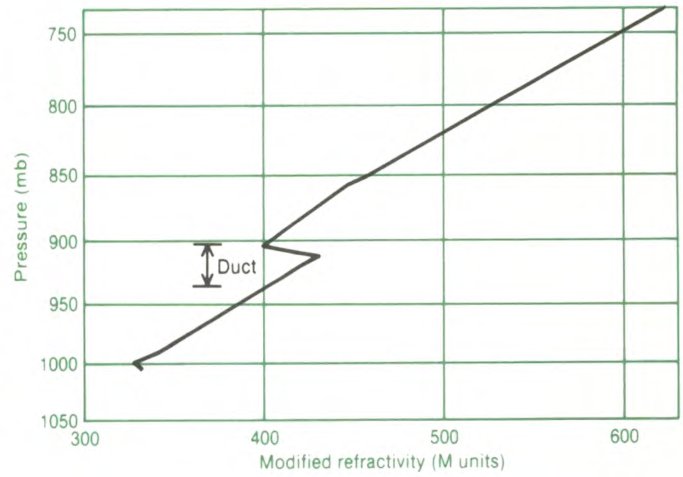
The Rock, Gibraltar looking south-south-east, showing levanter cloud (Photograph by courtesy Mr J.W. Davies)

Support to NATO

Office staff, accompanied by DNOM advisors for naval matters, represent both the United Kingdom and the Commander-in-Chief United Kingdom Air Forces (CINCUKAIR) on NATO Meteorological Committees. The function of these committees is to ensure that an adequate supply of meteorological information is available for planning and operational tasks during times of war. To produce accurate forecasts it is necessary to obtain observations rapidly from a wide geographical area. This is a difficult enough task in peacetime; in wartime, with possible disruption to communication lines and subsequent loss of observations, it would be even more difficult. The committees formulate plans so that the impact of this simultaneous disruption of communication lines and reduction in the number of available observations is kept to a minimum, and the supply of meteorological information to the Armed Forces is maintained at the best possible level. Recent developments include proposals for an Allied Command Europe meteorological information system to distribute forecasts and data to NATO forecasting centres. The proposed system has many similarities with the WIS that is currently being installed in this country.

The committees also discuss new developments in forecasting techniques. While every effort is made to minimize the sensitivity of new weapons systems to weather phenomena, truly weather-independent systems are still a long way off. Sensors which work in the infra-red wavelengths are an improvement on visible wavelength sensors but this advance can actually increase the demands on forecasters. The committees





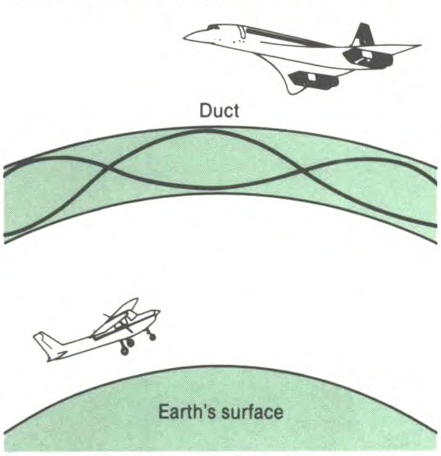
Tephigram (above) showing a strong inversion based at about 920 mb together with a vertical profile (right) showing the presence of a duct at about 910 mb

form a useful forum in which NATO nations may exchange the results of research into these problems.

In addition to planning for times of tension, crisis and war, there is also a need to co-ordinate the meteorological support for peacetime exercises. Not only is it important that all exercise participants receive meteorological advice, it is also necessary to ensure that the advice is consistent. During the year the Office participated in two major NATO exercises, WINTEX and OCEAN SAFARI. The former was primarily a test of procedures while the latter involved most of the outstation forecasting offices, as well as the Hercules aircraft of the Meteorological Research Flight which was deployed to practise its role in gathering meteorological data.

The forecasting of radar ducts

Military operations are becoming increasingly dependent on radars. The Airborne Early Warning aircraft is an example of this but many other air, ground, and shipborne radars are vital to the Armed Forces. However, radar beams are bent due to refraction as they pass through the atmosphere and, under certain conditions, such as near strong temperature inversions, become trapped in what is known as a duct. This is illustrated in the figure below. If an aircraft is flying within the duct it can 'see' and be 'seen' from an abnormally long distance away. Conversely, if it is flying just above or below the duct it can hide from, or alternatively not detect, other aircraft that are nearby, but on the opposite side of the duct. Such a feature is known as a 'radar hole'.



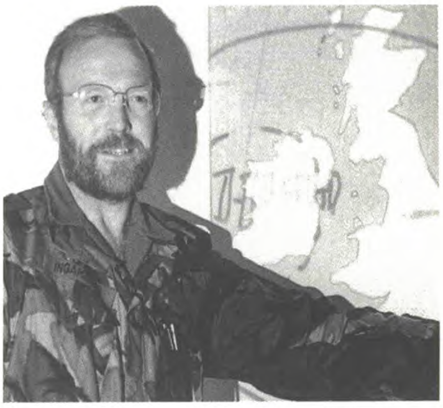
Schematic representation of a radar duct in the atmosphere

Aircrew need to be alerted to the existence of ducts so that they may fly at the altitude most suitable for their operational task. The forecaster is able to provide information about ducts from temperature and humidity profiles such as are shown top left. The strong inversion and hydrolapse at 920 mb typify the meteorological conditions suitable for duct formation, and the presence or otherwise of a duct may be determined by calculating the modified refractivity. From the vertical profile (top right) the strength and vertical extent of the duct may be determined.

To assist forecasters, a guide to forecasting radar ducting has been distributed to all outstations. Practical advice and assistance given to aircrew is already proving beneficial.

Services for the Army

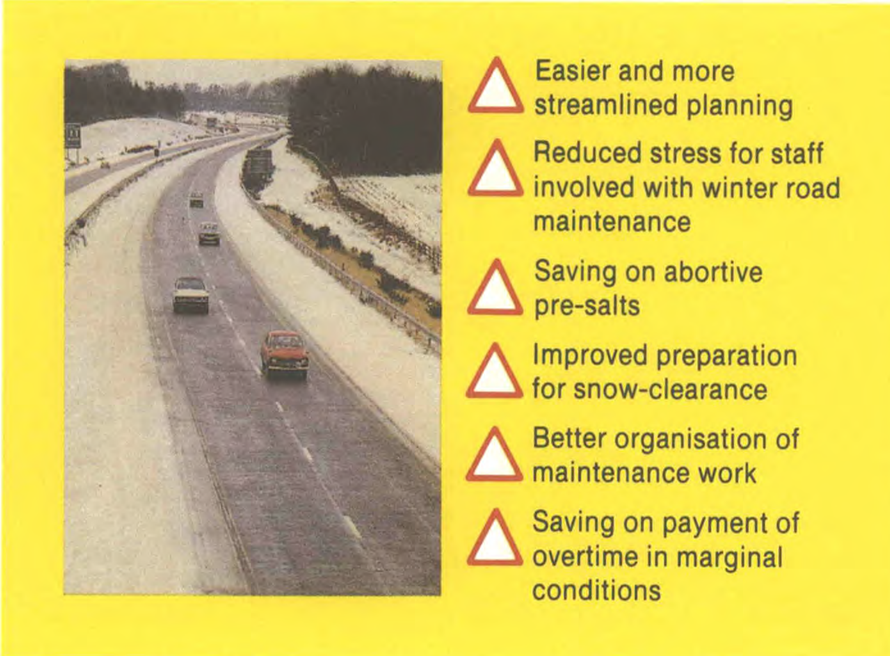
Army operations require meteorological support, and activity in this area is increasing. Army commanders have always been aware of the impact of weather upon their plans but, until recently, have been unable to take much positive action other than contingency planning. Improvements in forecasting and communications now permit a positive meteorological input to be made to the tactical decision-making process. The movement of vehicles in and around a battlefield can now be optimized by the use of trafficability assessments, which are derived from terrain analysis data and meteorological predictions. Modern surveillance and weapon-aiming systems are also weather sensitive, and accurate meteorological advice can be of considerable tactical importance to field commanders. Activity in these areas is mainly concentrated in the Federal Republic of Germany, where a senior meteorologist is attached to the staff of the Commander 1(BR) Corps. He provides advice to the Commander and his staff on all meteorological matters that affect Army operations. A Mobile Forecast Unit is deployed with Corps (Rear) Headquarters during exercises and also provides support to the meteorologist at the Corps (Main) Headquarters.



The Senior Meteorological Officer 1(BR) Corps providing a weather briefing

Army aviation consists mainly of helicopters and small fixed-wing aircraft operating at low level. Meteorological offices are located at the main Army Air Corps (AAC) bases, whilst AAC units in the United Kingdom, and in Cyprus, Gibraltar and the Falkland Islands, are supported by offices at nearby locations. Meteorological Office staff also instruct trainee AAC aircrew in aviation meteorology.

Image-enhancement devices can considerably improve the night-time capabilities of low-flying aircraft and the AAC have recently carried out extensive trials, using night-vision goggles. In support of these trials the Office provided data on astronomical background light levels and forecasts of the meteorological variables which enable estimates of actual background light levels to be prepared.



Part of the 'Open Road' leaflet

INDUSTRY, COMMERCE AND MARKETING

The value and the range of specialist meteorological services available to commerce and industry increased steadily during the year, and more companies began to realize and appreciate the benefits to be derived from them. Contributing to the higher value of the services were the further improvement in the accuracy and scope of the information available, the progress made in applying the discipline of the marketing approach to the interface between the Office and industry, and the effort devoted to devising the most appropriate packages of data for individual customer groups. A 6-month research program conducted in conjunction with the retail food industry resulted in the setting up in June of an operational market unit to provide a comprehensive package of weather information to major retailers in a form directly related to their routine operational decisions. It is designed to minimize weather-related wastage of fresh foods and allow plans to be made for the better provision of goods likely to be in high demand owing to weather factors.

Transport

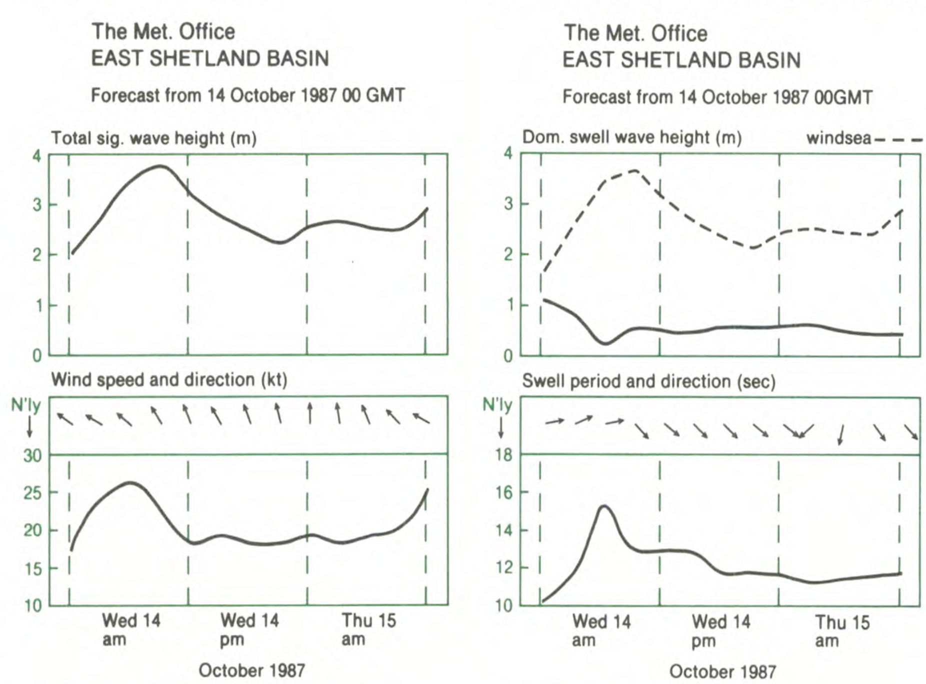
'Open Road' was launched late in 1986 specifically to help local authorities in their winter maintenance of highways. Detailed predictions for the coming night of road surface temperature and wetness, and their relationship to the formation of ice, are provided each afternoon from a microcomputer at a Weather Centre to the appropriate highways authority. These predictions are based on forecasts from the Central Forecasting Office at Bracknell of air temperature, wind, cloud and precipitation. Up-to-the-minute information from the Office's network of weather radars is added throughout the night and combined in some instances with observations from networks of sensors located in the road surface. Services for a few counties, chiefly in the Midlands, were provided in co-operation with Thermal Mapping International Ltd, a company linked with the University of Birmingham. A special study, commissioned from an independent contractor, into the cost-effectiveness of Open Road demonstrated a large saving in comparison with salting and gritting operations by authorities which did not take the service. Particularly noticeable were the benefits that accrued during the spell of severe weather in mid-January. Improvements introduced later in the winter included the transmission of forecast information in graphical as well as text form to the local authority computer work station.

Following the success of Open Road, the forecast service for British Rail's winter operations was substantially redesigned and expanded after a successful trial in Scotland during the winter of 1986/87. The new service provides, on a national basis (excluding Western Region), forecasts for 25 separate areas of Great Britain. For stretches of rail in coastal areas it includes forecasts of sea conditions and tidal information.

The offshore industry

The collapse in the price of oil in 1986 and the subsequent change in fortunes of the offshore industry led to substantial changes in its requirements for weather services. The 'Offshore Europe' exhibition in Aberdeen in September was used to launch new services including 'automatic' forecasts. These comprise 36-hour wind and wave forecasts produced automatically from the operational global and fine-mesh numerical weather prediction model output in a graphical format designed to be readily understood by the user. They represent an exciting development in the presentation of forecast information and a great deal of interest was shown in them not only by the oil companies but also by many smaller support companies operating from Aberdeen. In addition to the basic machine-produced forecasts, customers can get longer-range outlooks and detailed advice relating to specific tasks and projects. This new system was instrumental in helping to restore the Office's share of the forecast services for the industry.

In the most weather-sensitive operations, forecasters were detached offshore to work alongside oil company

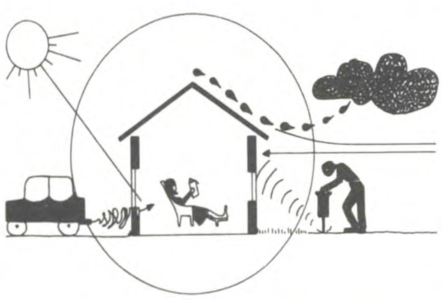


Example of a 36-hour wind and wave forecast supplied to the offshore industry staff. Routine offshore detachments continued at Ninian (Chevron) and Buchan (BP) during the summer and winter months respectively. In the early summer, forecasters worked on site at Ardersier and offshore for the float-out, launch and construction of Marathon's Brae 'B' jacket and superstructure.

The Marine Advisory Group at Bracknell handled numerous requests from the offshore industry, for historical data, in connection with design and planning studies. There was also an increased requirement for information on recent past weather and sea-state conditions for the assessment of claims relating to contract delays.

Building and construction

Demand for services to the building and construction industry increased considerably, and included support for some major new projects. The main requirements were for historical information in relation to the design of structures, forecast information during the construction period, and information on weather which might have interrupted building progress.



The aim of building climatology (By courtesy of the World Meteorological Organization)

Information required by architects and designers included averages and extremes of wind speed, temperature, humidity and rainfall, and some interesting combinations of these variables. Extremes of driving rain were needed in relation to the specification of infill for cavity walls, extremes of temperature and humidity for the specification of heating and air-conditioning systems, and information on snow and ice in relation to the loading on various structures. Advice was provided on winds at the road-deck levels of the proposed Dartford and Severn Bridges, the microclimate of the Channel Tunnel terminal at Cheriton, and for the Nuclear Inspectorate and the Central Electricity Generating Board (CEGB) in respect of future nuclear and conventional power stations. Research activities that support these and other studies were co-ordinated as necessary with specialist organizations such as the British Standards Institution and the Building Research Establishment. A more unusual request was for the winds likely to affect the operation of the lift system for a proposed ski development at Aonach Mor near Fort William. An automatic weather station was installed at 2000 feet and comparisons between winds observed there and at nearby long-period observing stations at lower altitudes were used to answer the request.

Stations whose reports are included in the inshore waters forecasts

For building and construction, particular requirements are for predictions of low temperatures in relation to concreting, rain in relation to external decorating and wind speed when it is near the limit for the operation of tall cranes. A large demand for weather information subsequent to the completion of contracts is met by a monthly bulletin, *Metbuild*. This contains statistics of the month's weather that relate to the particular weather thresholds which most often determine whether a construction job can be done or not for about 50 locations covering the United Kingdom. *Metbuild* has proved especially useful in connection with contractual disputes relating to deadlines for the completion of a contract or critical phases of it.

Probably the most publicized of all weather data services was that to the

Queen Elizabeth 2 (Photograph by courtesy of Cunard Line Ltd)

Department of Health and Social Security (DHSS) in connection with a scheme for the payment of supplementary benefits during periods of exceptionally cold weather. For a number of years the Meteorological Office has liaised with the DHSS over the operational aspects of this scheme and substantial quantities of data have been provided to support it.

Shipping

Gale warnings and shipping bulletins prepared at Bracknell for the open seas and the inshore waters are broadcast by the BBC (see map). Facsimile weather charts for the whole of the North Atlantic and the North Sea are also provided from Bracknell for use by ships at sea. British Telecom International, too, broadcasts coastal and North Atlantic shipping forecasts and storm warnings originated at Bracknell. Safety messages, including gale warnings and weather forecasts, are broadcast on Navtex, a navigational telex service which can be received by ships equipped with an automatic telex receiver. Originally confined to coastal waters of northern Europe, Navtex services have been introduced into the coastal regions of many countries. Special forecasts are broadcast on BBC Local Radio for fishing fleets and for inshore seafarers, especially during the summer sailing season.

After experiencing heavy-weather damage on encountering a particularly deep depression in the North Atlantic, the Cunard liner *Queen Elizabeth 2* became the latest convert to Metroute, the Meteorological Office's ship routeing service. Along with another passenger liner, *Norway*, she is regularly routed on transatlantic passages. Metroute provides guidance direct to shipmasters world-wide on the safest and most economical ways to achieve their destination. Advice on tropical cyclones and their expected movement is an important feature of the service, and ships and yachts of many nations subscribe to it.

Storm Tide Warning Service

Monitoring of tide levels at 11 stations around the United Kingdom, from Stornoway in the north-west via the east coast to Newhaven in the south, particularly during the dangerous winter months, has been undertaken by the Storm Tide Warning Service since its formation which followed the extensive flooding of parts of eastern England in 1953. Computers are now used to provide continuous data on tidal anomalies and the service issued 13 alerts to police and Water Authorities during the year, 9 of which were later 'confirmed'. There were 8 occasions on which the tide came to within 0.2 m of danger level but none when it was exceeded. For the benefit of deep-draft shipping in the shallow waters of the Strait of Dover, the Thames estuary and the southern North Sea, 13 warnings of negative surges were issued; levels were expected to fall 1 m or more below predicted low tide levels. Similar warnings of lower than normal tides were issued to the CEGB on 12 occasions so that adjustment of cooling water intakes at their stations on the River Thames could be made.

The water industry

Water Authorities have shared in the investment in the UK Weather Radar Network and use precipitation data from it. The radar data are used along with hour-by-hour forecasts of rainfall to assist in the regulation of river levels, the control of sewage treatment and the support of flood warning procedures. A trial service in which rainfall accumulations are forecast for each day up to 5 days ahead was provided to a few Authorities to assist them in river management. A radar data archiving system is being developed, and radar measurements of rainfall have been supplied from it to the industry. One use is in connection with recent legislation relating to the safety of dams.

Numerous bodies with responsibilities for water management receive the weekly operational water balance bulletin *MORECS* (Meteorological Office Rainfall and Evaporation Calculation System). The value of these bulletins has been increased by the completion of retrospective calculations of water balance variables for the period 1961–80, thus providing a historical perspective for current values. Work is in progress to update the depth– frequency relationships of 1-hour duration rainfall over the United Kingdom that were produced in the early 1970s by the Institution of Civil Engineers Flood Studies Report team.

More automation of hydrometric measurements by Water Authorities is likely to result in the increased use of automatic logging systems for rainfall with local recording or telemetry to central offices. Discussions are in progress with the industry on the transfer of both daily and sub-daily rainfall data using computer-based methods.

Legal and insurance

The Meteorological Office supplies a great deal of weather information for the legal and insurance professions. Occasionally there is a need for an expert witness to appear in court, but more generally the requirement is for certified statements, and reports relating such statements to the particular circumstances of a civil or legal case, for use by solicitors and barristers. Civil actions for which weather evidence is supplied typically derive from insurance and compensation claims ranging from simple accidents, such as slipping on ice, involving damages of a few hundred pounds, to building disputes with damages of over £1 million. Criminal cases in which knowledge of the weather may play a part can include anything from minor traffic offences to crimes that involve drugs or murder. During the year weather advice was given to the police involved in over 20 murder cases, and weather information was used for an estimation of the time of death of a victim, or to help prove or disprove alibis.

A large number of enquiries from the insurance industry were related to specific incidents, in particular the storms on 27 March and 15/16 October. The majority of questions asked concerned wind damage; others were related, for instance, to car accidents in heavy rain or on ice, and damage to buildings or property caused by lightning or hail. Notable examples, with compensation running into millions of pounds, were for information on the hail that caused damage to cars parked in Munich, the damage to a ship in Beirut harbour, and the cancellation of a concert by the international star Madonna because of a storm.

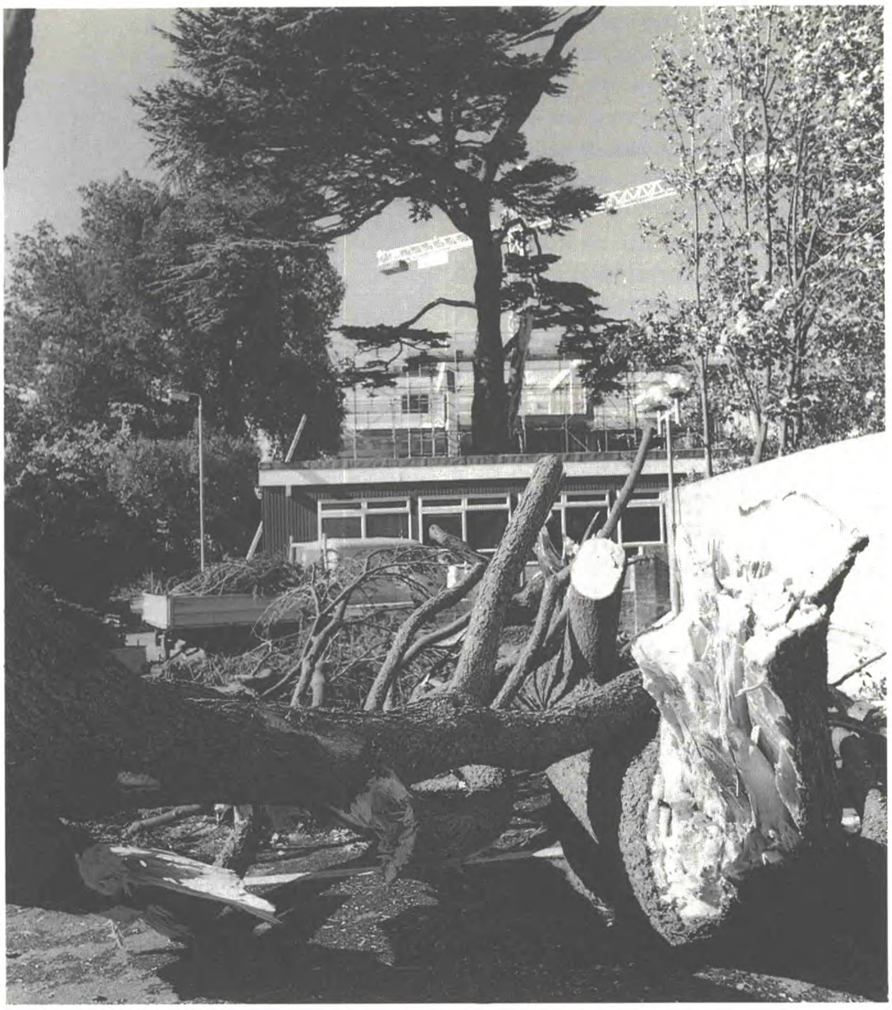
Agriculture

The Office maintains agrometeorological units in England and Wales at the various regional Headquarters of the Agricultural Development and Advisory Service (ADAS). These are paid for by the Ministry of Agriculture, Fisheries and Food. Direct computer links from these units to Bracknell enable the agrometeorological data base (FARMAID) and the general climatological data base to be accessed so that expert meteorological advice can be provided to ADAS. During the year the units were closely involved with a wide variety of farming problems. Typical among them were the assessment of crop damage by ozone produced by industrial pollution, the determination of the features of seasonal weather which trigger the onset of Johne's disease in cattle, the transport by the wind of lettuce root aphid from its winter host, the spread of *septoria* (a fungal disease of cereals) by rain splash and the temperature control of naturally ventilated pig houses. Agreement was reached on final forms of the meteorological data sets for a revised Agricultural Land Classification system that will be used for planning permission decisions.

FARMAID is also used to provide daily, weekly and monthly weather summaries and weather-related agricultural indices to a number of commercial customers. These data provide the basic input to computer models of evaporation from crops, soil chemical processes, and crop growth and development. Forecast data are incorporated into a number of these models. For example, the ADAS Irriguide advisory service uses quantitative forecast rainfall amounts for the following 2 or 3 days to predict site-specific irrigation needs. Encouraging results have been obtained in predicting changes in the sugar content of grass — an important factor in silage making — based on 5-day forecasts of temperature and sunshine. In co-operation with UK Fertilizers Ltd a trial was undertaken of a forecast service of 7-day accumulated temperatures based on direct output from the operational coarse-mesh numerical weather prediction model. Trial forecasts of weather favourable to the spread of blight were issued to a small number of farmers in south-west England at the request of ICI as a part of their campaign to control potato blight.

The Office also provides forecasts and warning services through its network of Weather Centres direct to various sectors of the agricultural industry. Particularly popular is the weather consultancy service that gives telephone access to a forecaster so that farmers can plan their weather-critical jobs such as the making of hay and silage. Weather information of all kinds is available on the Closed User Group videotex systems, Farmlink and Agviser, which are being used increasingly. These services were combined during the year and extended to include soil moisture and other data from MORECS for a variety of crops.

Services to the agricultural community were promoted at several of the agricultural shows. The small Meteorological Office stand at the Royal Show was awarded a prize by public poll for 'the scientists who most effectively communicate to visitors the results of their research'. The prize, an engraved silver water jug was presented by the sponsors, the Midland Bank, at a luncheon on 2 November.



Damage caused by the storm of 16 October

GENERAL PUBLIC

The general public have long been avid consumers of weather information. This is not surprising in view of the variability of the weather of the United Kingdom, which affects many of their day-to-day decisions. The Meteorological Office has made strenuous efforts to improve the weather presentations in the national Press and on television. The media have become more receptive to the idea of better coverage and, as a result, services to the public through national and local television and radio and through the newspapers have been much extended during the past year or two. Weathercall, the newly introduced premium-rated telephone service that gives access to weather forecasts for up to 5 days ahead, provides another means of satisfying the growing public appetite for weather information. The forecasts have become significantly better in recent years and public expectations have risen accordingly but it must always be borne in mind that the predictions will never attain perfection, however far we may go in reducing the margins of error.

Services originate at 14 Weather Centres widely distributed within the United Kingdom from Aberdeen to Plymouth and from Cardiff to Norwich. The offices are open 24 hours a day, throughout the year. The forecasters at these Centres gain an expert knowledge both of the local weather and of the weather dependence of the industrial and other activities in their areas. In addition to the Weather Centres there are three offices, at Bracknell for England and Wales, at Edinburgh for Scotland and at Belfast for Northern Ireland, which specialize in the supply of statistical and other information based on records of the weather compiled over many years. This is valuable for many planning purposes, from deciding where to retire, for example, to the estimation of the time likely to be lost through bad weather in building. The library and archives at these three offices are open to the public during normal working hours.

The exceptional storm of 16 October

The major weather event of the year, for those living in south-eastern areas of England, was the severe storm in the early hours of 16 October. The depression responsible tracked north-eastwards from Biscay during the evening of the 15th and intensified as it approached the British Isles. The system was in the south-west approaches with a central pressure of about 952 mb by midnight and then moved across the country and into the North Sea (filling to 959 mb) by dawn. Neither the depth of the depression nor the falls of pressure associated with it were particularly unusual. However, quite exceptional rises of pressure were recorded behind the system and the very strong pressure gradient to the south of the centre led to exceptionally severe winds.

Most of England south of a line from Bristol to the Wash experienced strong winds, but the region of highest winds and most damage was roughly south-east of a line from Southampton to Ipswich. The maximum wind speed at most coastal stations was between 50 and 60 kn with maximum gusts of around one and a half to twice this speed. At Gorleston in Norfolk the wind was even stronger reaching 68 kn, with a gust to 106 kn. Inland, winds were less strong but in many places were over 40 kn with gusts to over 70 kn. Although not particularly unusual over most parts of the country, storms of such severity are rare in south-east England, and there the winds often exceeded the 'once in fifty years' expectation. Other factors contributed to the extensive damage. October was mild and trees were still in leaf; this, together with the preceding wet weather which softened the soil, made trees particularly vulnerable.

In the ensuing media inquest, much criticism was levelled at the Meteorological Office. 'Why weren't we warned?' was a typical headline. In contrast, the letters received by the Meteorological Office from the general public and from commercial customers were much less critical. In fact notice of the storm had been posted as early as the 11th in the Sunday 'Weather for Farmers' program on BBC television; the summary caption read '... becoming very windy late in the week'. Other forecasts during the week also pointed to a stormy period ahead. The outlooks on Weathercall, for example, all featured the strength of the wind. In forecasts issued on the 15th there was frequent reference to wet and very windy weather and warnings of strong winds were issued for shipping, aviation, the police, etc. during the day. However, the exceptional severity of the wind was not anticipated until a few hours before the storm began. The severity of the coming night's weather was given prominence in the live 0020 Radio 4 broadcast: 'Just to re-emphasize, some dirty, wet weather to come especially for England and Wales, as a really nasty depression sweeps up from Biscay ... so some really unpleasant conditions if you are out and about on the roads and motorways tonight, some torrential rain, strong winds eventually, especially on the Channel coast, and there will be inland gales as well'. Shortly after midnight further warnings were sent to many authorities. For example, the Ministry of Defence was warned of exceptional weather which might call for military aid to be provided to the civil community. Procedures for warning the local police forces and emergency services were followed (and exceeded in some instances), but the need for national arrangements has become apparent and the Office is reviewing the situation with the authorities concerned.

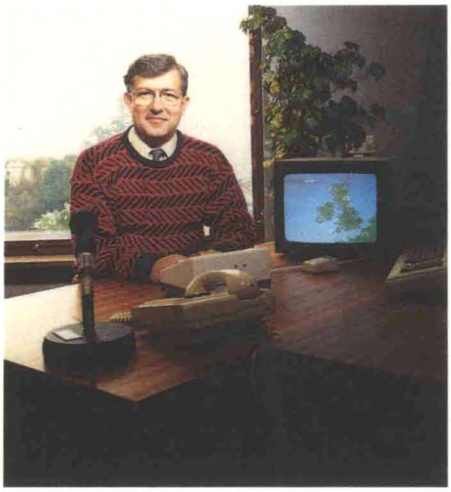
For the general public, besides the routine weather presentations, the Meteorological Office has long maintained a Weather Flash service; radio and television carry special warnings when weather occurs which may cause considerable inconvenience to a large number of people and/or present a danger to life. The service is activated only when very specific warning can be given with high confidence, the aim being to inform the public of the imminent onset of severe weather conditions. The service is important during the day when avoiding action, particularly by those intending to travel, can be taken. It is clearly less effective when, as on 16 October, the dangerous conditions occur at night. Nevertheless, Weather Flash messages were duly sent out on this occasion.

Immediately after the storm, the Director-General instituted the preparation of a report on the forecasts and the claims that the Office failed to give a timely warning. This involved amassing a considerable amount of evidence. In addition to collecting all the Office forecasts and studying the reasoning behind them, relevant forecasts from other Meteorological Services were also obtained and the sensitivity of the Meteorological Office computer forecasts to variations in the data input was studied. Two external assessors (Sir Peter Swinnerton-Dyer, KBE, FRS and Professor R. Pearce) were appointed by the Secretary of State to advise him on the contents of the internal Office Report on the storm. The report of the assessors and the internal Office Report are expected to be published early in 1988.

Television

Many national and regional television presentations are made daily by Meteorological Office staff on BBC and ITV channels, the best known, perhaps, being those given by the Weathermen who appear on national BBC television. Some television companies use their own presenters but nevertheless rely upon forecasts supplied by the Office.

Television companies are becoming increasingly aware of the advantages of using computer graphics in the presentation of weather forecasts. This awareness follows their successful introduction into the BBC's national television presentations. The advent of Daytime Television has also afforded new presentation opportunities. This success has led the Office to investigate the possibility of providing more widely the specialized digital data streams required for television weather presentations using advanced graphics systems. The number of potential users of such data is becoming greater with the growth of cable and satellite television broadcasting, and with possibilities for audiences on a European-wide scale. The BBC, with help from the Office, began supplying weather presentations for the new 'Superchannel' satellite television service in June. This is sponsored by the Goodyear Tyre Company and is distributed to several million cable television viewers throughout Europe. Audience reaction to it has been very favourable.



TV Weatherman Bill Giles in the Daytime Television studio

Radio

Forecasters at Weather Centres around the country meet the weather information needs of the local community radio stations of both the BBC and the IBA. There is a wide variety of presentational styles: in some cases, brief scripts are read by an announcer or disc jockey; in others, the local radio announcer conducts a live discussion with a forecaster at a Weather Centre. National forecasts on BBC Radio, prepared at the London Weather Centre and presented by the forecasters directly from their studio in the Weather Centre's 'shop window' in High Holborn, continue to be one of the most important sources of weather information for the general public.

Broadcasts describing weather developments around the world have been introduced in the BBC World Service. These are given by staff of the Central Forecasting Office at Bracknell from which forecasts can be made for all parts of the globe.

Newspapers

Services for the Press expanded in range and sophistication during the year. Weather forecasts and past weather reports have featured in newspapers for many years. However, rather than rely on the forecasts issued routinely to the Press Association as in the past, many newspapers now choose to take enhanced services suited to their individual styles. Attractive graphical presentations have been developed and the level of response from both national and provincial newspapers has been such as to help the Office to extend its services widely.

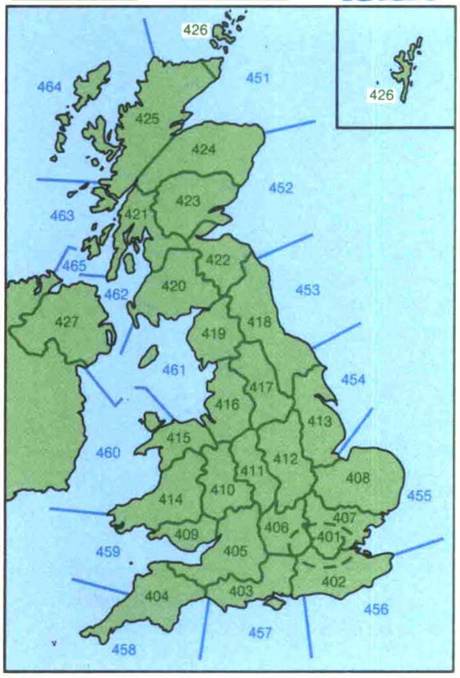
Telephone services

At the end of 1986, the Office took the opportunity to expand the content and quality of its recorded telephone message services through British Telecom's premium service network using the high-quality recording facilities of another company, Telephone Information Services. Two new services were introduced. One, Weathercall, contains 27 separate regional forecasts which cover the whole of the United Kingdom and are updated at least three times each day. In the other, Marinecall, forecasts are given for 15 sections of the coastal waters of the United Kingdom.

A very heavy demand for the Weathercall service was experienced in the middle of January when much of the country suffered extremely low temperatures and heavy snow. Weathercall and Marinecall were extended at the beginning of March with the introduction of national forecasts for up to 5 days ahead. For the first time information covering the 5-day period became accessible to every member of the community on a routine basis. Further additional information for European holiday areas, for Wimbledon and for outdoor activities in the Scottish Highlands (Mountaincall and Skicall) were introduced during the year. Demand for the new services has exceeded expectation.

Videotex

The development of meteorological services provided by videotex was helped by the introduction of a dedicated computer system. This allows forecasts, observations and historical data, stored in the Office's main computer facility,



Areas covered by Weathercall and Marinecall

COSMOS, to be automatically entered into external videotex systems.

The main external system served is Prestel, British Telecom's public videotex service now accessible by over 70 000 subscribers through the public telephone network, the information for which is displayed on a standard television screen. The Office has over 800 frames of information stored on Prestel. Their content ranges from nation-wide forecasts for the general public to information for special-interest groups such as mariners and aviators. The frames are updated several times daily to keep abreast of the latest weather and are amongst the most popular items on Prestel.

Publications

For many years the Office has used the printed word to communicate with the general public. In fact, the first *Daily Weather Report* was issued free to the Press in 1860 and for 60 years (1920–80) Her Majesty's Stationery Office (HMSO) had a printing press located within the Office. HMSO still looks after those publications, including handbooks, textbooks and periodicals, intended primarily for sale to the public. However, a wide range of departmental material, dealing mainly with climatology, is available directly from the Office.

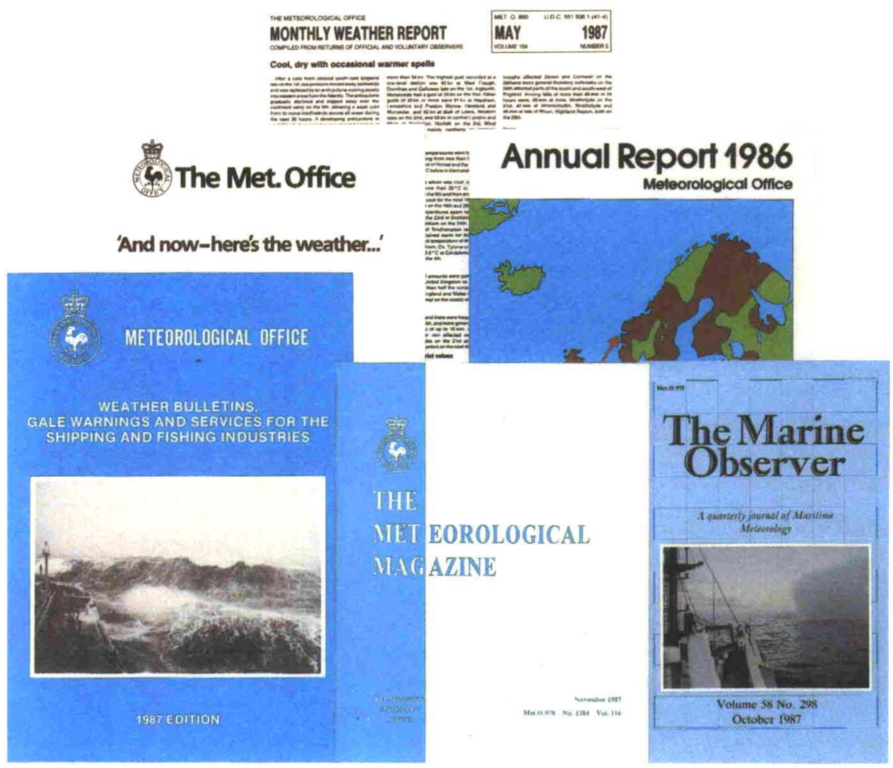
The ability to typeset copy in-house ready for direct printing (camera-ready copy) has led to shorter production time and has allowed the prices of periodicals to be kept stable whilst introducing more colour into them. An electronic link between the word-processor and the phototypesetter in the editing room has also increased efficiency. Another important planned development is the introduction of a desk-top publishing system.

A range of free leaflets describing the work of the Office is available, *And now here's the weather...* and *Weather bulletins, gale warnings and services for the shipping and fishing industries* being firm favourites with the public. Many of the leaflets have been redesigned to make them more attractive. A series of leaflets dealing with the commercial services available from the Office has been introduced. These are aimed at groups of people with special interests, such as farmers and builders, rather than at the public at large.

National Meteorological Library and Technical Archives

The National Meteorological Library and Technical Archives are open to the public and may be used by anyone with an interest in meteorology. Between them they maintain one of the most comprehensive collections of meteorological literature, photographs and climatological data in the world. The collection includes rare historical material held on behalf of the Royal Meteorological Society.

Archives, approved by the Public Records Office, in Belfast, Edinburgh and Bracknell are used to store weather observation registers and climatological returns. Also at Bracknell are records from overseas stations and a collection of official weather charts that start modestly in 1867 to the present, large selection of material produced by the Central Forecasting Office. A catalogue of observation registers is being compiled on COSMOS.

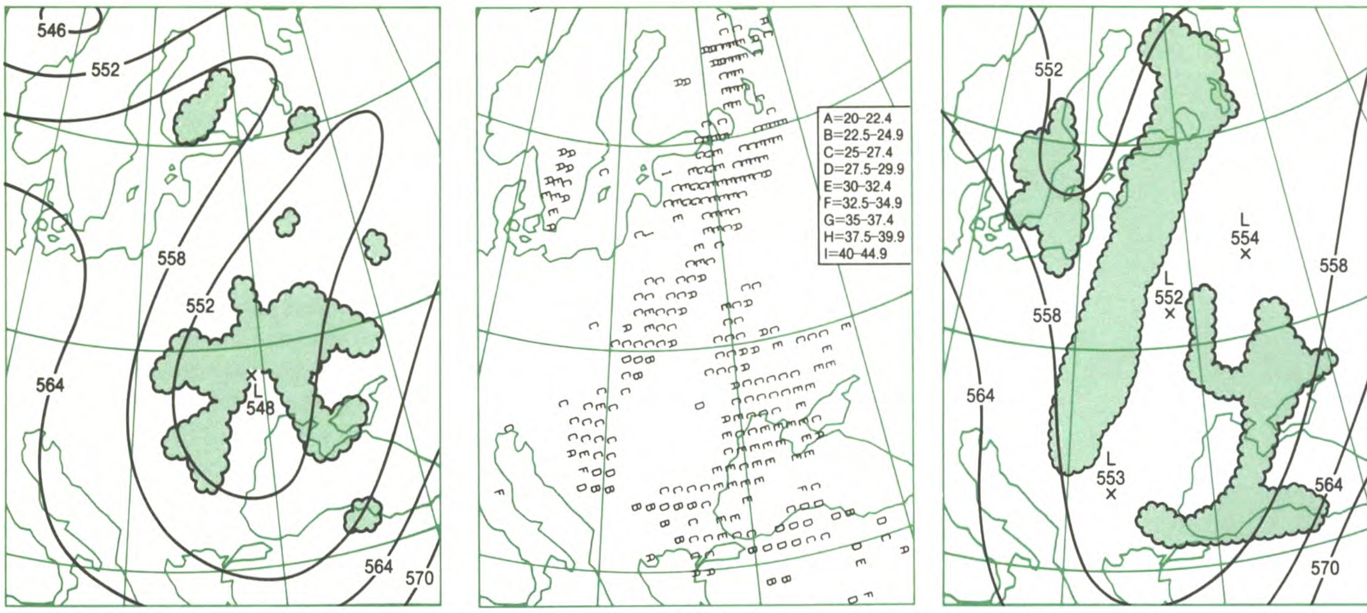


Some of the publications issued by the Office

CIVIL AVIATION

Civil aviation is the largest single civil user of the output of the Meteorological Office. The continuing improvement in the accuracy of forecasts has increased the economic attraction and popularity of the service, and more and more airlines world-wide now use the forecasts of upper winds and temperatures from Bracknell for flight planning.

The meteorological support provided for civil aviation in the United Kingdom conforms closely to the Standards and Recommended Practices of the International Civil Aviation Organization (ICAO). Within the terms of the ICAO regulations the Civil Aviation Authority (CAA) is the meteorological authority for civil aviation matters. The role of the Meteorological Office is to provide professional advice to the CAA and to provide meteorological services according to its requirements on a repayment basis. The greater part of these costs, about £17 million this year, are recovered by the CAA as part of the



The convective cloud pattern (shaded area) for a particular time is shown left with the 24-hour computer-generated forecast of convective cloud tops (heights in 1000's of feet) shown centre. The actual pattern for this time is shown right.

en route charges levied on aircraft that use the air navigation services within UK airspace.

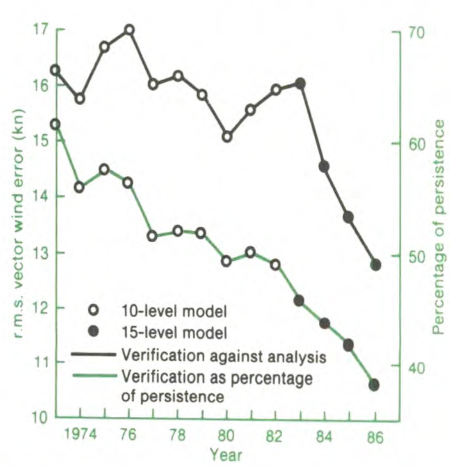
International responsibilities

The organization of meteorological services for civil aviation is centred upon the ICAO World Area Forecast System (WAFS), the initial phase of which was implemented in November 1984. At the heart of this system are two World Area Forecast Centres (WAFCs), one at Bracknell and one in Washington. Each provides global forecasts in digital form for a series of levels, twice per day, for 12, 18, 24 and 30 hours ahead. These forecasts, the direct output of global numerical weather prediction models, are sent to associated ICAO Regional Area Forecast Centres (RAFCs).

The Meteorological Office at Bracknell provides one of the three RAFCs in western Europe responsible for the conversion of digital data into chart format for distribution to State Meteorological Services and airports within the region. Four airlines (British Airways, Scandinavian Airlines System, Japan Air Lines and Pan American Airways) accept the global grid-point data directly from Bracknell for use in computerized flight planning. A fifth airline (Lufttransport-Unternehmen of the Federal Republic of Germany) takes grid-point data covering the northern hemisphere. Two communications companies acting on behalf of many other airlines also take the global data. They are the Société Internationale de Télécommunications Aéronautiques (SITA) and Aeronautical Radio Incorporated . These companies provide the data either in their original form or processed as flight-planning information to most of the major operators world-wide.

Automatically produced equivalent tailwind components have been made available to a number of air-tour operators and can be provided for most of the well used air routes in an area from Canada in the west to India in the east. These products enable the on-the-ground flight-planning time to be greatly reduced. Another advantage to the customer is that they utilize a denser array of forecast points than the coarser grid specified by ICAO for global use.

Before take-off, flight crews are provided with charts of the winds and air temperatures and of the significant features of the weather likely to be encountered *en route* to their destination. The RAFC at Bracknell provides the significant weather chart for all flights westbound across the North Atlantic from airports in Europe. The Central Forecasting Office (CFO) at Bracknell serves as the Meteorological Watch Office (MWO) for the Shanwick Oceanic Control Area. The function of an MWO is to generate warnings of hazardous weather within an airspace. These warnings can be passed directly to aircraft in flight by the appropriate air traffic control unit and so update the information provided before take-off. Forecasting offices at London/Heathrow Airport and in Glasgow have similar responsibilities as MWOs for the London and Scottish Flight Information Regions respectively.



Verification of the 24-hour forecasts of 200 mb vector winds for 1973–86

Considerable progress has been made in computer-generated significant weather forecasting; convective cloud-top forecasts have been particularly impressive. As the planned final phase of WAFS will include the production of global forecast significant weather data by the WAFCs, ICAO has set up a Study Group, with UK participation, to review progress. The Study Group will also consider whether forecasts should be issued more frequently and in greater detail than at present. The aim is to implement the final phase of WAFS as soon as is practicable and the advice from the Study Group will be important in specifying the requirements and setting a timetable.

Although ICAO and WMO have well defined procedures for dealing with meteorological reports made from aircraft in flight (AIREPs), there are many parts of the world from which these reports are not received. Air-tour operators are being encouraged, therefore, to send AIREPs from the data-sparse areas directly to Bracknell post-flight over SITA communication channels. This new facility was introduced late in the year and, with the support of the International Air Transport Association, it is expected that increasing amounts of data will become available for use with the global numerical weather prediction model. This should lead to an improvement in the model analysis and hence better forecasts.

National responsibilities

Civil aviation covers a wide spectrum of activities that range from supersonic commercial passenger transport to hang-gliding. However, some essential needs are common to all kinds of flying. Warnings are issued to aerodromes whenever weather conditions which could be a hazard to the safety of aircraft during landing and take-off, or when parked on the ground are expected.

At most civil airports weather observations are made, usually half-hourly, when the aerodrome is open. Normally the observations are transmitted in the form of METeorological Aviation Reports (METARs) by teleprinter on the Aeronautical Fixed Telecommunication Network (AFTN) to the CAA message switch at Heathrow. From there they are disseminated nationally through the OPerational METeorological (OPMET) teleprinter circuits and, for most major aerodromes, internationally over the Meteorological Operational Teleprinter Network, Europe (MOTNE). Terminal Aerodrome Forecasts (TAFs) are prepared routinely for major airports and exchanged via AFTN and MOTNE. Copies of TAFs and METARs are made available locally at aerodromes to supplement the flight forecast documentation supplied in chart form.

Forecast minimum pressure values are prepared every hour in the CFO for 21 Altimeter Setting Regions over and around the United Kingdom. Provision of these forecast pressure values is an important safety measure. They aid the safe clearance of high ground by low-flying aircraft and the safe vertical separation of aircraft. The forecast values are distributed by Meteorological Office teleprinter channels and by AFTN and are used primarily by aircraft in flight outside controlled air space.

The Meteorological Office, on request from the Accident Investigation Branch of the Department of Transport, provides detailed information on weather which may be relevant to an aircraft accident: copies of actual weather reports from observing offices near to the place of the accident, relevant forecasts and warnings valid at the time, and a résumé of the general weather situation.

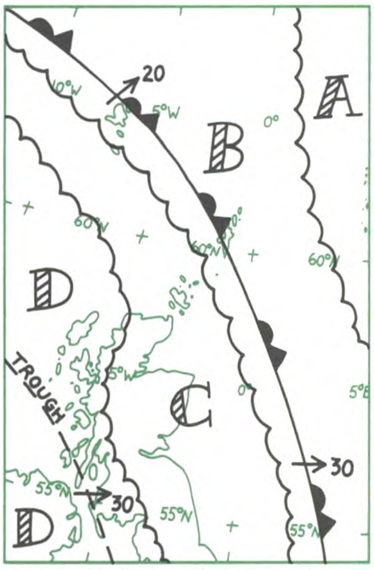
General aviation

General aviation covers a range of activities that includes recreational flying in private aircraft, gliding, hang-gliding, microlight flying and some commercial flying such as crop spraying, aerial surveying and air taxiing and is mainly concerned with flights below 10 000 ft. The Principal Forecasting Office at London/Heathrow Airport issues a forecast in chart form, four times daily, of the weather details from the surface up to 15 000 ft over the United Kingdom. This is supplemented by an appropriate upper-wind and temperature chart. These charts, plus appropriate TAFs and METARs, are distributed to aerodromes equipped with the means of receiving them, and provide sufficient information for most users. However, many general aviators are not able to receive these charts; their needs are met by a specific service introduced by the CAA during the summer.

The new service, Airmet, provides forecasts for three areas of the United Kingdom and near Continent. The forecast for southern England and the near Continent is prepared at Heathrow, that for northern England and Wales at the Main Meteorological Office (MMO) at Manchester, and that for Scotland and Northern Ireland at the MMO at Glasgow. They are issued four times daily and made available by AFTN, telex, a premium-rated telephone service and, together with a selection of about 40 TAFs, also on Prestel. Airmet has replaced the local area forecasts and many of the dedicated route forecasts prepared previously.

Special forecasts are prepared for the helicopter operations that support the offshore oil and gas industry. Forecasts for operations over the Irish Sea and the southern North Sea are issued from the MMO at Manchester; those for the northern North Sea originate in the MMO at Glasgow. After consultation with the helicopter operators the CAA decided that helicopter flights over the northern North Sea would be better served by supplying, at 3-hourly intervals, upper-wind and temperature charts that depict values at specified locations rather than on an area-by-area basis. These are supplemented by significant weather charts. This new service started in November and sets of charts are sent by document facsimile, four times daily, directly to the operators.

Examples of the documentation used for helicopter operations over the North Sea. Left significant weather chart, right spot wind chart



FIXED TIME CHART VALID 1800 UTC 10 NOV 1987
FORECAST WEATHER BELOW 10000 FT
Issued by M M O Glasgow at 10/1000 UTC

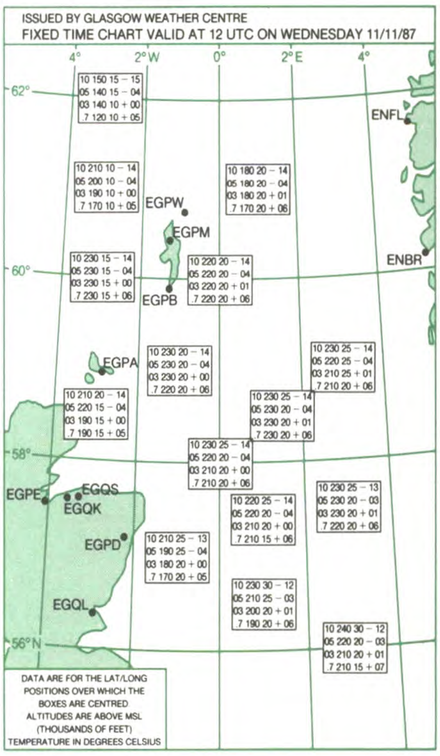
NOTES: Decode given in LAPform 216 or UK AIP
Visibilities in M or KM.
Hill Fog implies 200 M or less.
Heights are A M S L in hundreds of feet.
XXX = Over 10000 FT. TS & CB imply MOD/SEV Airframe Icing and Turbulence

SUITABLE FOR FLIGHTS BETWEEN 10/1200 AND 10/2100 UTC.

VARIANT	VIS	WEATHER	CLOUD, TURBULENCE, ICING, HILL FOG	0 DEG C
AREA A *	25	NIL	SCT/BKN CUSC 020/055) BKN/OVC	
OCNL	8	RAIN SH	BKN/CUSC 012/070) ACAS	025
			) 120/XXX	
AREA B *	10	NIL/	(SCT/BKN ST 012/015)	040 N
			(OVC SCAS 018/XXX)HILL	065 S
OCNL	6	RAIN	BKN ST 008/015)FOG	
LOCALLY	3500	RAIN	BKN ST 004/015)	
AREA C *	25	NIL	SCT/BKN CUSC 020/070)	035
OCNL	7	RAIN SH	BKN CU 012/100)HILL	
ISOL W	5000	RAIN SH/	(SCT ST 010/012)FOG	
		HAIL	(BKN CUCB 012/170)	
AREA D *	20		(SCT/BKN CUSC 018/080)	030
		RAIN SH	(BKN AC 120/XXX)HILL	
FRQ	7	RAIN SH	BKN CU 012/120)FOG	
OCNL	3500	RAIN SH/	(SCT/BKN ST 008/012)	
		HAIL/TS	(BKN CUCB 012/200)	
AREA				

* REMARKS, WARNINGS, ETC.

ALL AREAS: MOD LOC SEVERE TURB BELOW 070 DUE TO STRONG TO GALE FORCE SURFACE WINDS.



Developments in forecasting

Numerical models of the atmosphere are a central feature of weather forecasting in the Office. Many forecast products are based directly on the models' simulations of the motions and physical processes in the atmosphere. However, the limited spatial and temporal resolutions of the models prevent the direct representation of all atmospheric phenomena; the influence of unresolved features is expressed in terms of model variables using relationships (or parametrizations) determined from their physical and statistical characteristics. Careful parametrization is especially important when dealing with clouds and radiation and with the boundary layer (the region of the atmosphere, adjacent to the ground, where rapid transfers of momentum, heat and moisture occur).

Improvement in the detail that can be provided in weather forecasts depends on a better understanding of small-scale processes, such as line convection and the low-level jets associated with active cold fronts. Until recent years, the study of such mesoscale phenomena has been limited by the resolution of the conventional upper-air synoptic observing network which has, at best, stations spaced some 300 km apart. The 1987 Mesoscale Frontal Dynamics Project (see later) was designed to improve the understanding of the interaction between processes that occur on scales from 100 km to less than 1 km. Numerical models that make use of the data from this and other similar field experiments are being developed to examine the mechanisms that drive these phenomena. They are expected to lead to a better understanding of the small-scale processes and make possible their representation in a simplified way within large-scale operational models.

The range of products for which forecasts are required is ever widening. To meet this need the computer models have to simulate a wider variety of physical phenomena than before. For instance there is now a requirement for detailed cloud forecasts to be provided from the models. Forecasts for particular localities, where the weather may be affected by nearby topographic features that cannot be represented in the model, are obtained by statistical processing of the model output. As well as being used for forecasting the weather, the numerical models are used for other purposes such as predicting the spread of pollution (see later). Winds derived from the atmospheric models are also used to drive ocean models that predict surface waves and swell (see later).

Numerical forecast models

Higher resolution has been demonstrated to be beneficial in forecast models and will soon be available in the Office's operational models. The regional fine-mesh model has been used experimentally with grid points as little as 40 km apart. The present operational fine-mesh model uses a grid defined on a latitude–longitude sector of the globe. A new version has been developed in which a quasi-regular grid can be used over the area of interest without the need for a map projection. This model can be used for forecasting for areas located in any part of the world; it has been used for real-time forecasting in the Antarctic, for experimental predictions in the tropics and for high-resolution forecasts for the United Kingdom. At grid lengths less than 40 km the model formulation must be reconsidered. A mesoscale model has been developed with a 15 km grid spacing and, though not yet operational, it is in routine use. This model solves the full three-dimensional compressible equations of motion, rather than assuming hydrostatic balance. It incorporates equations for the turbulent kinetic energy which can be used to predict the gustiness of the wind. Convective motions are represented by parametrizing the updraughts, which are on a much smaller scale than the grid length, and by explicitly resolving the compensating subsidence. The model also incorporates a detailed representation of the physics of clouds and precipitation.

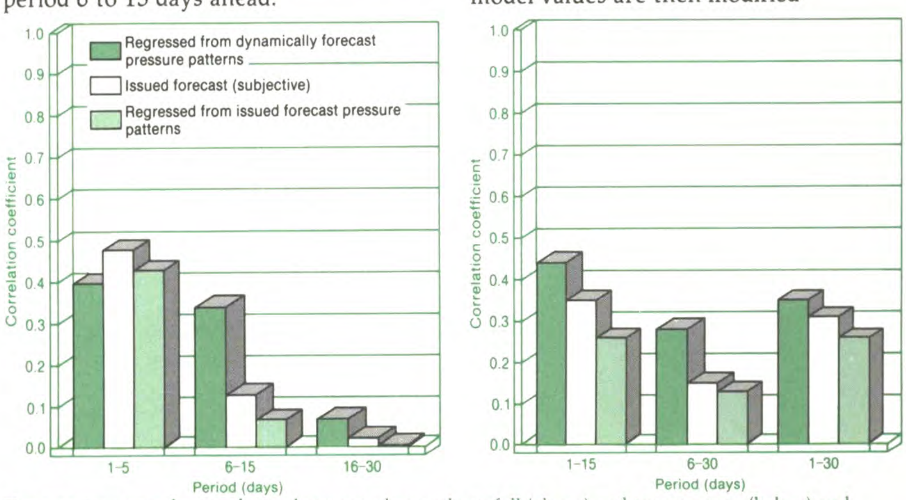
In order to meet the need for a wider range of products from the global and fine-mesh forecast models, physical processes, such as radiation and surface processes, are being represented in greater detail than before. Suitable schemes have already been developed for the climate model. To facilitate the transfer of relevant sections of computer code from the climate model to the forecast model it has been decided to move towards unifying the two models. As a step in this direction, a version of the finite-difference scheme used in the forecast model has been

The Hercules aircraft used in the Mesoscale Frontal Dynamics Project

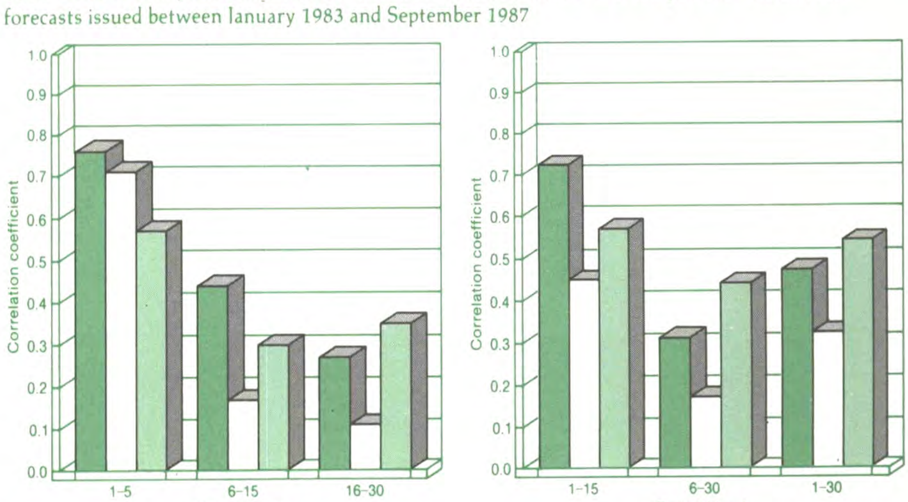
designed to satisfy the conservation properties necessary for the long time integrations needed for climate studies.

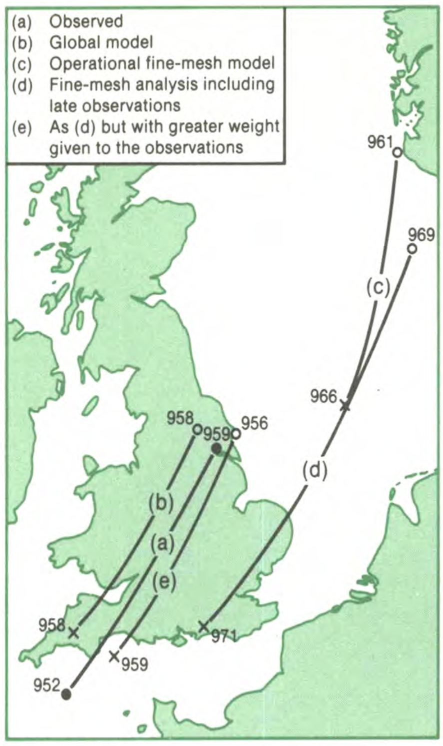
The use of higher resolutions in forecast models increases the range of processes that can be simulated explicitly. This gives the opportunity for forecasting in greater detail but it can create new problems where phenomena which were previously unresolved (and therefore parametrized) are now partly resolved; convectively driven motions are one example of this. The problem can be solved by using dynamically selective models which attempt to forecast explicitly only those motions which can be treated accurately. In order to design such models a much greater understanding of mesoscale circulations is necessary, involving field experiments and very high resolution modelling (see later). A particular form of dynamically selective model is being developed which, for instance, describes fronts explicitly but simplifies convective motions into representations of the initial and final states of a convective adjustment, rather than attempting to predict the detailed convective flow.

Another application of numerical forecast models is for long-range prediction. It has been demonstrated that dynamical models have reached a sufficiently advanced stage of development to have a higher level of skill in forecasting the surface pressure fields out to 15 or 20 days than the purely statistically based methods that have hitherto been used for long-range forecasting. It is planned that results from dynamical models will have a greater input to the experimental monthly long-range forecasts that are produced each fortnight. The skill of these routinely generated forecasts is, at best, modest but nevertheless higher than alternative ways of estimating conditions so far ahead. The statistical forecasting methods provide forecast fields of mean-sea-level pressure averaged over 15-day periods. In the past, the related rainfall and temperature forecasts were deduced subjectively. This information is now produced objectively using regression equations for each of ten areas of the United Kingdom. The diagrams show the correlations obtained when the new regression equations were applied to the surface pressure fields produced statistically and to those obtained from a set of 48 dynamical forecasts run over the same 4½-year period. Also shown is the skill of the temperature and rainfall forecasts produced by subjective interpretation of the pressure fields. It can be seen that for most of the forecast periods the best rainfall forecasts were produced by statistical interpretation of the dynamical forecasts, although the statistical significance of this result is hard to assess because of the different selection of cases. The differences between the three systems are more marked for temperature forecasts and hold out hope for some modest improvement of skill in the near future when greater emphasis is given to the dynamical predictions, especially for the period 6 to 15 days ahead.



Time-series anomaly correlation between observed rainfall (above) and temperature (below) and forecasts issued between January 1983 and September 1987





Central pressure (mb), position and track between 0000 and 0600 GMT of the depression that crossed the country on 16 October, together with the predictions obtained using different initial analyses of observations for 0000 GMT on 15 October (X 24-hour forecast, O 30-hour forecast)

Analysis of meteorological observations

The development of improved methods of analysing data is essential if the full advantage of better forecast models is to be obtained. The figure left shows the effect on the forecasts of the storm of 15/16 October 1987 of different initial analyses. The differences made by the use of extra data and by employing modified analysis systems are crucial in determining whether the exceptionally strong winds would be forecast to affect south-east England.

The observations available at a particular time are not sufficient to define the atmosphere everywhere. Sounding data from polar-orbiting satellites, for instance, are available only at times of overpass and along swaths. Moreover, in practice, the data arrive in a steady stream with varying delays in transmission.

The analysis technique uses the forecast model to provide an objective first guess at the locations of the observations. The model values are then modified

Root-mean-square errors of 6-hour forecasts compared with synoptic observations and radiosondes during the period 16 to 25 April 1987

	Northern hemisphere		Tropics (30°N–30°S)		Southern hemisphere	
	15-minute resolution	6-hour resolution	15-minute resolution	6-hour resolution	15-minute resolution	6-hour resolution
Mean-sea-level pressure (mb)	2.21	2.37	2.13	2.27	2.58	2.64
500 mb height (dam)	2.00	2.08	2.31	2.35	2.63	2.65
850 mb temperature (°C)	2.07	2.13	2.14	2.17	2.63	2.70
250 mb vector wind (kn)	14.80	15.50	16.10	16.50	19.10	20.50

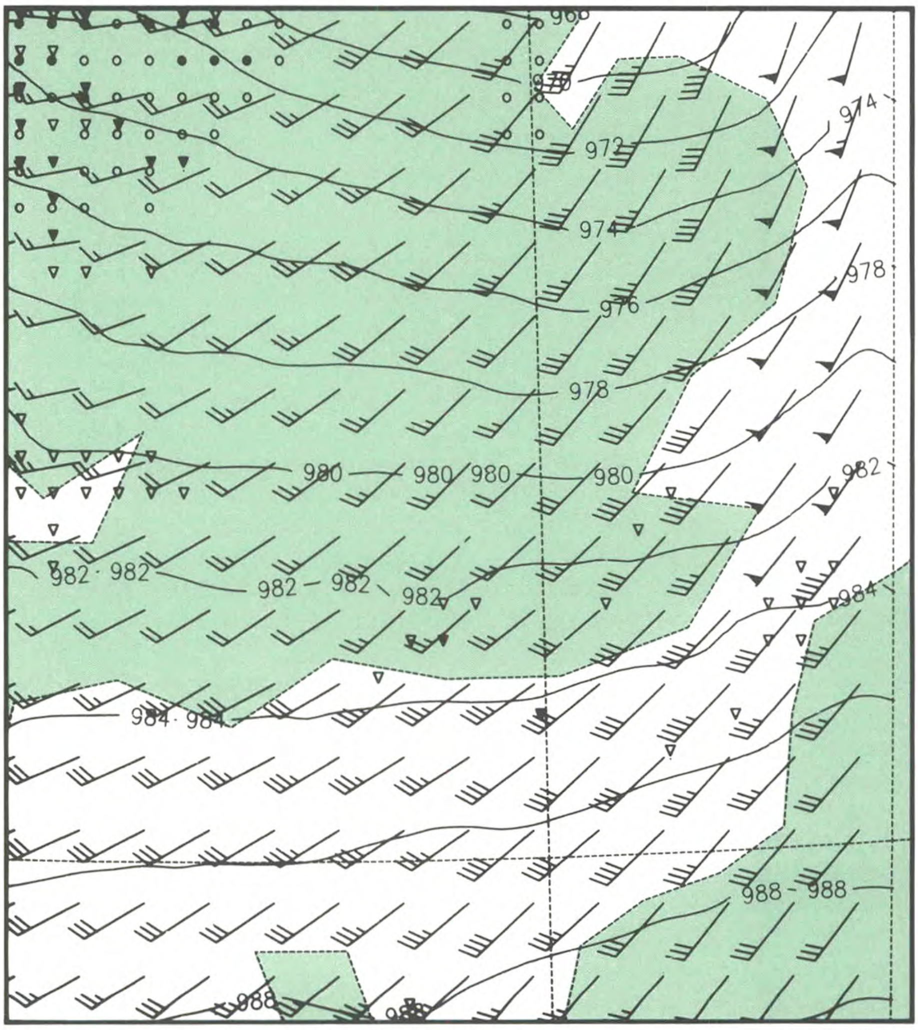
according to the difference between the observations and the first guess, taking into account the expected errors in each. The changes are spread in both space and time, using prior knowledge of the likely atmospheric structure. The table above indicates the improvements to short-range forecasts obtained by performing the analysis using the observations at their individually correct times, to within 15 minutes, rather than the present operational method for the global model, which treats all observations within a 6-hour slot as though they were made at the mid-time.

The technique has the potential for analysing a wide range of types of observations. For instance, a cloud map might be generated from the forecast model and compared with satellite imagery; the differences between them might then be used to improve the representation of both humidity and the vertical motion field in the model. Methods developed recently have allowed the temperature and horizontal wind fields to be improved by applying a similar procedure. A comparison of the rainfall pattern from the weather radar network and model rainfall rates is another possible application of the method. Observations of wave height have been converted by the same comparison technique into information about the wave energy spectrum needed by the wave models.

While much of the analysis process can be automated, some of the most informative data, such as satellite imagery, require human interpretation. By exploiting the pattern-recognition skills of the experienced forecaster, additional information can be extracted especially for mesoscale forecasts. For instance, the high vertical resolution in radiosonde observations can be spread horizontally using air-mass boundaries deduced from the satellite and radar imagery. A prototype system that allows forecaster intervention on the mesoscale has been in routine use during the last year. A powerful graphics work station is used to overlay observations and model variables, and a forecaster can manipulate the values selecting from a menu of appropriate modifications.

Experimental forecasts for particular case studies

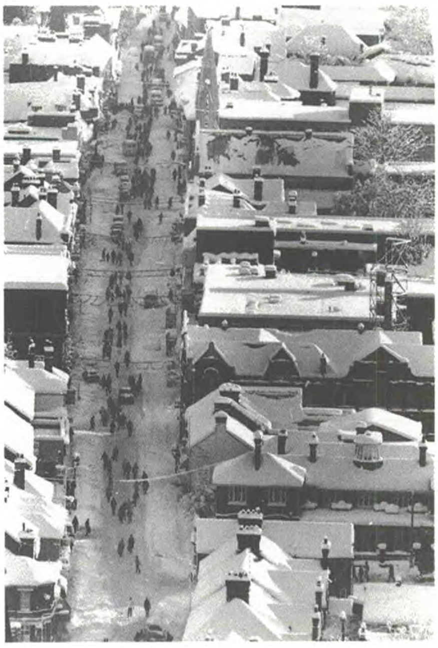
The storm of 15/16 October 1987 provided a very good opportunity to test the impact of higher resolution on the accuracy of numerical forecasts. A good forecast of both the strength and distribution of the wind was obtained from the mesoscale model in which the



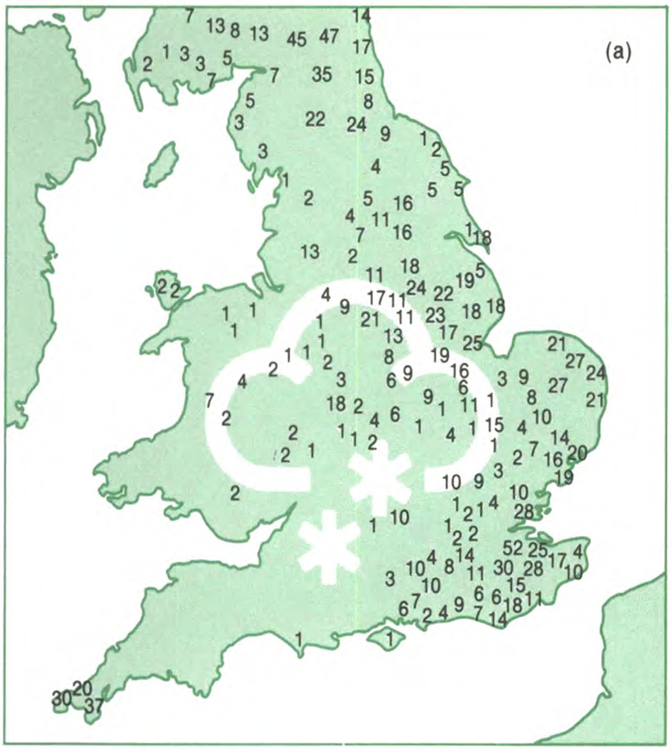
Forecast of 10-metre winds for 0600 GMT on 16 October 1987 produced by the mesoscale model

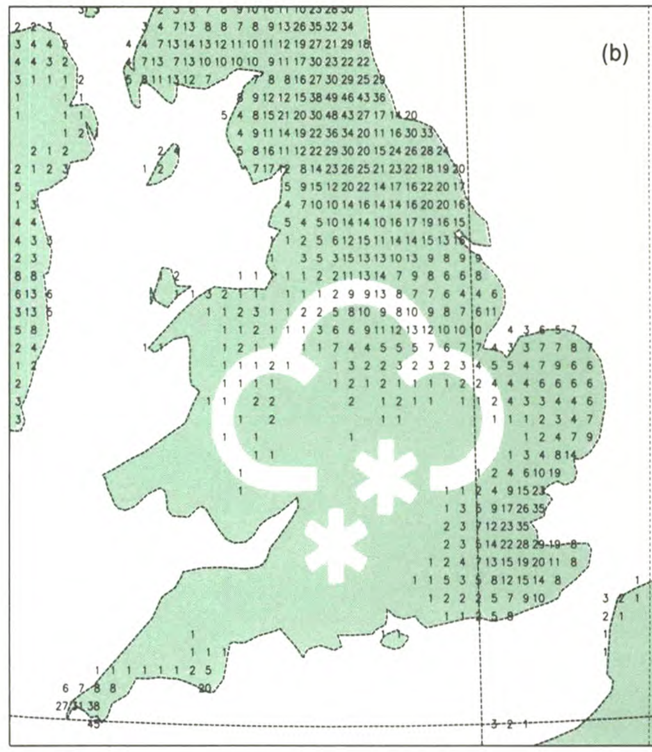
boundary-layer structure can be represented in more detail than in the operational models. The potential of this model, however, is limited by the small area covered and by the need to use boundary values obtained for the regional model.

A second example in which the detail of the air flow was modified by land–sea contrasts occurred during the period 12–13 January 1987. A very cold easterly airstream covered much of Europe. Heavy snow showers generated over the North Sea spread a few miles inland, giving accumulations up to 52 cm, mainly in a narrow coastal strip. Around



A snowbound street in Sittingbourne, Kent on 12 January 1987 (Photograph by courtesy of The Times Newspapers Ltd)



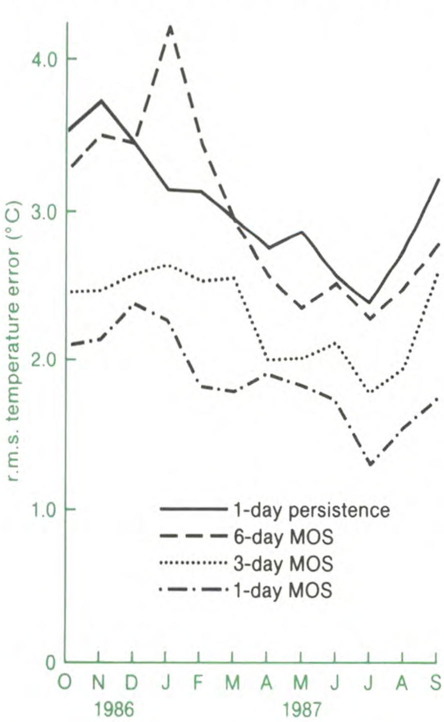


Observed (a) and forecast (b) accumulation (cm) of snow at 0900 GMT on 13 January 1987

the Thames estuary the shape of the coastline generated a mesoscale wind circulation which greatly enhanced the snowfall. Convergence of the wind caused by the land–sea temperature contrast produced heavy snow in a band along the English Channel, giving 37 cm of snow in south Cornwall while inland areas remained snow-free. Since this pattern was generated by the shape of the coastlines, the mesoscale model was able to give a very accurate prediction.

Local weather forecasting

The forecast models predict the temperature both at and near the earth's surface. The effect of clouds is allowed for using techniques described later. However, in reality, temperature at a given location is strongly influenced by small-scale factors which are not allowed for in the model. The model's predictions can therefore be improved by enhancing them statistically. Because the models are undergoing continuous improvement, the statistical algorithms must also be continuously updated. They are therefore recomputed every month from information for the previous month. Day maxima and night minima are now predicted routinely for 35 stations in the British Isles. At present the input data are taken from the regional model but it is hoped to extend the technique to the higher-resolution mesoscale model in the future.



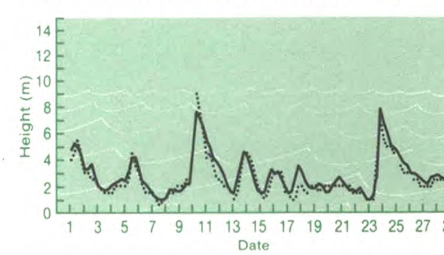
Root-mean-square (r.m.s.) errors of Model Output Statistics (MOS) forecasts of night minimum temperature based on global model output

By interpreting the global model forecasts in a similar way, temperatures up to 6 days ahead can be generated. The errors are smaller than typical day-to-day variations up to 4 days ahead. This method is being developed to produce forecasts for meteorological stations world-wide.

Statistical methods are also used to provide a number of other aids to the forecaster. For example, a procedure that uses the regional model output for forecasting the evaporation duct over the open ocean is under trial. The information is important for predicting radio propagation.

Wave models

The operational forecasting suite contains models that predict wave heights and periods both globally and, at higher resolution, for an area around Europe. The wave energy spectrum is predicted first, and other properties of the waves calculated from it. At present the calculations rely entirely on surface winds derived from the weather prediction models. The initial data are deduced from the past history of the winds, rather than from direct wave observations which are difficult to come by. It is hoped to improve the assessment of the wave predictions by making use of measured wave data from buoys in real time in preparation for the European Remote-sensing Satellite, ERS-1, planned for launch in 1990, which will provide an extensive wave data base. In the illustration below a



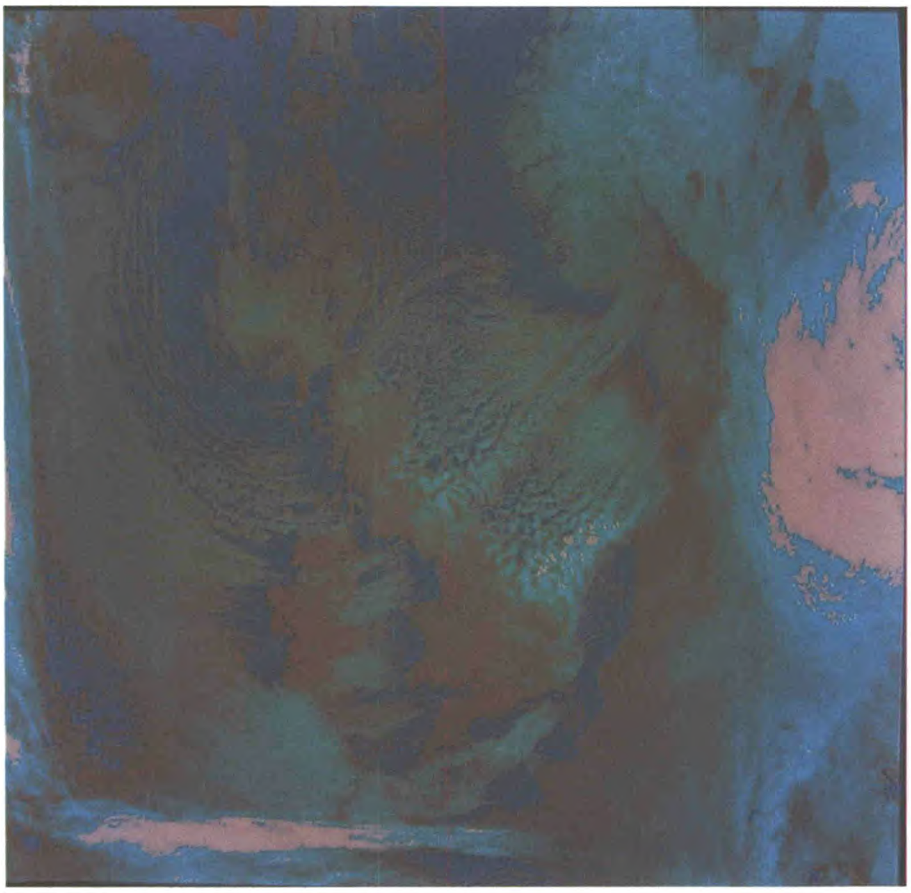
Time series of observed significant wave heights at 38.5° N, 70.7° W (dotted line) compared with model analyses at the nearest grid point (solid line) during February 1987

time series of significant wave heights from one of the buoys operated by the USA is compared with the values for the same location deduced by the model. As a result of such comparisons, and other recent research, improvements have been made to the models during the past year. These include better representations of the wave energy growth and of wave dissipation.

Mesoscale Frontal Dynamics Project

Mesoscale systems are not well understood partly because the conventional observing network is not dense enough. Detailed observationally based studies, as undertaken in the Mesoscale Frontal Dynamics Project, are therefore essential as a basis for mesoscale prediction.

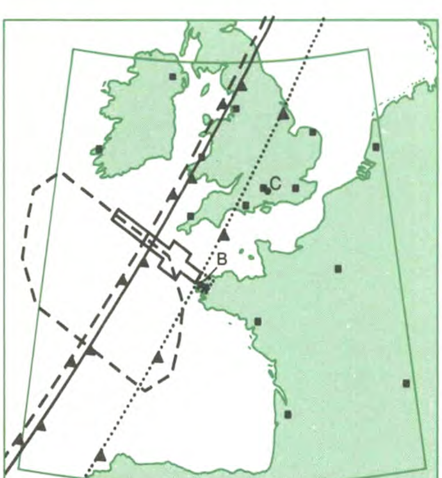
The main field phase of the Project took place from October to December. The Office collaborated with UK university groups and with research groups in France and the Federal Republic of Germany. The aim was to study active cold fronts as they approached Brest from the west or north-west by intensive observation programs over periods of 36 hours. Extra radiosonde soundings were made in the experimental area and the moving weather systems were observed: by French dual Doppler and millimetric radars and other facilities near Brest, by the Rutherford Appleton Laboratory dual polarization radar at Chilbolton, and by other remote-sensing instruments at Aberystwyth and in Brittany. The Meteorological Office balloon facility was detached to the Isles of Scilly and, as described below, extensive aircraft observations were made.



NOAA-10 satellite photograph valid for 0826 GMT on 12 January 1987 — the day of the heavy snow showers illustrated on previous pages

Each experiment had three phases. In the first, the Hercules aircraft of the Meteorological Research Flight (MRF) released dropsondes in a pattern

The area for the Mesoscale Frontal Dynamics Project. The regions for the aircraft observations in phase 1 (dashed), phase 2 (solid line) and phase 3 (dotted line) are shown, together with the frontal position at the start of each phase assuming movement from 300° at 10 m s^{-1}. Radiosonde stations are denoted by ■ and the specialized radars at Brest and Chilbolton by B and C.

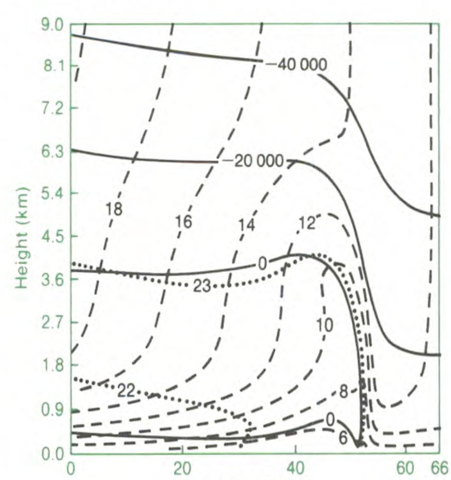


straddling the surface front. They provided, in real time, temperature, humidity and wind soundings with a spacing of 20–100 km. In the second phase, French and German aircraft made measurements in the boundary layer and in the low-level jet. In the third, cloud dynamical and microphysical data were obtained *in situ* by the Hercules and the French aircraft at the same time as the cloud structure and microphysical properties were observed by the French radar systems. The experiment was planned so that during each phase approximately the same air was observed but with increasing resolution over a smaller area. Data from all the observing systems are being collated and will be made available to the participating groups.

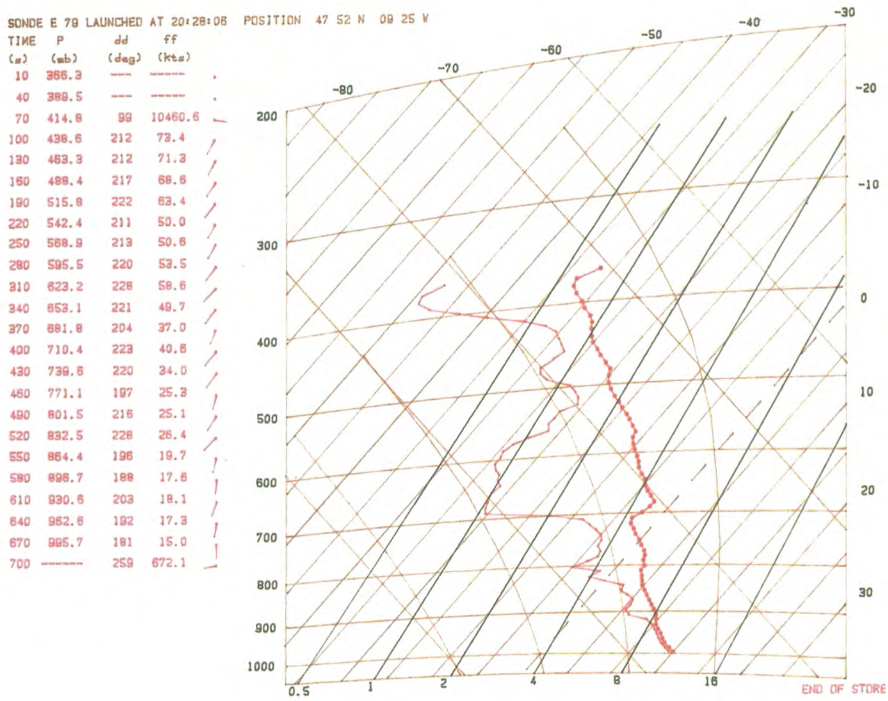
The first experiment took place from 18 to 19 October on a cold front which brought considerable flooding to south-west England and Wales. Thirty-one dropsondes were released to obtain five vertical cross-sections normal to the front.

Analytical and numerical models are being developed in association with the field program. They have been used to assess the importance and the representation of a form of mesoscale circulation known as slantwise convection. In this process the release of latent heat in frontal regions intensifies the vertical motion which is dependent on the stability measured along the frontal surface. Instability may occur in a slantwise direction even though the atmosphere is stable to vertical displacements. Another mesoscale feature being investigated is the low-level jet ahead of active surface cold fronts. A cross-section through a simulated cold front, obtained using a two-dimensional version of a mesoscale model with a 2 km grid, shows flow

Vertical section of a simulated cold front showing isotherms of potential temperature, °C, (dotted line) stream function, $m^2 s^{-1}$, (solid line) and contours of along-front wind speed, m s^{-1}, (dashed line). Note the tongue of cold air and rapid ascent over its leading edge, with slight descent behind.



normal to the surface front along the potential isotherms with a maximum in the flow parallel to the front ahead of the nose of cold air; this is the low-level jet. The circulations demonstrate the persistence of such small-scale features over time-scales characteristic of much larger-scale phenomena.



TIME (s)	P (mb)	dd (deg)	ff (kts)
10	366.3	----	------
40	389.5	----	------
70	414.8	99	10460.6
100	438.6	212	73.4
130	463.3	212	71.3
160	488.4	217	68.6
190	515.8	222	63.4
220	542.4	211	50.0
250	568.9	213	50.6
280	595.5	220	53.5
310	623.2	228	58.6
340	653.1	221	49.7
370	681.8	204	37.0
400	710.4	223	40.6
430	739.6	220	34.0
460	771.1	197	25.3
490	801.5	216	25.1
520	832.5	228	26.4
550	864.4	196	19.7
580	896.7	188	17.6
610	930.6	203	18.1
640	962.6	192	17.3
670	995.7	181	15.0
700	-------	259	672.1

A sounding plotted in the Hercules in real time during an experiment on 18 October; the dropsonde was released behind a cold front

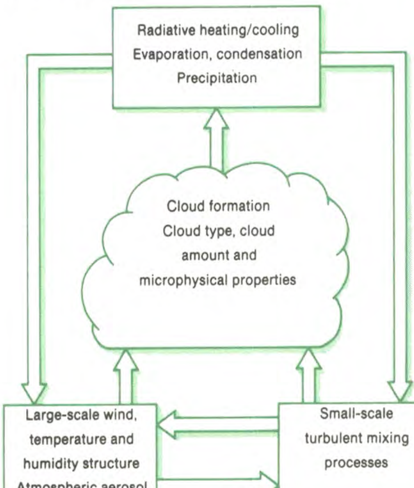
The dropsonde deployed by the Hercules to obtain profiles of wind, temperature and humidity

CLOUDS AND RADIATIVE PROCESSES — SPECIAL TOPIC

Clouds are a vital element in the earth–atmosphere system. Precipitation originates within clouds, and heat exchange during evaporation and condensation has very important thermodynamic consequences for atmospheric dynamics. Also, clouds generally cause profound changes in the radiation balance. Almost all areas of meteorological activity are affected. Short-range predictions of temperature, frost and fog depend on accurate cloud forecasts. The prediction of low cloud base is an important element for aviation. Mixing in the boundary layer may be very different when clouds are present with implications for pollution transport, and it is essential to take washout by precipitation into account when considering deposition, as the Chernobyl incident proved. Clouds also have a strong influence on the earth's climate since they control the distribution of radiative heating which is the ultimate energy source driving both the atmospheric and oceanic circulations. Clouds are therefore especially important in coupled ocean–atmosphere models.

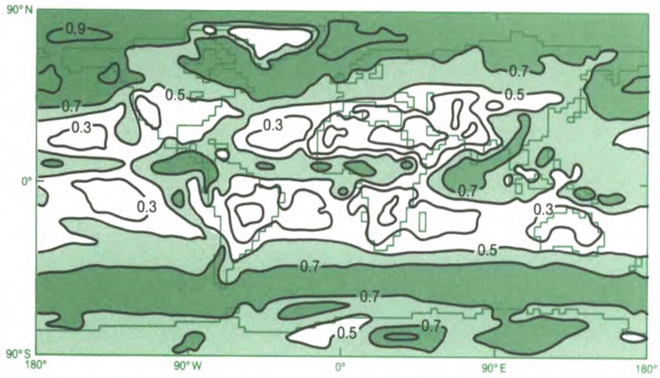
An immediate consequence of allowing clouds to interact with other modelled processes, especially radiation, is that many aspects of clouds must now be represented in much more detail. These are associated with a number of interlinked physical processes that occur on a wide range of scales. Cloud depends not only on the wind, temperature and humidity fields which are usually predicted by models, but also on the atmospheric aerosol and small-scale turbulent mixing processes. Nucleation, the initial formation of micron-sized cloud particles, and subsequent interactions between particles determine the numbers and nature of the particles making up the cloud. These in turn affect the radiative properties of the cloud and the likelihood of precipitation. Mixing processes control the internal structure of clouds and the relationship with their surroundings, thereby influencing the amount and type of cloud formed. The whole system is highly interactive: once clouds form, the consequential changes due to radiative effects, phase change and microphysical processes feed back to modify the thermodynamic structure, the mixing processes and therefore the clouds themselves.

The major goals of current research are to understand the interactions, to identify the important physical processes occurring in various cloud types and to use this knowledge to develop and test improved cloud parametrizations in models.

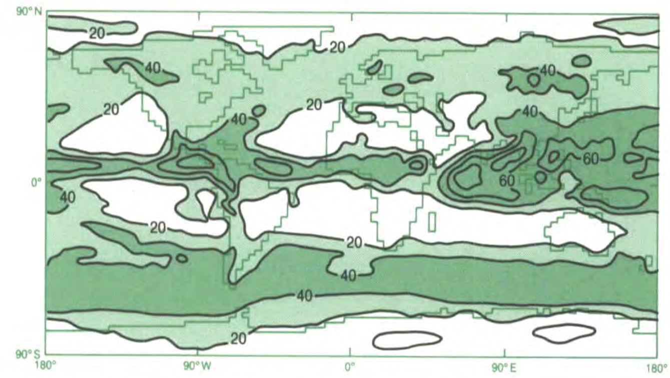


Physical processes involved in cloud formation

The correct representation of clouds and radiative heating is of great importance in the global models used for long-range forecasting and climate research. Clouds reflect the incoming sunlight, tending to cool the earth–atmosphere system. In contrast, they trap the outgoing thermal radiation, enhancing 'greenhouse' warming. The net effect of clouds is determined by the balance between these opposing influences. Whether the overall effect is a warming or a cooling depends on such properties of the clouds as their height, type and thickness. Until recently, clouds were diagnosed from the predicted temperature and humidity fields which allowed only a very limited range of cloud descriptions and little scope for interaction with other modelled processes. However, the latest model incorporates an explicit cloud liquid-water (and ice) variable which has led to improved cloud and radiation simulations. The figure overleaf illustrates the total cloud cover averaged over the northern summer season from this model. The enhanced cloudiness associated with the Inter-Tropical Convergence Zone and monsoon regions is evident. There is much less cloud over the subtropical oceans and in particular over the deserts, while at high latitudes the persistent cloud in the storm tracks of both hemispheres is clearly marked. Comparisons with



Modelled total cloud amount averaged over the northern hemisphere summer season

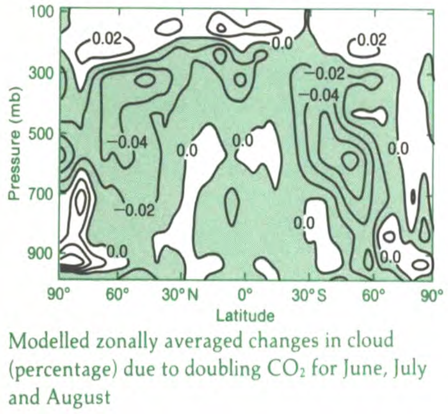


Modelled distribution of cloud radiative forcing ($W m^{-2}$)

climatologies compiled from surface observations and with the satellite data being collected during the International Satellite Cloud Climatology Project (ISCCP) show that considerable progress is being made, but that improvements are required in many areas, for example the representation of low-level clouds.

In the context of climate studies, the primary reason for modelling clouds is to be able to compute fields of radiative heating, so it is also necessary to compare these fields with observations. Again, satellites have provided valuable data, although in the past it has proved difficult to separate the effects of clouds from those of the clear atmosphere and the surface. However, the Earth Radiation Budget Experiment (ERBE) is providing estimates of clear-sky radiative fluxes which allow the difference between a cloudy situation and an identical one with the clouds removed to be derived. The figure top right shows the modelled distribution of this difference in the thermal part of the spectrum. Note the significant greenhouse warming by the cold, high clouds associated with deep convection in the tropics. The interaction between this warming and that due to latent heat released by convection could provide an important positive feedback tending to maintain precipitating systems, and is the subject of current research.

Since clouds exert a profound influence on climate, it is not surprising that they are also an important component in the



Modelled zonally averaged changes in cloud (percentage) due to doubling CO_2 for June, July and August

determination of climate change. Model studies of the effects of doubling atmospheric carbon dioxide (CO_2) show a marked decrease in cloud throughout much of the lower atmosphere. This leads to increased absorption of solar radiation and hence heating of the earth–atmosphere system. There is also an increase in the less-reflective high cloud which further augments this heating by reducing the cooling to space by thermal radiation. Taken together, these changes in cloud increase the simulated warming at the surface by an amount equal to that resulting from the doubling of CO_2 alone, thus doubling the response. Current research is aimed at understanding these feedbacks between cloud and climate.

Regional cloud forecasting

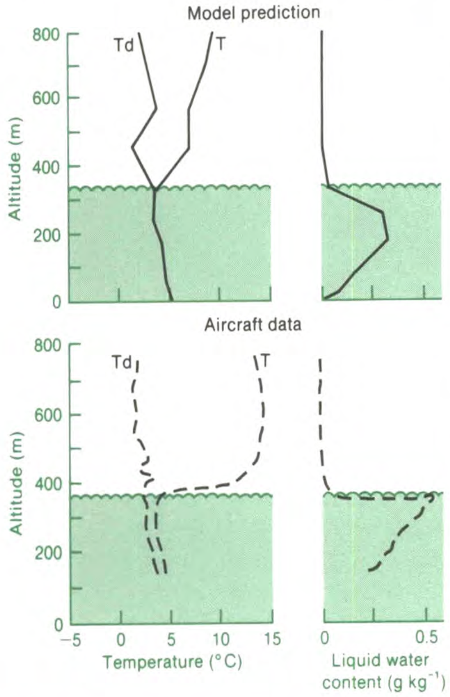
Cloud forecasts are provided by both the fine-mesh and mesoscale models. The fine-mesh model has grid points spaced 75 km apart, 15 vertical levels and covers Europe and the North Atlantic. This grid spacing is too coarse to provide a detailed forecast of cloud, so a general forecast is made by statistically relating the cloud amount and height averaged over a model grid square to the forecast humidity.

The mesoscale model covers the British Isles at higher resolution and has 16 vertical layers, although experimental versions have used 29 layers. The cloud forecasts from this model are capable of providing greater detail, in particular the height of cloud base. Consequently, the description of the small-scale physical processes is more detailed than that in the fine-mesh model, incorporating a statistical parametrization of the effects of partial cloud cover. A more sophisticated representation of the processes causing precipitation also enables rainfall and snowfall predictions to be based on firmer physical principles than relying solely on statistics. This produces better agreement with observations in a number of situations, especially precipitation from stratus clouds in winter.

The mesoscale model has also been used to predict fog. An occasion when the MRF Hercules obtained detailed observations in the Moray Firth (where sea fog is a problem for aviation) was chosen for study. In order to make the forecast, an initial description of the fog distribution was needed at a resolution not available from the routine observing network. The area covered by the fog was therefore determined from high-resolution satellite data and vertical information inferred from the routine upper-air sounding at nearby Shanwell. (Similar procedures will be used by forecasters to produce operational mesoscale analyses in the future.) The resulting forecast correctly predicted the marked temperature contrast between the fog-free Highlands and the coastal plain. This initiated a mesoscale circulation which led to the clearance of the fog from the south coast of the Moray Firth as observed. The comparison between the predicted and observed fog structure is shown right; the model correctly predicts the fog depth and reproduces the observed increase in liquid water content up to a maximum near the fog top. The model does not reproduce the very large temperature inversion at the fog top seen in the observations but spreads it over several model layers. This is because the sharpness of the inversion was not represented in the information available in the routine upper-air sounding.

Field programs

Observational programs are the primary means for increasing our basic understanding of the interactions among the various physical processes influencing clouds. Observations of cloud particle properties, cloud dynamics and radiative transfer obtained in field programs are themselves of great value in responding to a diverse spectrum of enquiries from the public, industry and aviation, and provide a means of testing parametrization methods in numerical models. Conceptual models derived from the interpretation of field data provide the physical basis for future improvements in the representation of clouds and radiative processes. Field programs also play a vital role in assessing the methods used to retrieve information from satellite observations.



Predicted and observed profiles through fog in the Moray Firth (T temperature, Td dew-point)

This summer, the MRF Hercules and instruments from the Meteorological Research Unit (MRU) Cardington made a major contribution to the First ISCCP Regional Experiment (FIRE), which was a large international collaborative effort, based in San Diego, USA, designed to investigate the extensive sheets of marine stratus cloud commonly found over the oceans beneath the subtropical anticyclones. These low-level cloud layers tend to form above the relatively cool ocean surfaces to the west of the continental land masses and have a major effect on the global radiation balance because they are highly reflective to incoming sunlight. However, they are not well predicted in present models. One of their unusual features is that the internal mixing is primarily driven by radiative effects, notably cooling from their tops. This often results in a characteristic cellular pattern. However, the radiation is very sensitive to the distribution of water within the clouds, which in turn is controlled by the internal turbulent mixing processes. There is clearly a subtle balance between the cloud structure, radiative transfer and turbulent mixing which is not yet fully understood. A summary of the processes thought to be important is illustrated schematically overleaf.

FIRE investigated intensively the processes that cause marine stratus to form, evolve and eventually break up. It sought to measure and explain the physical properties of the clouds and to relate these to the radiation seen by satellites. The location and timing of the field program were chosen to maximize the chance of encountering large areas of stratus cloud, and indeed these clouds covered extensive regions for the duration of the experiment. The collaborative nature of the project enabled the largest and most diverse set of observations ever gathered in these conditions to be assembled, and ensured that the experiment included the wide range of observational and theoretical expertise necessary to obtain and interpret the data and subsequently to apply the results in numerical models. The results should eventually lead to better numerical simulations of stratus cloud.

Simultaneous measurements of thermodynamic quantities, turbulence, radiative fluxes, aerosol and cloud particles were made from the Hercules, mainly at low level. Most flights were co-ordinated with other research aircraft and with satellite overpasses or were made in conjunction with the ground-based instrumentation on San Nicolas Island (see overleaf). This collaboration made it possible for the first time to extend the detailed measurements onto a regional scale, a perspective missing in previous experiments.

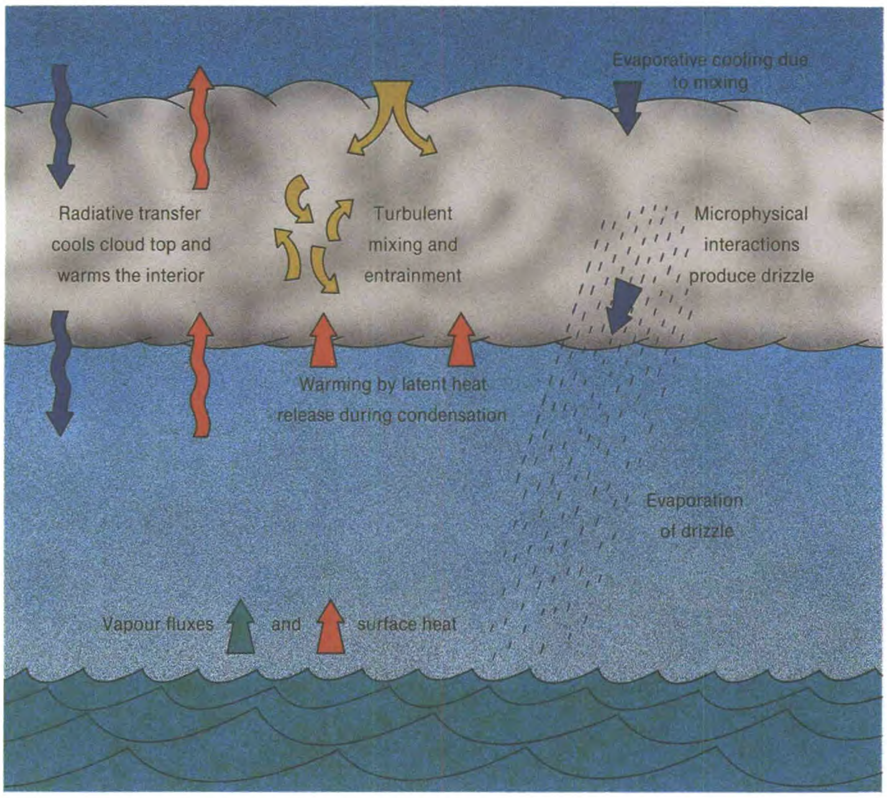
A multi-channel radiometer developed initially by the Rutherford Appleton and Clarendon Laboratories for the Nimbus satellite and adapted by the MRF for use on the Hercules aircraft flew successfully for the first time during the project. It is a directional device that measures radiation intensity at several visible and infra-red wavelengths. Comparisons of different but simultaneous views of the same cloud field from similar equipment on other participating aircraft and satellites will be particularly useful in determining how satellite data might be used to infer cloud properties. The data will also be used to test calculations of the absorption of radiation by clouds.

New probes from MRU Cardington were suspended from a tethered balloon system supplied by the National Aeronautics and Space Administration. Turbulence and radiation measurements were made at several levels simultaneously and were concentrated in the region near the cloud top to study mixing across the cloud-top interface. Data from the probes and the aircraft will be compared with numerical simulations from one-dimensional models with very high resolution (tens of metres) which are currently under development.

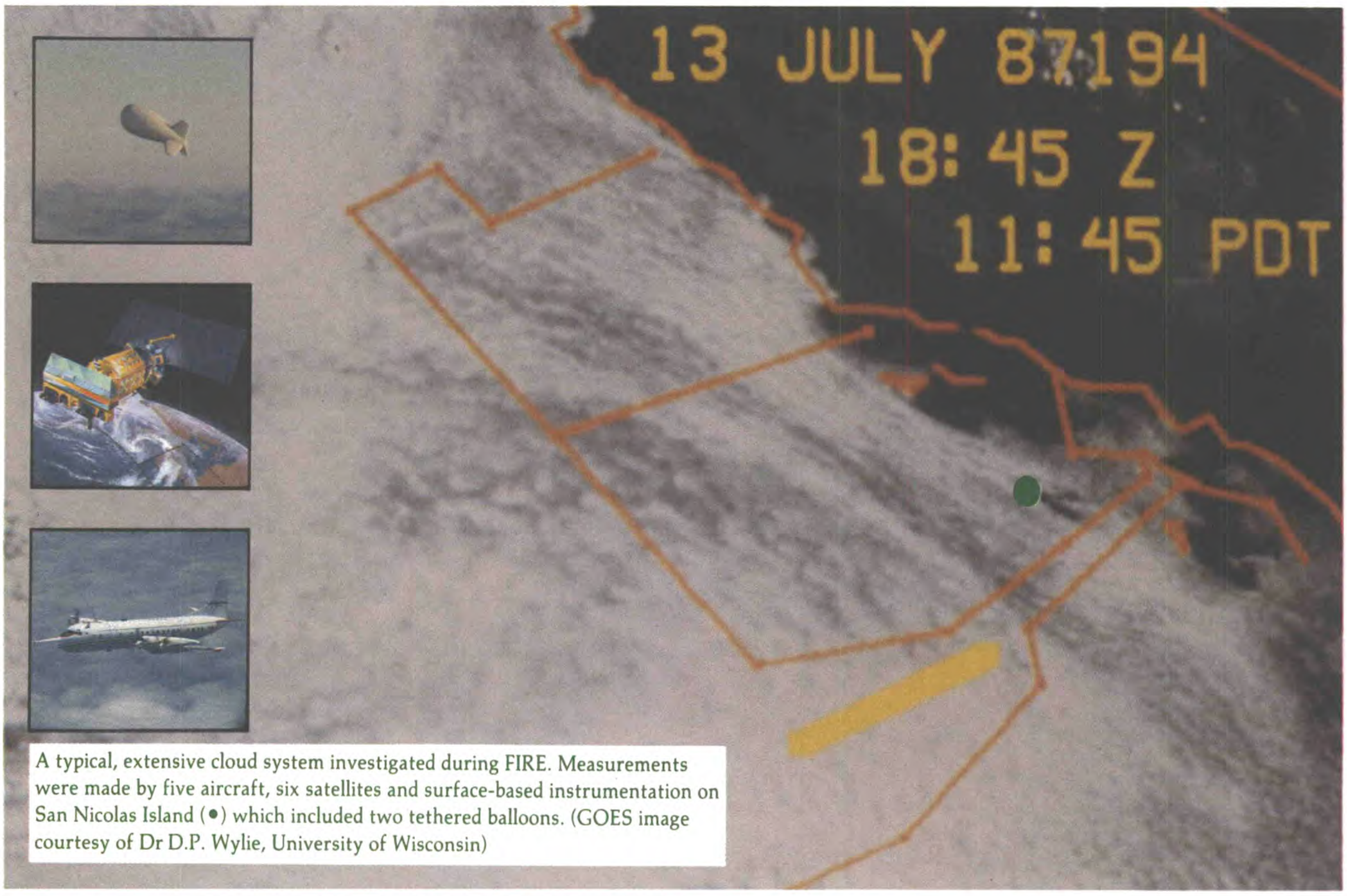
The Office has also carried out other smaller-scale observational programs in the United Kingdom to investigate other important properties of clouds and their interaction with radiation. To predict the properties of broken or inhomogeneous cloud fields is particularly difficult, yet such conditions are probably more common than any other. Work in this area is still at an early stage and, although statistically based parametrizations have been incorporated into some models, there is still considerable uncertainty about how the cloud properties can best be described, how they are controlled and how the radiative fluxes respond. The degree to which cloud optical properties may be modified by aerosol is also a current active area of research.

Clouds containing ice present special problems. Our knowledge of the ways in which ice particles form and the many different possibilities for particle growth and interaction which accompany the appearance of the ice phase is still rudimentary. Results from Hercules flights have shown that ice multiplication processes which increase the numbers of ice particles by many hundreds of times are active in certain clouds where water and ice coexist. Such processes are potentially important for precipitation formation, but radiative transfer calculations are more difficult because information on phase, shape and possibly particle orientation is needed. Similar difficulties are encountered with cirrus cloud (which again has had little comprehensive observational study, despite its widespread global occurrence), its recognized importance to the global radiation balance and its effect on satellite data retrieval. The processes governing its formation and evolution and the properties of the clouds themselves are not well known, so forecasting cirrus and representing high cloud in numerical models remains uncertain. For these reasons, a number of observational studies of cirrus are currently under way or are being planned, including the possibility of mounting a future joint European study.

Continued progress towards improving the treatment of clouds and related processes in forecast models depends on advances being made in a number of interrelated areas, requiring a balance between observational and theoretical work. Detailed observational studies are necessary to increase our understanding of the fundamental processes governing the formation, evolution and eventual dispersal of clouds. This knowledge will allow better representations of clouds to be designed for use in numerical models and will permit model predictions to be tested. As models become more sophisticated, improved cloud forecasts will also require better initial input data. Remote-sensing methods appear to offer the only practical source of data, and here again the combination of field measurements and modelling, emphasizing the interaction between clouds and radiation, will be needed to develop the techniques of interpretation. Only through this close co-operation between observation and modelling can real progress be achieved.



Physical processes acting in the marine stratus layer



A typical, extensive cloud system investigated during FIRE. Measurements were made by five aircraft, six satellites and surface-based instrumentation on San Nicolas Island (•) which included two tethered balloons. (GOES image courtesy of Dr D.P. Wylie, University of Wisconsin)

Boundary-layer processes

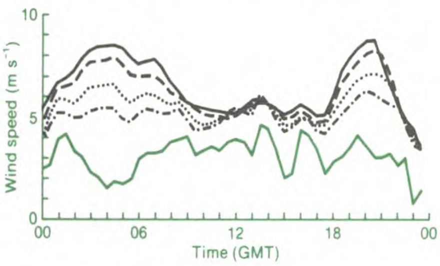
Air flow in the planetary boundary layer is turbulent, and this turbulence is driven by either the wind or buoyant convection, or both. Overland the depth of the boundary layer can vary from some tens of metres under clear skies at night to 1 or 2 kilometres during the day, and for various reasons an accurate description of its properties is required. Information on wind shears, wind gusts and the temperature and humidity structure of the layer has application to aviation, building, agriculture and radio signal propagation; a topic of particular importance is the dispersion of gaseous or particulate materials. In addition to these direct applications, numerical weather prediction models require a description of the gross transfer of heat, moisture and momentum within the layer. Much of our knowledge of the boundary layer is based purely on observations; this is in common with other disciplines concerned with turbulent flows. Theoretical descriptions of these complex flows are deficient but in general terms can be applied to everyday forecasting problems.

Special instruments are required to measure the transfer and dispersion properties at heights throughout the boundary layer. Production of a new system of balloon-borne turbulence probes which measures turbulence at heights up to 2 km has been completed and computer programs to process the resulting data thoroughly tested. This new system was used in the Isles of Scilly during the autumn as part of the Mesoscale Frontal Dynamics Project and provided details of the boundary-layer flow and structure near fronts. It was also used to investigate the processes leading to the entrainment of free atmospheric air into the maritime boundary layer, a key problem in forecasting low-level cloud over the sea.

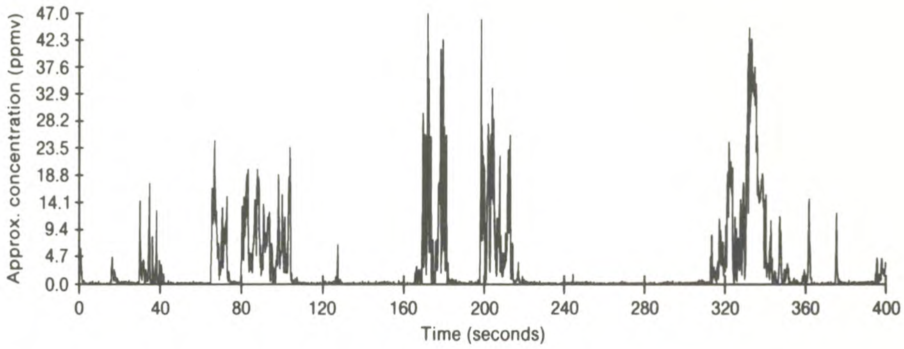
New instruments capable of near-continuous data recording were introduced at MRU Cardington. These include a commercial Doppler acoustic sounder that measures velocity at heights up to about 600 m and ultrasonic anemometers that give continuous measurements of boundary-layer fluxes at a height of 21 m. Data from these instruments are to be used to validate, and diagnose errors in, output from forecast models.

The development of instrumentation able to record concentrations of trace gas with a response time of 0.1 s has also been completed and preliminary statistical studies have been made of concentrations at distances up to 200 m from the source. The figure (top right) shows an example of the time variation of concentration measured during these studies.

There is much interest currently in flows in hilly and heterogeneous terrain and especially how such terrain should be represented in numerical forecast models. Earlier studies were entirely theoretical but now observations are allowing confident advances. The analysis of the data from a major field experiment conducted near Llanthony in the Black Mountains of South Wales during 1986 is almost complete. This study provided unique direct measurements of momentum transfer in the boundary layer over hilly terrain



Time series of wind speeds measured by Doppler acoustic sounder (black) and ultrasonic anemometer (green) at MRU Cardington. The heights at which the measurements were taken were: 180 m (solid line), 140 m (dashed line), 100 m (dotted line), 60 m (dot-dashed line) and 21 m (solid green line). These profiles illustrate the increased wind shear present in the more stable nocturnal boundary layer compared with the more constant wind speed with height present in the well mixed daytime boundary layer.



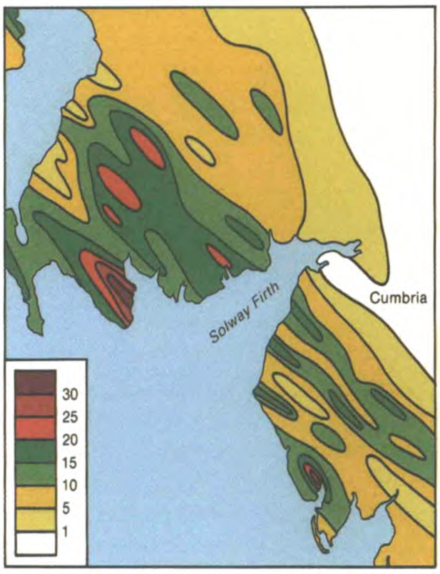
Time series of tracer gas concentrations recorded at 10 Hz (ppmv — parts per million by volume)

which show that under strong wind conditions the drag due to the hills is large (equivalent to a roughness length of 10 m). Complementary to this study, theories on areal average values of roughness length in heterogeneous terrain have been developed and tested.

Transport of pollution

When inflammable or toxic materials are released into the boundary layer the peak concentrations are likely to be important in determining the hazards. Even for averaging times of some tens of minutes, peak values of concentration may be an order of magnitude greater than the long-term means. To meet the critical need for forecasts of these fluctuations, observations and theoretical work have been undertaken. To help provide general forecast rules the so-called 'random walk models' which were developed previously for predicting mean concentrations have been extended to give predictions for concentration variability by considering the relative motion of pairs of fluid elements. Initial tests of the approach have been made against laboratory data in simple flows and the agreement between model and observations is encouraging.

In last year's Annual Report the consequences of the Chernobyl incident were discussed in some detail; they continue to be felt, with hill sheep still being contaminated by caesium-137 of Chernobyl origin. The Meteorological Office is collaborating with other organizations to develop a model that will predict the transport and deposition of radioactive debris. The model will use radiological and meteorological data; the latter include output from the fine-mesh numerical weather prediction model as well as surface and upper-air observations. In addition, output from weather radars in the United Kingdom and across Europe will be brought together to form a composite picture and be supported by surface rain-gauge data and satellite information to produce high-resolution rainfall fields. These fields will be vitally important in ascertaining where large amounts of radioactivity may have been, and are expected to be, deposited by precipitation. Measurements of the deposition of caesium-137 to the ground during the passage of the Chernobyl radioactive cloud, made by the Harwell Laboratory and by the University of Liverpool, confirm the efficiency of the wet deposition process. Washout factors inferred from these measurements were combined with estimates of dry deposition to give the total deposition of caesium-137 to the ground. The figure below shows the estimated total empirical depositions in the Solway Firth area, based on estimated airborne concentrations and rainfall data from surface gauges, resulting from the thundery storms at the time. Other forms of precipitation, such as that associated with fronts, may yield significantly different washout factors. A study of the comparable washout of airborne sulphate (inferred from measurements made in the European acid rain study) in different cloud conditions is being undertaken.



Detailed deposition of caesium-137 in kilobequerels per square metre after the Chernobyl incident, estimated from airborne concentrations and rain-gauge data

World climate

The climate system

The global climate is governed by complex interactions between the atmosphere, oceans, sea-ice and land surfaces. The interactions operate on a variety of time-scales determined by the properties of the various components. Thus, for example, changes in the deep ocean may take centuries or millenia to develop, while the large-scale atmospheric flow varies over time-scales of only a few days or so. Studies of the global climate are undertaken in order to understand the mechanisms underlying climate variations, which whether they occur as long-term transitions or as variability from year to year can, by shifting normal weather patterns, disrupt agriculture and fishing, and cause starvation, loss of life and damage to national economies. The time-scales of climatic variation can be seen in long observational records. For example, rainfall in the Sahel region of Africa during the last 20 years has been persistently lower than during the earlier part of the twentieth century and clearly indicates a major variation in climate at least. In contrast, the occurrence of 'El Ninõs' (see below) in the tropical Pacific every few years is an example of interannual variability.

There is much current interest in the possible impact on world climate of man-made pollutants. Changes in the concentrations of certain trace gases can lead to important modifications to the chemistry of the atmosphere and to alterations in the atmosphere's radiation balance. Of particular concern are the increases in the atmospheric concentration of carbon dioxide, brought about by the burning of fossil fuels; variations in ozone amounts in both the troposphere and stratosphere, brought about by catalytic photochemical reactions, on which there was a major international program in the Antarctic; and particulate pollutants left in the atmosphere as a consequence of nuclear war.

Interactions between the components of the climate system can be investigated in climate simulations by numerical climate models, and by careful analysis of observational records. Laboratory studies of rotating fluids can elucidate more fundamental aspects of climate dynamics. The numercial model of the complete atmosphere, ocean, sea-ice and land surface system is a major facility within the Office for studying the physics of climate and climate change.

Modelling physical processes

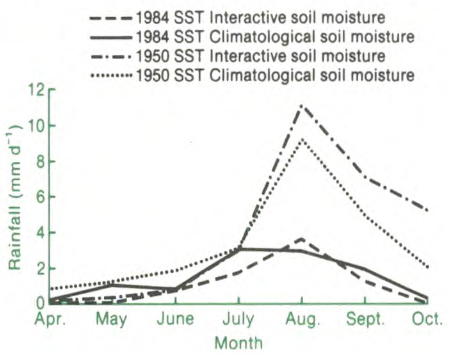
Improvements in the representation of layer cloud in the atmospheric model, important for the proper representation of the atmosphere's heat budget, are described in the section entitled 'Developments in forecasting'. Convective heat release is also important in this respect. A comparison of the model's convective scheme with observed data and with a more elaborate model of convection led to the development of improvements to the model's representation of convective downdraughts initiated by the evaporation of precipitation. Tests made after the improved scheme was introduced showed that the changes have a marked impact on the large-scale flow over the western Pacific in summer. This sensitivity appears to be associated with interactions between the convective scheme and the intra-seasonal oscillation in the model.

The modelled climate is also known to be sensitive to land surface processes. These can now be represented much more realistically than before. Geographic variability of parameters, which had been restricted to snow-free albedo, was extended to others, such as deep-snow albedo, fractional vegetative cover, average root depth and surface roughness. Preliminary studies after inclusion of the new variables showed a beneficial impact on the model's surface climate, with increased rainfall in tropical regions, faster spring snowmelt in mid latitudes and an increased diurnal range over hot deserts. Further improvements were also achieved by the inclusion of rapid evaporation of rainfall intercepted by vegetation. A simple representation of the insulating effects of snow gives surface temperatures that are more realistic in winter over northern continents and maintains slightly higher soil temperatures.

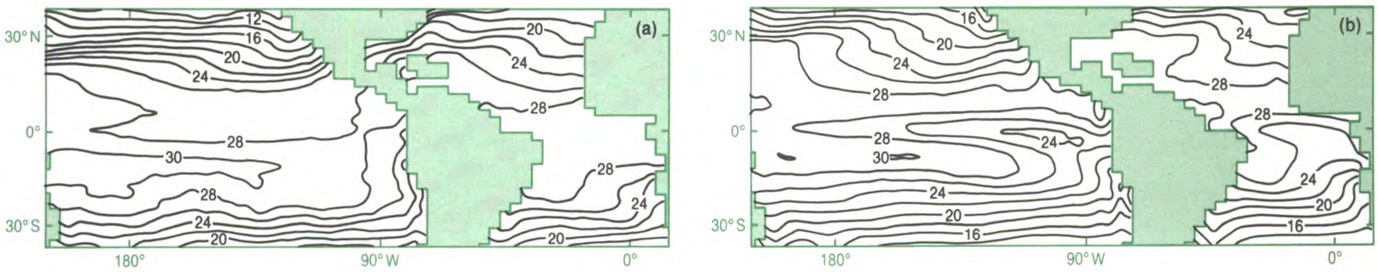
The significance of sea surface temperature (SST) anomalies to variations in the climate of the Sahel was investigated using the climate model. The model was run from April to October, with the SST fields for 1950, one of the wettest years in the Sahel, and then for 1984, one of the driest. Heavy rains were simulated in the Sahel in the first and drought conditions in the second. Further experiments comparing results using a moisture scheme that was either climatologically fixed or fully interactive indicated that the soil moisture feedback mechanism enhances the contrast between the 2 years, though the effect is only clear towards the end of the rainy season (see figure below).

From a statistical viewpoint, Sahel droughts tend to be associated with cold SST anomalies in the North Atlantic and western Pacific and warm anomalies in the South Atlantic, eastern Pacific and Indian Ocean. Numerical integrations with the climate model confirmed that the individual patterns for the three ocean basins each contributed but the effect of all three was greater than the sum of the individual effects.

The oceanic component of the coupled model requires a representation of run-off from the land because of its effect on salinity, particularly in the northern polar seas where salinity strongly affects the density structure and, through this, the sea-ice extent. The run-off from selected large basins was compared with observations and found to be in reasonable agreement, given realistic modelled rainfall. The inclusion of an explicit scheme for sea-ice is essential for representing the processes over the high-latitude oceans and the ice-albedo feedbacks, important for climate change.



Simulated time series of Sahel rainfall



SSTs (°C) for March (a) and June (b) as simulated in year 2 of a run of the coupled ocean–atmosphere model

An experiment which includes a representation of sea-ice thermodynamics in the coupled model, allowing the prediction of both the fractional cover and the thickness of ice over a grid square, has completed 2 years of simulation. The modelled sea-ice extents expand and contract with the seasons in a fairly realistic manner (see below) although too much ice is predicted, particularly for the summer.

Lateral mixing in the oceans is known to take place along surfaces of constant density. Using this, rather than horizontal mixing, leads to a marked improvement in the strength of the modelled Antarctic circumpolar current, primarily because the temperature structure (including the SST distribution) is more realistically modelled. Realistic representation of SSTs is essential for simulating the interaction of the ocean with the atmosphere correctly, especially in the tropics where SST anomalies have their maximum influence on the global atmosphere. Examination of the annual cycle of SSTs produced by the coupled model shows that the seasonal changes over the tropical Atlantic and Pacific Oceans are well reproduced (see above), though the warmest waters, for example those to the south of the equator in the Pacific, are rather too warm.

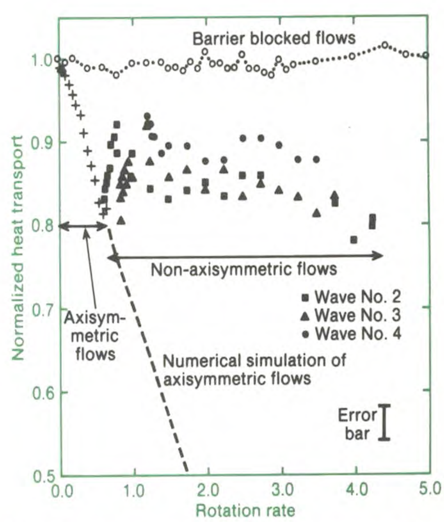
Heat transport in rotating fluid systems

The thermal structure of the atmosphere and oceans is determined by the total heat transported by large-scale motions. This is therefore a key factor in understanding climate. The magnitude of the heat transport is strongly influenced by many processes which are, as yet, poorly understood in detail. Certain aspects of the dependence of the total heat transport on factors such as system rotation rate and boundary conditions can, however, be studied to good effect in laboratory experiments on thermal convection in rotating fluids; reliable and accurate measurements of total heat transport can be obtained under highly controlled conditions.

The broad variation of the total heat transport on rotation rate, for example, is found to depend on the shape and, in particular, the topology of the boundaries of the system. Three general types of behaviour have been identified, each with its own dependence on rotation rate, and these are shown in the figure right; namely (a) the heat transport decreases quickly with increasing rotation rate (typical of purely axisymmetric flows), (b) the heat transport decreases with increasing rotation rate, but at a much slower rate (characteristic of flows exhibiting wave motion) and (c) the heat transport is virtually independent of rotation rate (typical of flows in a system where continuous zonal motion is completely blocked by a barrier). The earth's atmosphere is an example of the second type whereas the oceans in the northern hemisphere may approximate to the third type.

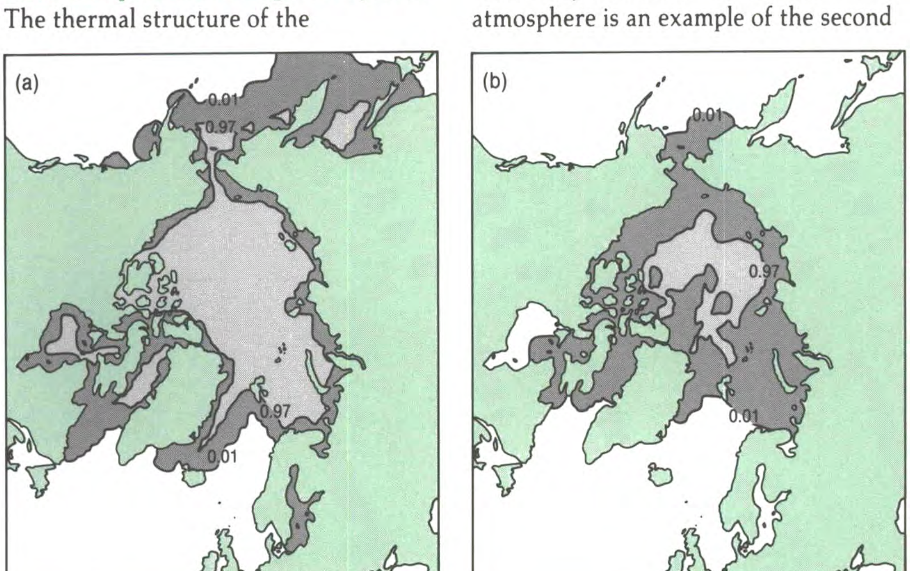
The middle atmosphere

The development of a numerical model of the middle atmosphere (the region above the tropopause and below 85 km) is being carried out collaboratively with the Department of Atmospheric Physics, University of Oxford, which is devising ways of representing the effects of radiation and gravity waves. Besides several short-period (20 days or so) integrations of the model to study sporadic phenomena such as sudden stratospheric warmings, an integration over a complete annual cycle has been completed; this successfully reproduced a number of observed features of seasonal changes in the middle atmosphere.



Dependence on rotation rate of the measured total heat transport for three laboratory flow systems

Observational studies of the middle atmosphere have been carried out using data from Stratospheric Sounding Units which were supplied by the Meteorological Office and flown on the US NOAA (National Oceanographic and Atmospheric Administration) series of satellites. Daily global synoptic maps over a period of 9 years are now available for various levels in the stratosphere. Attention is being given to the dynamics of the southern hemisphere circulation and its contrasts and similarities with the northern hemisphere. This is directly relevant to



Arctic sea-ice concentrations (tenths) for February (a) and September (b) as simulated in year 2 of a run of the coupled ocean–atmosphere model the understanding of middle atmospheric processes as a whole, including changes to the photochemistry brought about by the presence of pollutants and the consequences of these for the maintenance or depletion of the ozone layer.

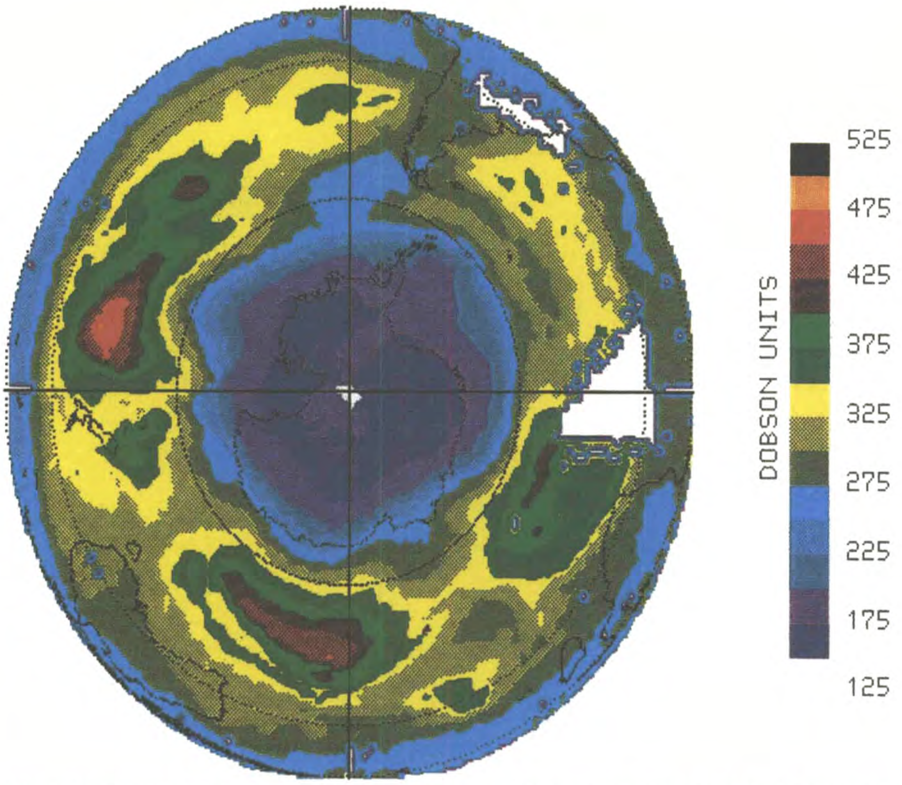
Atmospheric chemistry

Stratospheric chemistry and the ozone hole

Under the auspices of the World Meteorological Organization, the Office is actively involved in monitoring ozone. It maintains observing stations at Bracknell, Lerwick and St Helena, and provides assistance for several others that use Dobson spectrophotometers to measure the total column atmospheric ozone. Ozone, most of which is in a layer between 10 and 50 km, is an important absorber of solar radiation at wavelengths shorter than 310 nm, thereby heating the upper atmosphere and protecting the earth's surface from damaging ultraviolet radiation.

In recent years a rapid decline has been noted in observed ozone concentrations over Antarctica in the early spring, followed by a recovery to normal levels a few months later. The most recent observations indicate that the spring reduction has become more intense; in 1987 a 50% reduction from normal in column-ozone was observed. The phenomenon is so striking that it is often referred to as the 'ozone hole' in both the scientific and the popular Press. Although numerical models contain the mechanisms for predicting changes in the distribution of ozone caused by anthropogenic emissions of chlorofluorocarbons and other source gases, this rapid decline was not foreseen and much effort is now being devoted to understanding its cause and the global implications. Hypotheses vary from the purely dynamical, such as the upwelling of ozone-deficient tropospheric air, to the entirely chemical, such as the depletion of ozone by anthropogenic chlorine and bromine compounds. A major shortcoming in the investigations of the phenomenon has been the absence of sufficiently comprehensive chemical and meteorological measurements.

During the southern hemisphere spring of 1987, the ozone depletion was the largest yet detected by the Total Ozone Mapping Spectrometer instrument on the Nimbus 7 satellite (first launched in October 1978). An initially gradual decline during September became rapid with the appearance of regions of exceptionally low column-ozone on the periphery of the polar vortex, co-located with deep surface depressions in the circumpolar trough, which then spread to occupy an area centred on the South Pole.



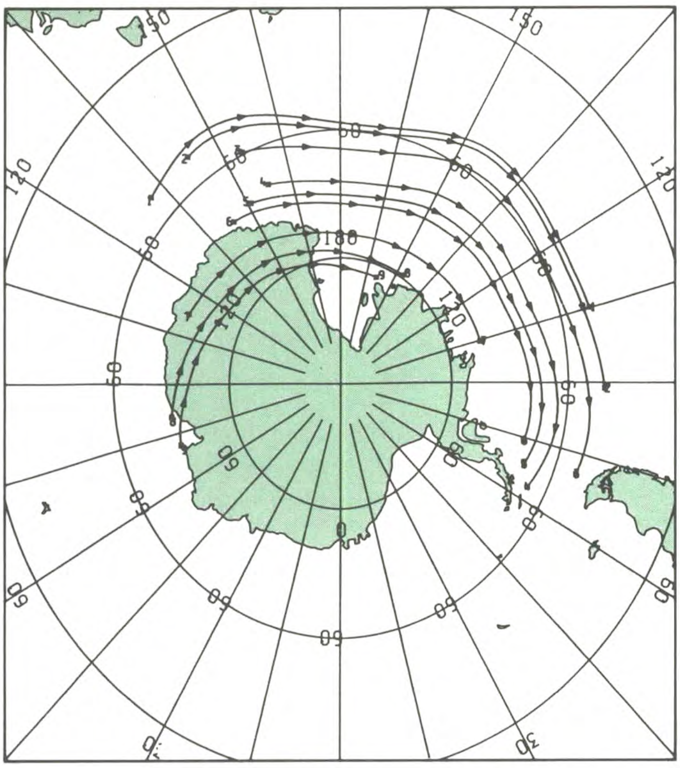
False-colour image of the column-ozone distribution over the southern hemisphere for 24 September 1987 measured by the Total Ozone Mapping Spectrometer instrument on the Nimbus 7 satellite. (By courtesy of Dr A.J. Krueger, Goddard Space Flight Center) The uncoloured regions denote areas where data were unavailable. Exceedingly low column values (150–175 Dobson units) are visible in the centre of the vortex.

The Airborne Antarctic Ozone Experiment

In August and September the Office participated in the Airborne Antarctic Ozone Experiment based at Punta Arenas, Chile. During a 6-week period, two aircraft (a high-altitude reconnaissance ER 2 and a research DC 8) operated by the National Aeronautics and Space Administration (NASA) made several flights into the ozone-depleted region. The aircraft carried a variety of instruments for measuring the concentrations of gases thought to be directly involved in ozone photochemistry and of other more inert tracer gases which could be used to identify the source of the air. Meteorological variables were also measured.

Throughout the experiment the Office was closely involved in the scientific planning for the flights and with the interpretation of the measurements made. The Office also provided the local

An ER 2 pilot being briefed at Punta Arenas (Photograph by courtesy of Mr P.R.S. Salter)

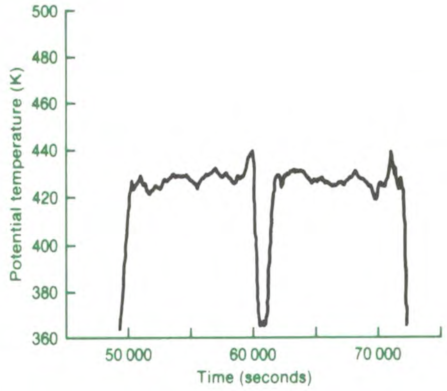


48-hour forecasts made at 1200 GMT on 2 September 1987 of air masses first encountered 3 days earlier by the ER 2 on 30 August 1987. Arrowheads are marked every 6 hours. The trajectories follow the 428 K isentropic surface and were calculated from wind fields predicted by the global model. The forecast shows the air masses coming within range (about 70°W) late on 4 September. The ER 2 flew on that date.

and regional forecasts necessary for flight planning. Numerical guidance was provided by the operational global forecast model and an experimental regional version of the fine-mesh model. Analyses and forecasts of winds and temperatures up to 30 mb were sent to Punta Arenas twice daily in chart form from Bracknell via a dedicated telecommunication network. Two Office forecasters, detached to Punta Arenas, used this information to provide meteorological guidance, which, in view of the extreme operating conditions for the aircraft, proved invaluable. Wind and temperature observations from both aircraft were sent in real time to Bracknell for inclusion in the numerical forecast runs.

A technique has been developed to compute air-mass trajectories from numerical forecast model velocity fields. This technique was used to predict the subsequent positions of air masses sampled by the ER 2 on each flight. Up to 48 hours' warning was given of when the air masses were expected to cross the flight track; this allowed the air masses to be re-encountered by the aircraft. Sampling the same air mass on several occasions facilitated the identification of chemical changes. A second important aspect of the scientific forecasting was the prediction of pressure altitudes of isentropic surfaces. These allowed the ER 2 to adjust its flight path to be along isentropic surfaces, rather than on the constant pressure surfaces usually flown by aircraft. Since large-scale air flow is approximately along isentropic surfaces this facilitated the scientific interpretation of measurements.

In collaboration with NASA and NOAA the Office is contributing to the study and interpretation of the chemical observations made from the ER 2. A numerical model has been developed that calculates the evolution of different chemical species within a parcel of air as it follows a trajectory computed from wind fields derived from the numerical analyses and forecasts. In one version of this model nitric acid is removed from the air after condensation to simulate gravitational settling after adsorption on to particles. Preliminary results suggest that in the cold temperatures found in the vortex only small amounts of nitric acid will remain in the vapour phase. Once the amount of nitric acid is reduced, the results from the model, which assumes currently accepted chemical reaction rates, show significant ozone depletion.

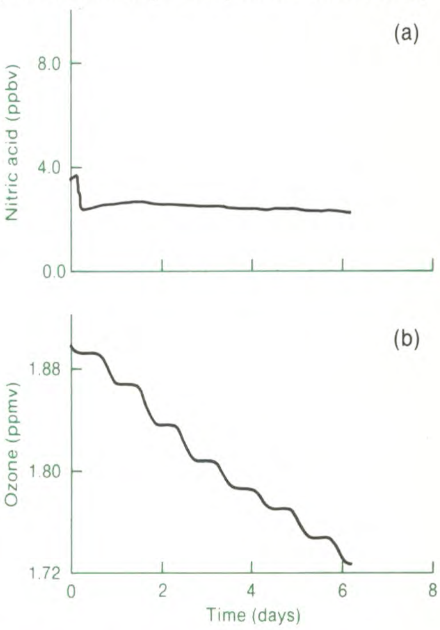


Potential temperatures computed from *in situ* pressure and temperature measurements made during the ER 2 flight along a predicted isentropic surface on 30 August 1987. The dip at 61 000 seconds was a profile at the southernmost latitude (72°S) designed to sample vertical structure. The ascent from and descent into Punta Arenas are also visible. Flying on the isentropic surface required ascending from about 70 mb at 55°S to about 50 mb at 72°S.

Tropospheric chemistry

Photochemical reactions in the troposphere are initiated by the photolysis of ozone molecules. The ozone is either produced *in situ* by chemical processes or it has its source in the incursion of ozone-rich stratospheric air across the tropopause. As hydrocarbons and nitrogen oxides injected into the troposphere (primarily as a consequence of man's activities) are involved in the chemical reaction chains that catalytically create or destroy ozone, a detailed quantitative understanding of the chemical processes involved in the ozone balance is necessary if pollution-control measures are to be effective.

Research on ozone photochemistry is being undertaken using chemical-sampling instruments on board the Hercules aircraft of the Meteorological Research Flight. In collaboration with scientists at the Kern Forschung Anlage at Julich in the Federal Republic of Germany, detectors for nitric oxide, total reactive nitrogen, and carbon monoxide are shortly to be installed; these are in addition to the detectors for peroxyacetyl nitrate, hydrocarbons, ozone and water vapour already available. Measurements from these instruments will be used to test hypotheses about tropospheric ozone photochemistry. To optimize such a test,



Calculations of chemical evolution from a photochemical model integrated along a 6-day trajectory in early September 1987 on the 428 K surface. The model was initialized with 8 parts per billion by volume (ppbv) of nitric acid in vapour form. Assuming saturation over particles containing equal amounts by weight of nitric acid and water, approximately 6 ppbv of nitric acid is condensed at the cold vortex temperatures and is removed from the model (a). In the low nitrogen oxide environment and with surface reactions releasing reactive chlorine from stable reservoirs, ozone is then destroyed at about 1.4% per day (b).

it is desirable to make measurements in the same air mass on successive occasions, several days apart; suitable meteorological conditions can be found in the relatively stagnant conditions in the centres of large slow-moving anticyclones such as the 'Azores high' Several experiments in this region are planned over the next 2 years.

Short-term climate variability

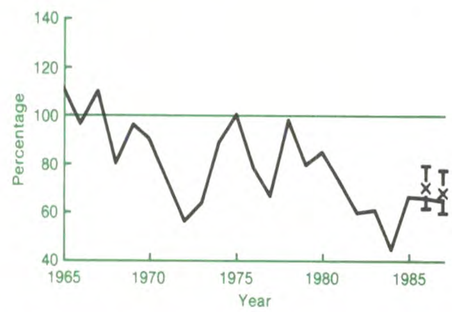
Year-to-year climate variability may arise from interaction between relatively short-period phenomena and the annual cycle. For example, it has been suggested that the date of onset of the Indian monsoon may be modulated by planetary-scale waves with a period of 30–50 days which propagate slowly west to east along the equator. However, the slowness of the wave propagation is difficult to explain theoretically. A simple model which assumes that the entire earth is covered by an ocean and that atmospheric motion is symmetric about the equator produces well-defined waves indicating that in the real world neither mountains nor longitudinal asymmetries are essential for their existence (see figure below). The period of the waves has been found to be approximately proportional to the static stability; in reality this is affected by the release of latent heat suggesting that the propagation speed is sensitive to cloud- and rain-producing processes.

Though variations of tropical rainfall are thought to be linked to 30–50 day period waves, they also appear to depend strongly on the distribution of SST. One of the clearest examples of this is the variation from normal of tropical Pacific SSTs during an event commonly referred to as the 'El Niño'. This year has seen the continuation of the El Niño which started in the late summer of 1986; SST anomalies of over 1 °C have been maintained over large areas throughout the subsequent 12 months (see bottom right). The timing of this event was unusual in that most El Niños develop in the northern spring.

A model which couples together the atmosphere and oceans has been designed to focus on the role of the tropical Pacific in the global climate system. A trial run of the model simulated an El Niño with accompanying atmospheric circulation changes (usually referred to as an El Niño–Southern Oscillation (ENSO)) which was similar in many respects to that which actually occurred in 1982–83, even though the initial state had not been specially primed. This result has directed attention to a number of interesting processes in the atmospheric model, such as the representation of evaporation in gusty convection regimes and the very important part played by the interaction of radiation and clouds in the ENSO evolution.

A highly simplified model with only a single active oceanic layer of varying depth is being used to investigate the effects of a variety of physical processes on the stability and interannual variability of the tropical ocean–atmosphere system. One use of this model is to study the conditions that are required for the slow growth of instabilities intrinsic to ocean–atmosphere coupling. Such instabilities may be characteristic of the initial development phase of an ENSO event; their growth could depend on factors such as interaction with the seasonal cycle and triggering by 30–50 day period waves.

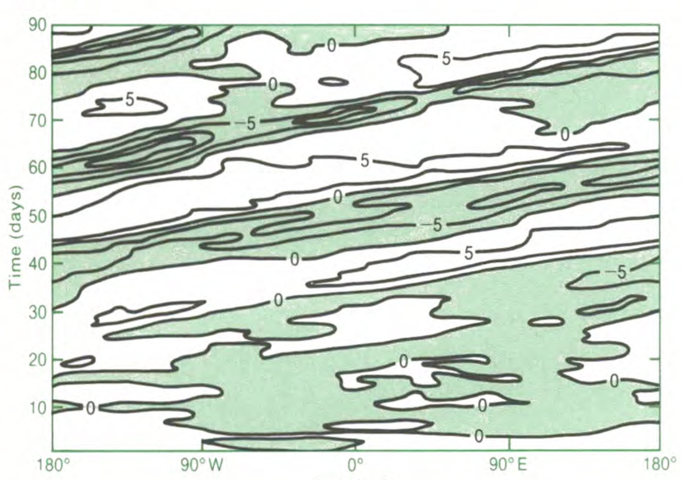
Statistically significant relationships have been established between rainfall in the Sahel and observed SST anomaly patterns in the months before the rainfall season. This has stimulated the development of two methods of predicting Sahel rainfall; one is a regression technique which provides a forecast of a specific rainfall value with an estimate of the expected margin of error, the other is a discriminant analysis technique which predicts the probablility that the rainfall amount will fall within one of a number of predefined ranges. A forecast for the 1987 rainfall season in the Sahel was sent to all Meteorological Services in Africa because the success of these techniques in 1986, when a forecast was also sent to them, led to requests for further forecasts. The 1987 forecast again proved accurate, the prediction that the rainfall would be about 69% of the 1951–80 normal comparing with an observed value of 65%. The applicability of similar techniques to forecasting rainfall in Kenya and Brazil is being assessed.



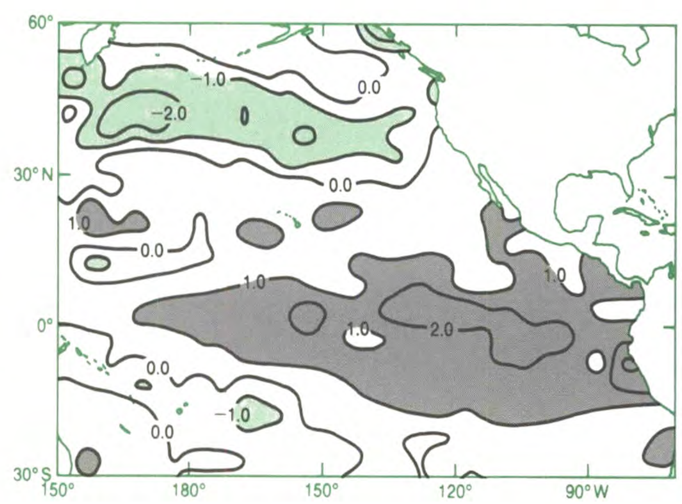
Observed Sahel seasonal rainfall as a percentage of the 1951–80 normal, and forecasts for 1986 and 1987 with 50% probability ranges

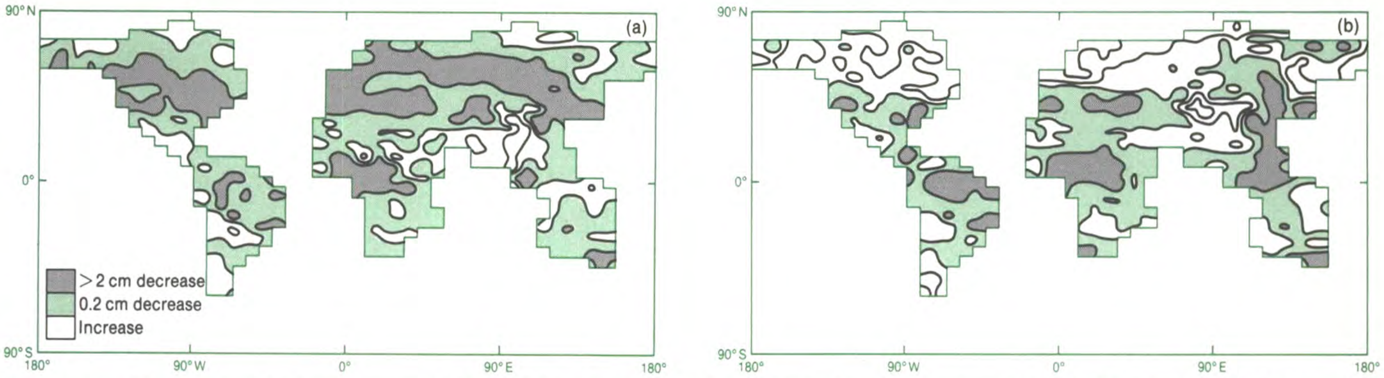
The atmosphere may also be affected on relatively short time-scales by man. There has been speculation that smoke from the fires after an extensive nuclear conflict might lead to drastic changes in climate, such as large reductions in surface temperature, because little solar radiation would be able to penetrate the smoke pall. The Meteorological Office model indicates a cooling of a similar magnitude to that predicted by other climate models when the same assumptions about a heavy smoke cover are made. However, experiments with successively smaller quantities of smoke show that, when there is sufficient radiative penetration, the effect is no longer to cool the surface but to warm

Waves in the aqua planet model as shown by the 150 mb velocity potential ($m^2 s^{-1}$)



SST anomalies (°C) for September 1987, based on 1951–80 normals





Soil moisture difference (cm) for June–August with doubled CO_2. In (a) snowmelt is added to the soil moisture and in (b) is allowed to run off the ground.

it. Further experiments demonstrated that the neglect, in some published work, of ground heat storage and of the effects of atmospheric stability produces large, though approximately compensating, errors. These results emphasize the need to include all relevant physical processes in 'nuclear winter' experiments.

Climate change

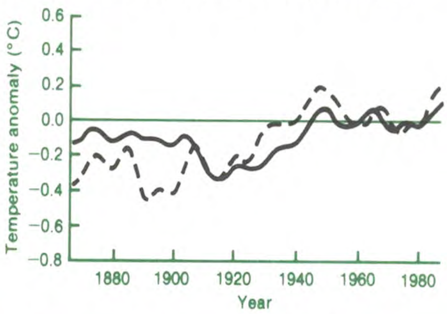
The causes of spatial variations in SST changes such as those associated with the Sahel drought are not clear; possibly they have no external cause but are internal variations of the climate system. Assessment of trends is an important part of climate monitoring; an upward trend in globally averaged temperatures could be the first sign of a climate shift, perhaps due to increases of radiatively active trace gases in the atmosphere. Assessments have been made using ocean temperatures from the Meteorological Office Historical Sea Surface Temperature Data set and land temperatures from a data set covering a similar period compiled by the Climate Research Unit of the University of East Anglia. Both these sources of data contain inhomogeneities which must be eliminated if climate trends are to be accurately estimated. The most recent work, on the estimation and correction of the errors in SST records from before World War II when the buckets used from ships were uninsulated and thus subject to considerable evaporative cooling before the temperatures could be measured, indicates that the corrections are not sensitive to the exact type of bucket nor to the environmental conditions. If these results are confirmed, then it may be possible to put greater reliance on the estimation of climatic variations on regional and global scales.

Up to the 1940s, the globally averaged SST rose by about 0.4 °C from a minimum in the first decade of the century (since then, there have been fluctuations on shorter time-scales). This trend is generally consistent with estimates deduced from the land surface observations. However, in the second half of the nineteenth century the two sources of data show different trends and, in the decade 1881–90, differ relative to present-day climatology in the northern hemisphere by about 0.3 °C. Some of this difference is attributable to the paucity of land data in the tropics and to the dominant influence of land masses north of 60°N, which were particularly cold at the time.

Effects of greenhouse gases

The climatic consequences of increases in carbon dioxide (CO_2), caused mainly by the burning of fossil fuels, are thought likely to be compounded by those due to increases in other radiatively active trace gases, for example methane, nitrous oxide and chlorocarbons. It is considered that the climatic effects of these latter gases will be comparable to those of CO_2 within the next few decades. One of the main uncertainties is the extent of any amplification or damping of the responses by feedbacks within the climate system, for example through changes in water vapour (the major 'greenhouse' gas) and in the role of clouds.

Variations in snow and ice extent, which alter the reflectivity of the earth, provide a positive feedback, i.e. increase the warming due to greenhouse gases. A comparison was made between two experiments where the amount of CO_2 was doubled; in one, sea-ice was allowed to respond to the change in climate predicted by the model and in the other the present-day sea-ice was prescribed.



Global SST anomalies (solid line) and land surface air temperature anomalies (dashed line), based on 1951–80 normals

The global mean warming was reduced by 20% when the feedback between the sea-ice extent and temperature was removed. Studies carried out elsewhere have obtained substantially different estimates of the size of this feedback; the results show that these differences may be due in part to differences in assessment method.

An important question in the context of trace gases is — 'what are the expected regional changes?'. The difficulty in answering this question is illustrated by the sensitivity of simulations to the representation of land surface processes. One of the important findings is that, because of increased evaporation, northern extratropical continents might become drier in summer, with potentially serious consequences for agriculture as greenhouse gases increase. It has been demonstrated that the magnitude of the simulated drying is dependent on the assumed properties of the soil. Furthermore, when the model is altered so that snowmelt runs off directly over frozen ground, as opposed to being absorbed in the soil, high latitudes become wetter as CO_2 increases (see figures above). This is because, in the original experiment, spring snowmelt was allowed to saturate the ground so that the model's memory of the greater autumn precipitation that occurs with increased CO_2 was erased.

Training and career planning

A career in the Meteorological Office

Staff are recruited into the Meteorological Office under regulations laid down by the Civil Service Commission. Whilst the recruitment procedure inevitably places individuals in one of a number of job categories, the broad range of work undertaken within the Meteorological Office provides scope for widely differing career paths. Opportunities exist for specializing in particular aspects of the work or for moving from one area of expertise to another, depending on the needs of the Office and on the preference and skills of the individual. Training in basic meteorology, observing methods, weather forecasting, atmospheric science, technical skills, computer programming, management, marketing and other topics is provided at suitable points during a career. Promotions, which are based on recommendations in Annual Staff Reports by line managers and (usually) competitive interviews by promotion boards, depend on merit and on the ability to fill positions that are more responsible. Careers for most staff are overseen by either the Main Career Development Panel or the Personnel Management Branch, while those of others are supervised by appropriate career management sections within the Ministry of Defence.

It would be misleading to discuss the concept of an average career path for an individual recruited with a given level of qualifications. A better feel for the sorts of career that are followed within the Office is gained from consideration of the actual progress of specific individuals. To aid comparisons, the following illustrative examples are restricted to the careers of individuals who are currently at Grade 7, although it should be borne in mind that not all staff reach this grade and some rise to higher levels.

Bert Foord

'As a young school-leaver just after the War, I started my career as what is now called an Assistant Scientific Officer. I worked in the Meteorological Office at Prestwick, a very busy forecasting office where all the transatlantic aircraft started from in those days. National Service was spent on a radiosonde station, sending instrumented balloons into the upper atmosphere. This was followed by 3 years at Eskdalemuir Observatory in southern Scotland working on climate and magnetism.

I then volunteered for 3 years on Ocean Weather Ships in the North Atlantic, sailing from the Clyde to stations as far apart as the Denmark Strait near Greenland and the Bay of Biscay. Then, after my Initial Forecasting Course, I spent 4 years forecasting at various RAF stations.

By this time the Weather Centres were about to open and I helped to start offices at Glasgow and Manchester before moving to London, where I spent 13 years dealing with the Press and public, including what turned out to be thousands of radio and television broadcasts. By this stage of my career I had progressed to the grade of Higher Scientific Officer. After further promotion and a Tropical Meteorology Course I went to Gan in the Maldive Islands for a year and then closed that office when the RAF withdrew from

east of Suez. A period at Heathrow in civil aviation, where Concorde forecasts were just starting, was followed by 5 years in charge of different stations in Germany. Promotion to Grade 7 brought me back home where I am now a Senior Forecaster at the Principal Forecasting Office for Defence Services, providing forecasts for military aircraft flying as far afield as California and the Arabian Gulf.'

Brian Golding

'I was an amateur weather observer from an early age and spent a summer in the Office's Geophysical Fluid Dynamics Laboratory whilst pursuing a mathematics degree in which I specialized in fluid mechanics and numerical analysis. I joined the Office in 1973 and after a month at Thorney Island did the Scientific Officers' Course at the Meteorological Office College at Shinfield Park. After that I came to Headquarters where I worked on improvements to the initialization of the 10-level numerical weather prediction model, gaining promotion in 1975 to Higher Scientific Officer. My work on the model, plus my previous 'vacation student work', provided a platform for a research degree in conjunction with the University of Reading and the award of a PhD in 1981. Meanwhile my work changed dramatically in 1976 when I got involved in wave modelling after a request from the London Weather Centre for numerical guidance on sea

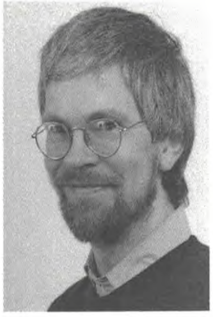
The Lodge, Shinfield Park, houses many recreational and social amenities

state. This led to contact with several organizations, to attendance at international conferences, and eventually to marketing archived forecast products. In 1977 I gained promotion to Senior Scientific Officer.

Following implementation of the wave forecasting system I was attached to the Central Forecasting Office for 18 months' forecasting experience — valuable preparation for my move to Forecasting Research in 1981 on promotion to Grade 7. The need for new observing techniques, the ability to model small-scale physical processes and the interaction between man and machine has brought me into contact with many parts of the Office. Here, as leader of the group developing the mesoscale model, I have returned to the challenge of trying to predict numerically the weather that the observer will see.'

Chris Little

'I joined the Office in 1972 and initially worked in a small team responsible for implementing a new computer-based analysis scheme. During this time I also attended the Scientific Officers' Course to learn meteorology (my degrees were in maths and general relativity). My first promotion, to Higher Scientific Officer, followed shortly afterwards in 1974. After the analysis scheme became operational I successfully applied for a 3-year secondment to the European Centre for Medium-range Weather Forecasts (ECMWF) in 1976. There I was again involved in developing and implementing a new operational analysis



system. Though this used different mathematical methods, the practical problems were similar. Work at ECMWF was demanding and stimulating, and gave me a different, fresh, perspective on the Office and its work. On my return to the Office I implemented some of these new analysis techniques on the recently acquired supercomputer, a Cyber 205.

I was soon keen to do something else, and so I investigated the use of computer graphics for the Office's mesoscale research model. This, and my wider interest in the issues raised by software development, led me to transfer to the Data Processing Branch of the Office where I took charge of the Programming Techniques and Training Team. By this time I was a Senior Scientific Officer, having gained my second promotion in 1981.

Promotion to Grade 7 in 1985 brought wider responsibilities, notably for the Synoptic Data Bank and computer graphics as well as computer programming techniques and training. Responsibility for the teams has now altered the emphasis of my work to a more managerial, planning, role. I joined the Office partly by accident rather than design, but have stayed because the work has been varied, stimulating, rewarding, and even exciting.'

Marjory Roy

'My interest in meteorology developed whilst I was studying physics at the University of Edinburgh, when I took the optional course provided by the Department of Meteorology as part of the final honours syllabus. After graduating I spent a further year preparing an MSc dissertation on atmospheric ozone — a subject that is still of major interest and controversy — before being offered an appointment in the Meteorological Office as a Scientific Officer.

Before attending the Scientific Officers' Course, I had about 10 months in the Long-range Forecasting Branch, where I learnt not only the difficulties involved in long-range prediction, but also how to program and operate the Ferranti Mercury computer which the Office had at the time. Having been trained I spent 4 years in forecasting, the first of these at the Main Meteorological Office at Preston. This was very valuable experience as I had to deal with all types of forecasts and, after a short apprenticeship, take responsibility as senior duty forecaster, Northern Region. Later, while working at High Wycombe, I was promoted to Senior Scientific Officer.

For most of the rest of my career I have worked in agricultural meteorology and climatological services. The former involved working closely with agricultural specialists and advisers, and 4 years spent on secondment at the Grassland Research Insitute later proved invaluable in my work in the Agricultural Meteorology Branch. Promotion to Grade 7 came in 1974, and since 1981 I have been Superintendent of the Climatological Office in Edinburgh, a post which also carries wider responsibilities as the Director-General's representative in Scotland.'

Professional training

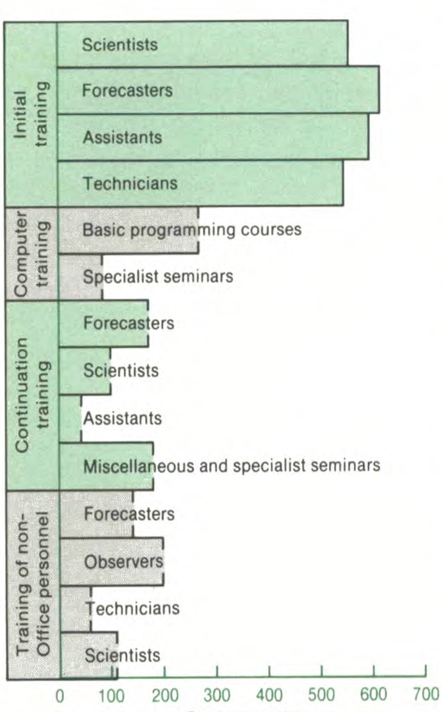
Training, in its broadest sense, extends throughout an individual's career in the Office. It consists of a mix of formal courses of instruction on particular topics, less-formal colloquia and other discussion meetings, and the learning of skills 'on the job'. The Meteorological Office College at Shinfield Park, Reading provides the venue for most of the professional training courses*, though for some specialized topics (management and commercial skills are two examples) recourse is made either to established outside institutes, such as the Civil Service College, Sunningdale, or to commercial teaching organizations. Appropriately qualified staff may embark on fully funded external education at technical colleges or universities, or they may read for higher degrees while employed at the Office. Others may obtain financial support for day release or Open University courses. One of the largest training requirements is for newly recruited Assistant Scientific Officers (ASOs) or Scientific Officers (SOs). Depending on academic qualifications and initial posts within the Office, these staff attend an appropriate induction training course. The lengths of such courses range from 6 weeks to 5 months. However, the continuation of staff training is also regarded as very important. The basic strategy is to provide some form of College-based training for the majority of scientific staff at appropriate intervals. This is achieved by various courses, typically about 3 weeks long, undertaken by staff at particular stages in their career. It is an essential element in the maintenance and development of skills demanded by the ever-changing needs of the Office.

*Details are available from: The Principal, Meteorological Office College, Shinfield Park, Reading RG12 9AU.

The newly refurbished squash court at the College

The Meteorological Office College offers residential training facilities for just over 100 students at any one time. With a complement of 17 instructors and 10 support staff, the College runs some 26 different courses which vary in length from a few days to several months and which span a wide variety of needs from short courses for non-scientific staff to intensive induction courses for newly recruited graduates with good honours degrees. Instructors are staff members drawn from a cross-section of the Office — forecasters, supervisors, support scientists and researchers. Typically they spend about 4 years teaching at the College and then move back into mainstream activities within the Office. A turnover of staff on this sort of time-scale ensures that the background knowledge of the instructors is up to date and relevant to current needs. It does, however, require a program of training in teaching skills for the instructors themselves and the Civil Service College provides one source of such training. Additionally this year a course in teaching techniques was provided by the Academic Support Centre of the University of Reading.

The overall requirements for training within the Office are kept under review by the Training Board. Developments and changes in the nature of the work undertaken inevitably lead to demands for new or modified training programs. Recent examples of this are the increasing emphasis now placed on commercial activities, the expanding use of microcomputers and word-processors and the changing role of forecasters, especially at outstations. Training in commercial skills has now begun for appropriate staff, with the assistance of external consultants John Wilmshurst Marketing Consultants Ltd; over the next 2 years it is anticipated that some hundreds of forecasting and support staff will be trained. Courses in microcomputers and word-processors are also being given. Some of this instruction is being given on site at the offices concerned, rather than centrally at the Meteorological Office College. Again some hundreds of staff are involved. It is generally recognized that the role of the forecaster is changing as a result of additional customer requirements, substantial improvements in the accuracy of numerical weather forecasts and the availability at outstations of new technology. To ensure that the future training of forecasters matches the changing needs, the Training Board has initiated a thorough reassessment of forecaster training requirements.



Student weeks of training at the College during 1987

In addition to the formal courses of instruction, less-formal colloquia, summer schools and workshops are important features of the Office's overall training policy. They take various forms and are aimed at particular categories of staff.

Colloquia

Outstations staff colloquia are designed primarily for outstation forecasters, with the purpose of providing not only up-to-date information on new and relevant developments but also a forum for discussion of future plans. Each colloquium lasts 1½ days, and brings together about 40 outstation staff. Four colloquia, with a common program, are run each year, and in this way within a period of 3 years the majority of outstation forecasters take part in this training program, which is completely revised every third year. Topics being addressed in the current series include the Weather Information System, chemical and nuclear emergencies, commercial activities, the development of advisory services and the interpretation of satellite products.

The Conference of Chief and Principal Meteorological Officers, as its title implies, is attended by the heads of the Office's major outstations, both in the United Kingdom and overseas. Held annually and lasting 2 days, it is a means of providing the latest information on new developments, and a forum for discussion of policy and plans. At this year's conference, held in January, the Director-General looked to the next 10 years in the Office. Other topics on the agenda included future plans for the Central Forecasting Office, developments in marketing, communications, and services in the Defence area.

To meet part of the training needs of the large number of meteorologists and staff based at Bracknell there is a program of in-house colloquia, typically single lectures on specific topics with discussions, and lectures by visiting scientists. In 1987 approximately 30 such lectures were given, with speakers being drawn from both research and services Branches, and also from beyond the Office. The diversity of topics covered reflects the wide range of activities undertaken by the Office; a small sample of these topics is sufficient illustration — numerical simulation of the El Niño, measurement from space of precipitation, forecasting radio ducts, services to the media, and data assimilation in wave prediction models.

Speakers from several of the world's leading meteorological research centres gave lectures on a diversity of topics. A distinguished speaker, who attracted an over-capacity audience, was Sir Hermann Bondi, KCB, FRS, of Churchill College, Cambridge. His chosen subject was 'Energy'.

Meteorological Office Summer School

The second Meteorological Office Summer School was held at the College from 6 to 10 July (the first was in 1985). These Summer Schools bring together practising forecasters and active research workers, from both within and beyond the Office, to address a subject of mutual interest. The topic chosen for this year's School was 'Diagnosis of Numerical Weather Prediction Products'. It was jointly organized by the Office, the University of Reading and ECMWF, and had the same distinctive format as that established in 1985 — morning lectures complemented by afternoon practical work where small working groups looked at case-study material that co-ordinated with the lectures. The subject of numerical weather prediction usage and interpretation is a very topical one and the School attracted some 60 participants, including researchers and forecasters from within the Office, and representatives from several UK universities and from some of the European Meteorological Services.

Workshop on Satellite and Radar Imagery Interpretation

The Workshop on Satellite and Radar Imagery Interpretation addressed a subject of direct interest to forecasters. Held at the College from 20 to 24 July, the Workshop was convened with the main aim of providing a forum where leading research workers in the field of imagery interpretation could present current work to an audience of forecasters and researchers. A total of 75 participants from 22 countries took part in what proved to be a highly successful meeting. There were six speakers from the Office and others invited from the USA, Canada and Europe. The four major topics were: mid-latitude frontal systems and cyclogenisis, mesoscale convective systems, the application of imagery in combination with numerical model products, and the potential of using a combination of AVHRR channels. Informal working group sessions focused attention on three major areas of imagery interpretation of particular relevance to the practising forecaster. The first of these areas was that of conceptual models — imagery interpretation is helped if the forecaster has such models to provide a basic framework. The second area was training — a need for a basic manual covering the principles of imagery interpretation was recognized. The third was concerned with the methods of handling data with particular concern for the volumes of data involved, and the best ways of presenting such information to the user; both aspects pose challenging problems in which appreciable effort and progress are likely to be seen in the next few years. It was clear that the Workshop fulfilled a useful role in bringing together complementary work from both sides of the Atlantic. It was also clear that further collaboration would be highly desirable, and to that end two further Workshops are planned.

World Meteorological Organization Symposium

As part of the World Meteorological Organization's (WMO's) Education and Training Programme, the Office hosted a Symposium in July at which 147 participants from 62 countries spent a week discussing how potential users of meteorological information, products and skills might be taught and encouraged to obtain maximum benefit from them. The underlying motive was to strengthen the ability of the world's Meteorological Services to help improve the economy of their countries. Participants were welcomed by the Honourable Timothy Sainsbury MP, Under Secretary of State for Defence Procurement, and the Symposium was formally declared open by the Secretary-General of WMO, Dr G.O.P. Obasi. The Office provided the UK member of the International Organizing Committee and the Director of the Symposium.

The Director-General presented a keynote paper on 'Economic and other benefits of meteorological and hydrological services' and five other members of the staff of the Office presented invited papers. In total, 47 papers were presented by speakers from 20 countries and 3 agencies of the United Nations. They spoke on a wide range of ways — and fields of human endeavour — in which meteorological data and knowledge may be applied and how its users, by encouragement and through teaching, could benefit from them. Topics included: how to design an organization to meet a customer's needs for meteorology; the use of meteorology in economizing on the use of fuel and other natural sources of energy; meteorological effects on human health, tourism and sport; crop forecasting for food security; transport by air, land and water; water resources; and many more. Study visits were made to ECMWF, the Meteorological Office College, the Office's operational wing at Bracknell and the nearby experimental site at Beaufort Park, the Thames Barrier at Woolwich, the University of Reading and the Institute of Hydrology.

In conjunction with the Symposium, which met in the lecture theatre of ECMWF, the Office sponsored a 2-day exhibition of meteorological equipment and services in the grounds of the Meteorological Office College close by. Run for the Office by Mack-Brooks International Conferences Ltd, and known as METEX '87, the exhibition attracted 46 exhibitors from the United Kingdom, the Federal Republic of Germany, Norway and the USA. The exhibition was visited by almost all the participants in the Symposium as well as hundreds of other visitors with specialist interests.

French students who visited the College in November working with their UK contemporaries

International

Delegates at the WMO Education and Training Symposium

Since the invention of the electric telegraph, meteorology has been of daily operational use to the community only through continuous collaboration between National Meteorological Services (NMSs). Today, with world-wide communications, supercomputers, global models and global needs, collaboration is more detailed, more complex, more widespread and more necessary than ever before. A specialized agency of the United Nations, the World Meteorological Organization (WMO), provides the framework for this co-operation.

Through the Office, the United Kingdom supports many of WMO's programs and activities. It is a member of all the relevant constituent bodies and working groups of WMO, which make possible many essential basic functions, such as the exchange of observational data and of products from the supercomputers. In addition, some special activities were of note this year.

At the Tenth World Meteorological Congress in Geneva in May, the Director-General, Dr J. T. Houghton, was elected Third Vice-President of WMO. As principal delegate for the United Kingdom, at a time when the finances of bodies in the United Nations system were under heavy fire from several different directions, and as UK delegate on the newly established Financial Advisory Committee, he played a significant role in the very difficult negotiations which resulted in a budget being agreed for the period 1988–91. He subsequently attended a session of the WMO's Executive Council and the first meeting of the Organizing Committee for the Second World Climate Conference.

As part of WMO's Education and Training Programme, the Office hosted a Symposium at which 147 participants from 62 countries discussed how all potential users might make best use of meteorology.

In support of the Organization's Voluntary Cooperation Programme, the United Kingdom supplied a Plessey WF33 wind-finding radar to help re-establish Maun (Botswana) as an upper-air reporting station. Thirty precision aneroid barometers were supplied to Ghana, as were an electrical anemograph and electronic workshop equipment to the Caribbean Meteorological Organization. Under the WMO CLICOM Project, which helps NMSs to provide users with climatological information, the United Kingdom donated microcomputer-based systems to a number of countries, including Fiji, Liberia, Seychelles, Sierra Leone, Sudan and Vanuatu, as well as to the Caribbean Meteorological Institute. Fellowships were provided to NMSs so that their staff might follow courses at the Meteorological Office College and at other colleges and universities in the United Kingdom. Visits were made to Thailand and Zimbabwe to advise on the enhancement of data-processing facilities.

When a tropical cyclone caused extensive damage in Vanuatu, a modest cash donation and a technician were quickly provided to help re-establish the operational observing program.

The Office helped to support some participants in international meetings on: the usefulness of the products of models of the global atmosphere (Bangkok), significant weather elements (Toulouse), modern weather forecasting (Addis Ababa), building climatology (Moscow), mesoscale analysis and forecasting (Vancouver), the interpretation of satellite and radar imagery (Shinfield Park) and modelling ocean waves (Woods Hole, Massachusetts). The Marine Superintendent sometimes represented WMO at meetings of the International Maritime Organization.

Other senior staff of the Office continue to serve on a large number of international bodies including the WMO/United Nations Environment Programme Panel which monitors and models acid deposition in Europe, the Special Advisory Board for Scientific Policy of the International Union of Geodesy and Geophysics and bodies managing the North Atlantic Ocean Stations, the Operational World Weather Watch Systems Evaluations for the North Atlantic and for Africa, the Aircraft to Satellite Data Relay system and the Drifting Buoy Programme.

Co-operation continued with the Overseas Development Administration (ODA) towards supporting the African Centre of Meteorological Applications for Development (ACMAD). Ministers of the Economic Commission for Africa decided that ACMAD should be located at Niamey, Niger, where there is an existing regional centre for agriculture, hydrology and meteorology. Discussions continue on how best to ensure that meteorology is applied effectively in the social and economic development of Africa through ACMAD, through Drought Monitoring Centres elsewhere in the continent and in other ways. Towards the end of the year, the Office and ODA were discussing how their proposals might fit in with major new proposals of the World Bank.

Within Europe, co-operation continued: for example, on research and operational forecasting for the medium range (4 to 10 days) at the European Centre for Medium-range Weather Forecasts (ECMWF), Shinfield Park, Reading, on limited area modelling at the Meteorological Office College, and on the development and use of satellites for meteorology in the EUropean METeorological SATellite organization (EUMETSAT) headquarters at Darmstadt, Federal Republic of Germany. Dr A. J. Gadd continued as a member of ECMWF's Scientific Advisory Committee and the Office provided the UK representatives to ECMWF's Council and Finance and Technical Advisory Committees, as well as those to EUMETSAT's Council and its Committees. Dr J. T. Houghton is Chairman of the Earth Observation Advisory Committee of the European Space Agency and other members of the staff sit on several of that Agency's committees.

Interaction with the national infrastructure

The Meteorological Office interacts with the national infrastructure in many ways. In connection with its forecasting and advisory services it works closely with the Building Research Establishment of the Department of the Environment and the Agricultural Development and Advisory Service of the Ministry of Agriculture Fisheries and Food. There is liaison with the Departments of Transport, Energy, Health and Social Security, Trade and Industry, the Home Office, the Health and Safety Executive, the Central Office of Information, British Nuclear Fuels, the Civil Aviation Authority, the British Standards Institution and the Crown Prosecution Service.

Staff also serve on government interdepartmental committees and other bodies. Of particular interest in 1987 is the Meteorological Office involvement in the Interdepartmental Committee on Post-Chernobyl Activities, and its National Response Plan for overseas nuclear accidents. The Meteorological Office has a major role in this Plan in two areas; monitoring radioactivity levels in the atmosphere as part of a new UK network, and making predictions of the movement and deposition (both wet and dry) of radionuclides released to the atmosphere. The latter will involve the development of an operational numerical model designed for this purpose, in collaboration with scientists at Imperial College, the United Kingdom Atomic Energy Authority and the National Radiological Protection Board.

Examples of other interdepartmental committees and other government bodies on which Meteorological Office staff serve are the Physical Sciences Committee of the Chemical and Biological Defence Board, the Working Group on Atmospheric Dispersion Modelling of the National Radiological Protection Board, the Civil Aviation Research and Development Board, the Central Electricity Research Laboratory Advisory Panel on Environmental Research, the Interdepartmental Committee on Hydrology, the Department of the Environment/ Meteorological Office Stratospheric Ozone Review Group, the Department of the Environment Review Groups on Photochemical Oxidants and Acid Rain, and the Interdepartmental Committee on the Surface and Ground Water Archive.

The Office is closely involved in the promotion of meteorology through the Royal Meteorological Society: two Vice-Presidents, a Secretary and the Editor of the Quarterly Journal are all members of the staff.

The Office also interacts with other scientific communities through the Royal Society and its committees, the research councils and through contacts with the universities. Three members of staff, Drs J.T. Houghton, R. Hide and K.A. Browning, are Fellows of the Royal Society and several members of staff serve on its committees; Dr Browning is Deputy Chairman of the British National Committee for Geodesy and Geophysics and Chairman of its subcommittee on Meteorology and Atmospheric Physics. Other staff serve on the British National Committees on Problems of the Environment, Solar Terrestrial Physics, Space Research and the World Climate Research Programme.

Meteorological Office representatives serve on the Natural Environment Research Council, its Marine Science Committee, Services and Facilities Committee, Polar Science Committee and its Aquatic and Atmospheric Physical Sciences Grants Committee. The Director of Research is Chairman of the Meteorological Office/Research Councils' Committee on Climate. The Deputy Director for Computing is a member of the National Policy Committee for Advanced Research Computing which advises the Computer Board and the Research Councils on strategy for deploying all types of computers, including those of unusual design. Staff also serve on the United Kingdom Coordination Committee for the World Ocean Circulation Experiment and the Steering Committee on Hydrological Applications of Weather Radar.

The Director-General is a member of the Management Board of the British National Space Centre and is Chairman of its Earth Observation Programme Board. The Office is also formally represented on this latter Board and members of staff serve on a number of committees and working groups.

The Director-General (right) at the Tenth World Meteorological Congress in Geneva in May (Photograph by courtesy of L. Bianco)

Personnel

Staff numbers

Deputy Secretary (Grade 2)	1
Under Secretary (Grade 3)	1
Science Group	
Chief Scientific Officer (Grade 4)	2
Deputy Chief Scientific Officer (Grade 5)	5
Senior Principal Scientific Officer (Grade 6)	28
Principal Scientific Officer (Grade 7)	113
Senior Scientific Officer	303
Higher Scientific Officer	393
Scientific Officer	442
Assistant Scientific Officer	545
Administrative Group	
Assistant Secretary (Grade 5)	1
Senior Principal (Grade 6)	1
Senior Executive Officer	2
Senior Executive Officer Management Accountant	1
Higher Executive Officer	7
Higher Executive Officer Management Accountant	2
Executive Officer	13
Administrative Officer	60
Administrative Assistant	59
Professional and Engineering Group (including Marine Superintendent staff)	
Superintending Engineer (Grade 6)	1
Principal Professional and Technology Officer (Grade 7)	3
Senior Professional and Technology Officer	5
Higher Professional and Technology Officer	16
Professional and Technology Officer	7
Telecommunications staff	
Senior Telecommunications Technical Officer	8
Higher Telecommunications Technical Officer	31
Telecommunications Technical Officer	52
Assistant Telecommunications Technical Officer	47
Signals grades	33
Teleprinter grades	37
Typing and miscellaneous non-industrial grades	77
Security officers	11
Industrial employees	40
Locally entered staff overseas	52

As has been the trend for more than a decade, the number of staff on the strength of the Meteorological Office has continued to fall, standing at 2399 on 31 December 1987. This figure excludes staff on loan or seconded to other organizations (principally the Civil Aviation Authority), but includes locally engaged employees at some overseas stations. The reduction from the previous end-of-year figure is 147, one of the largest falls in recent years. Among the Science Group, which constitutes nearly 80% of staff, the bulk of the reduction has come from the Assistant Scientific Officer and Scientific Officer grades, with a combined loss of 96.

Because of the stringent limits on manpower, the requirement for recruitment to the scientific grades was relatively small and was met without undue difficulty. For the first time, the Office sponsored a few very promising school-leavers embarking on university courses relevant to a career in the Office.

A number of changes introduced centrally within the Civil Service had a significant impact on the Office and were welcomed by staff and management alike. Notable among these were the Flexible Pay system for scientists and engineers, which responds to high demand for scarce skills and has the ability to reward excellent performance; a complete re-structuring of the Telecommunications Technical Officer grades; and arrangements to give additional financial assistance to staff transferred from a low-cost to a high-cost housing area. These last arrangements have helped alleviate the growing difficulty of transferring staff from less expensive areas to Bracknell and other locations in the south-east of England.

Staff hours and awards

The Imperial Service Medal was awarded to Mr I.R.G. Richard and Mr L.C. Taylor (both now retired). The medals were presented to them by the Director-General.

The L.G. Groves Memorial Prize for Meteorology was awarded to Dr S.Nicholls.

Finance

Statement of operating expenses for the Meteorological Office for the year ended 31 March 1987

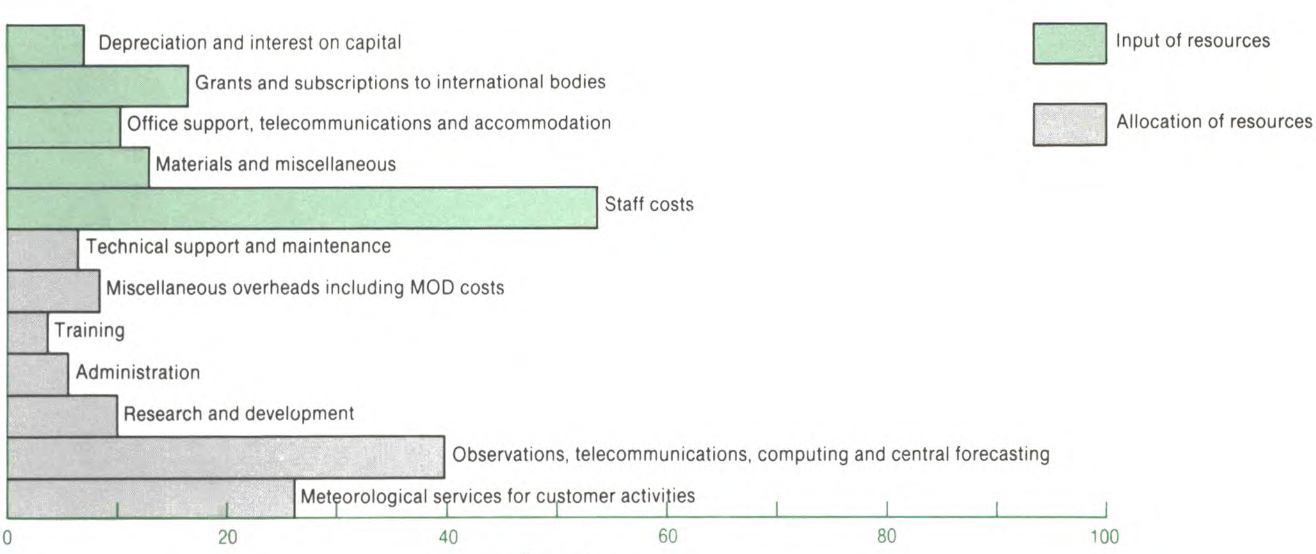
	1986/87	1985/86
	£000	£000
Customer activity costs	21 137	19 728
General Meteorological Office core activity costs:		
Research	8 113	7 961
Administration and personnel	4 331	2 945
Central Forecasting Office	3 541	3 327
Computing	1 196	867
Maintenance	2 351	2 234
Observations	22 150	21 494
Technical support	2 837	2 509
Telecommunications	5 392	4 179
Training	3 005	2 380
Others	2 818	2 252
Total Meteorological Office management costs	76 871	69 876
Share of MOD HQ costs and interest on capital	3 958	3 782
Total Meteorological Office costs	80 829	73 658

Statement of the cost of meteorological services for the year ended 31 March 1987

	1986/87		1985/86	
	£000	£000	£000	£000
Total meteorological services (cost accounted)		80 829		73 658
Receipts		23 608		21 755
Net expenditure:				
Defence and other Exchequer departments	32 993		29 903	
General public services and international	24 228		22 000	
		57 221		51 903

On a fully cost-accounted basis the total cost of the Office in 1986/87 was £80.8 million compared with £73.7 million in 1985/86. The net cost after earnings from services was £57.2 million compared with £51.9 million in 1985/86. Charges for repayment services were increased to cover Meteorological Office pay and price increases on 1 April 1987.

The Office's voted expenditure is borne on the Defence Budget to which all receipts from repayment services are credited. Details are shown in the *Annual Statement of Defence Estimates*. However, for costing purposes, a fully cost-accounted Memorandum Operating and Trading Account (MTA) is also maintained and the chart below summarizes the costs and receipts involved. These figures include non-Voted costs that are not shown in Defence Votes in Parliamentary Estimates, such as pension contributions, notional insurance provision, interest on capital and depreciation. By the same token, the cost of major items of equipment, which appears in Defence Votes for the year of acquisition, is excluded from the table, being covered by annual interest and depreciation charges in the usual commercial accounting manner.



Appendices

APPENDIX I
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APPENDIX II

A SELECTION OF LECTURES AND BROADCASTS GIVEN BY MEMBERS OF THE STAFF

ANDREWS, D.G.
Dynamics of the southern hemisphere middle atmosphere: some basic questions. *Middle Atmosphere of the Southern Hemisphere Workshop, Adelaide, Australia*. 18–21 May.
Modelling the middle atmosphere. *Royal Meteorological Society Australian Branch, Melbourne, Australia*. 28 May.

ASHCROFT, J.
A comparison of monitoring statistics from the Meteorological Office and ECMWF. *ECMWF/WMO Workshop on Radiosonde Quality and Monitoring, Shinfield Park, Reading*. 15 December.

AUSTIN, J.
Evidence of planetary wave breaking using a photochemical model. *6th Conference on Dynamics and Chemistry of the Middle Atmosphere, Baltimore, USA*. 12 March.

AXFORD, D.N.
The achievement of COST 43. *COST 43 Seminar on Operational Ocean Weather Stations Network, Brest, France*. 16–18 June.

BELL, R.S.
Evaluation of local weather forecasts produced by the Meteorological Office mesoscale model. *WMO Workshop on Significant Weather Elements Prediction and Objective Interpretation Methods, Toulouse, France*. 22–26 June.

BENNETTS, D.A.
The meteorological response to various civil emergencies, *Civil Defence College, Easingwold*. 30 November.

BRACHER, C.H.
Sensitivity studies with a 2nd generation wave model. *Presentation to WAM Meeting, Massachusetts, USA*. 4–7 May.

BROWNING, K.A.
Organization and mechanisms of synoptic and mesoscale precipitation systems in mid-latitudes. *40th Anniversary Conference on Radar Meteorology of the American Meteorological Society, Boston, Mass.* 12 November.

BROWNSCOMBE, J.L.
Climate and silage maize growing. *Interview BBC Radio 4 'Farming Today'*. 3 October.

CALLANDER, B.A.
Agrometeorological information for use in agricultural production, including weather forecasting. *WMO Symposium on Education and Training in Meteorology with Emphasis on the Optimal Use of Meteorological Information and Products by all Potential Users, Shinfield Park, Reading*. 13–18 July.
Meteorological Office services for agriculture. *University of Nottingham School of Agriculture, Sutton Bonington*. 23 June.

CATTLE, H.
The parametrisation of physical processes in atmosphere and ocean models. *Course of 10 Lectures, Institut d'Astronomie et de Géophysique, Université Catholique de Louvain, Louvain-la-Neuve, Belgium*. 19–30 January, 8–20 June.

COLLIER, C.G.
Forecasting rain using radar, satellite and conventional meteorological data. *AGM British Hydrological Society, Aston University, Birmingham*. 7 December.

CONWAY, B.J.
Weather forecasting using interactive analysis of radar and satellite imagery. *Royal Society, London*. 11 March.

CULLEN, M.J.P.
Finite difference methods for tracking discontinuous atmospheric flows. *Oxford University Computing Laboratory*. 30 March.
Prospects in numerical weather prediction for the next 10 years. *Royal Meteorological Society, Imperial College, London*. 16 December.

DAVEY, M.K.
A model of the 30–60 day oscillation. *Royal Meteorological Society, London*. 18 March.

DAVIES, T.
Modern methods of weather forecasting. Institution of Electrical Engineers, Rugby. *21 January*.
Institution of Electrical Engineers, Swindon. 3 February.
Institution of Electrical Engineers, Leeds. 17 February.
Institution of Electrical Engineers, Bournemouth. 10 March.

DIXON, J.C.
Climatology and highway design. *The City University*. 13 November.

FIELD, M.
The quality, availability and timeliness of observations from drifting buoys in the North Atlantic during 1985/86. *COST 43 Seminar on Operational Ocean Weather Stations Network, Brest, France*. 16–18 June.
Monitoring of remote radiosonde observations in the Atlantic by the U.K. Meteorological Office. *ECMWF/WMO Workshop on Radiosonde Quality and Monitoring, Shinfield Park, Reading*. 14–16 December.

FLOOD, C.R.
Applications and benefits of short period weather forecasts. *IAMAP Mesoscale and Forecasting Conference, Vancouver*. 17–19 August.

FOLLAND, C.K.
Two lectures: (1) The influence of sea surface temperature and soil moisture anomalies on Sahel rainfall, (2) Assessments of probability forecasts of temperature and rainfall for the United Kingdom 1979–1987. *2nd WMO Workshop on Diagnosis and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe/WMO Symposium on Ocean–Atmosphere Interaction Relevant to Long Range Forecasting, Toulouse, France*. 15–19 June.
Recent and possible future climate fluctuations. *BBC Radio Overseas Service 'Your World'*. 27 August.

FOREMAN, S.J.
Air–sea interaction in a coupled ocean–atmosphere general circulation model. *Royal Meteorological Society Summer Meeting, Southampton.* 15–17 July.
Aspects of climate modelling in the Meteorological Office. *University of Hamburg, Federal Republic of Germany.* 16–27 November.

FRANCIS, P.E.
The North European Storm Study (NESS). *SUT Conference, London.* 1–2 April.

GADD, A.J.
Modern weather forecasting. *WMO Seminar, Addis Ababa.* 30 November–4 December.
Applications of numerical weather prediction. *MSc Course, University of Reading.* 13, 16, 18 March.

GAIR, A.
Total ozone measurement at Lerwick Observatory. *BBC Radio Shetland.* September.

GOLDING, B.W.
The UK Meteorological Office mesoscale model. *International Conference on Energy Transformations and Interaction with Small and Mesoscale Atmospheric Processes, Lausanne, Switzerland.* 4 March.
Clouds and precipitation in a mesoscale model. *Royal Meteorological Society Meeting on Clouds and their Role in Atmospheric Dynamics, Imperial College, London.* 15 April.
Strategies for using mesoscale data in an operational mesoscale model. *IUGG General Assembly, Vancouver.* 19 August.
A balanced Lagrangian model of mesoscale processes. *IUGG General Assembly, Vancouver.* 22 August.
Prospects for short and medium range weather forecasting. *Royal Meteorological Sociey, Imperial College, London.* 16 December.

HALL, B.A.
Meteorological forecasting techniques for weather elements affecting transport, ie ambulances etc. *Southern Branch of the Institute of Hospital Engineering.* 20 May.

HALL, C.D.
The use of numerical models in weather forecasting. *RAE Bedford Technical Society.* 19 February.
Forecasting tropical cyclones by an operational model. *17th Conference on Hurricanes and Tropical Meteorology, Miami.* 9 April.

HIDE, R.
Orographic contributions to angular momentum exchange between the atmosphere and solid Earth. *Royal Meteorological Society, London.* 18 February.
Excitation of Chandlerian Wobble. *Royal Astronomical Society, London.* 8 May.
Geophysical fluid dynamics and related topics. *IUGG General Assembly, Vancouver.* 13 August.

HOUGHTON, D.M.
Making the most of weather information. *Exhibition of Meteorological Equipment and Services, Shinfield Park, Reading.* 10 July.
Automatic forecasting. *Institute of Petroleum, Aberdeen.* 3 November.
Responses to climatic variability. *University of Birmingham.* 2 December.

HOUGHTON, J.T.
Remote sensing from space. *Hooke Institute, University of Oxford.* 5 February.
Marine remote sensing — perspectives. *Nansen Symposium, Bergen, Norway.* 17 June.
The work of the Meteorological Office. *British Astronomical Association.* 1 July.
Economic and other benefits of hydrological and meteorological services. *WMO Symposium on Education and Training in Meteorology with Emphasis on Optimal Use of Meteorological Information and Products by all Potential Users, Shinfield Park, Reading.* 17 July.
Science of forecasting. *London Bible College.* 5 November.
Predictability of weather and climate. *University of East Anglia.* 1 December.

HUNT, R.D.
Winter chaos — can we buy our way out of it? *Institution of Civil Engineers' Conference, London.* 31 March.
The Met Office. *Series of interviews BBC World Service 'Omnibus'.* May.
Forecasting for winter road maintenance. *Highway Engineers Course, The City University.* 16 October.

IBBOTSON, G.R.
The big freeze. *Interview TSW TV.* 21 January.

INGRAM, W.J.
Cloud changes and cloud feedback in CO_2-induced warming in a general circulation model. *Joint Meeting of the European Union of Geophysics and the European Geophysical Society, Strasbourg, France.* 9–14 April.

JONAS, P.R.
Cloud seeding. *BBC External Services.* 14 July.

JONES, D.E.
Experiments in prediction of African rainfall. *The First Technical Conference on Meteorological Research in Eastern and South Africa, Nairobi.* 6–9 January.
Developments in long range forecasting. *2nd WMO Workshop on Diagnosis and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe/WMO Symposium on Ocean–Atmosphere Interaction Relevant to Long Range Forecasting, Toulouse, France.* 15–19 June.
Climatological information to enable planners to prepare for the onset of droughts. *WMO Symposium on Education and Training in Meteorology with Emphasis on the Optimal Use of Meteorological Information and Products by all Potential Users, Shinfield Park, Reading.* 13–18 July.

JONES, R.L.
Lagrangian studies of ozone in polar latitudes. *NOAA Aeronomy Laboratory, Boulder, Colorado.* 4 March.
Ozone in polar latitudes. *Heriot-Watt University, Edinburgh.* 23 March.
The lagrangian approach: implications for the Airborne Antarctic Ozone Experiment. *NASA Ames Research Centre, California.* 25 March.
Antarctic ozone. *Radio 4 'World tonight'.* 17 August.

KERSHAW, R.
Orographic effects on the Asian monsoon. *Royal Meteorological Society Meeting on Orographic Effects on Large-scale Atmospheric Flow, Imperial College, London.* 18 February.
The onset of the Indian summer monsoon and the 40-day oscillation in the tropics. *17th AMS Conference on Hurricanes and Tropical Meteorology, Miami.* 10 April.

LITTLE, C.T.
Graphics at the UK Meteorological Office. *Conference on the Future of Graphics Software, British Computer Society, London.* 28 October.

LORENC, A.C.
Analysis methods for NWP. *Seminar, National Centre for Atmospheric Research, Boulder, Colorado.* 8 January.
Optimal nonlinear objective analysis. *Extra-tropical Cyclone Workshop, Monterey, California.* 20 February.
Data assimilation. *Workshop, National Severe Storms Laboratory, Norman, Oklahoma.* 19 March.
A survey of quality control techniques. *STORM Workshop on Regional Data-assimilation, Virginia.* 5–9 October.

LUNNON, R.W.
High resolution numerical modelling of cold fronts. *IAMAP Session on Mid Latitude Cyclones, Vancouver.* 20 August.

MACKIE, G.V.
Weather routeing of ships. *Nautical Institute, South Wales Branch, jointly with the Royal Institute of Navigation.* 4 February.

MANSFIELD, D.A.
Forecasting stratus over the British Isles. *IAMAP Symposium on Mesoscale Analysis and Forecasting, Vancouver.* 17–19 August.

MANSTON, S.J.
Meteorological Office services for agriculture. *Hampshire College of Agriculture, Sparsholt.* 18 March.

MASON, P.J.
Large eddy simulation. *US Army Atmospheric Sciences Workshop on Mesoscale Meteorology, Risø National Laboratory, Roskilde, Denmark.* 13 May.
Large eddy simulation of the convective atmospheric boundary layer. *6th Symposium on Turbulent Shear Flows, Toulouse, France.* 7 September.

MINHINICK, J.H.
Agrometeorology and vegetable growing. *Warwickshire Vegetable Growers Study Group, Pershore.* 7 October.

MITCHELL, J.F.B.
Climatic effects of nuclear war: the role of atmospheric stability and ground heat fluxes. *SCOPE-ENUWAR Meeting, Imperial Hotel, Bangkok.* 6–13 February.
Clouds and climate. *Royal Meteorological Society Meeting on Clouds and their Role in Atmospheric Dynamics. London.* 15 April.
Modelling the effects of CO_2 and other trace gases on climate. *DOE/NERC Discussion Meeting on Man-made Climatic Change: Planning UK Strategy, Wallingford.* 28–29 April.
Some recent Meteorological Office climate sensitivity experiments. *Geophysical Fluid Dynamics Laboratory, Princeton University, New Jersey.* 5 June. *Goddard Institute for Space Sciences, New York.* 8 June.

MORRIS, R.M.
Range of output available from the operational 15 level model. *WMO Workshop on Significant Weather Elements Prediction and Objective Interpretation Methods, Toulouse, France.* 22–26 June.
Meteorological Office services to air, sea transport. *Royal Institute of Navigation Conference.* 29–30 September.
Meteorological Office aspects of 'The Storm'. *Presentation, Direction de la Meteorologie, Paris.* 3–4 November.

MURPHY, J.M.
Monthly prediction experiments using an 11-level general circulation model. *Royal Meteorological Society, London.* 18 March.

NASH, J.
The relevance of the WMO International Radiosonde Intercomparison results to the global operational radiosonde network. *ECMWF/WMO Workshop on Radiosonde Quality and Monitoring, Shinfield Park, Reading.* 14–16 December.

NICHOLLS, J.M.
The Operational World Weather Watch Systems Evaluation, and its relevance to drifting buoys. *COST 43 Seminar on Operational Ocean Weather Stations Network, Brest, France.* 16–18 June.
National and international routines for system evaluation and fault reporting. *ECMWF/WMO Workshop on Radiosonde Quality and Monitoring, Shinfield Park, Reading.* 14–16 December.

NICHOLLS, S.
The cloud-capped boundary layer. *Royal Meteorological Society Meeting on Clouds and their Role in Atmospheric Dynamics, London.* 15 April.

O'NEILL, A.
The seasonal evolution of the middle atmosphere. *Vikram Sarabhai Space Centre, Trivandrum, India.* 13 May.
Inter-comparison of data and derived quantities for the middle atmosphere of the southern hemisphere. The seasonal evolution of the southern hemisphere. *Middle Atmosphere of the Southern Hemisphere Workshop, University of Adelaide, Australia.* 18–21 May.
The seasonal evolution of the stratosphere: observations and theory. Final warmings in the stratosphere of the northern hemisphere. *IUGG General Assembly, Vancouver.* 17–21 August.

OWEN, J.A.
Sea surface temperature anomalies and Sahel rainfall. *Royal Meteorological Society Meeting on Long Range Forecasting and its Physical Basis, London.* 18 March.

PARKER, D.E.
The influence of global sea surface temperature on African rainfall. *The First Technical Conference on Meteorological Research in Eastern and South Africa, Nairobi.* 6–9 January.
Improved estimates of long-term fluctuations in global and regional mean temperatures. *Royal Meteorological Society, London.* 21 January.
Forecasting seasonal rainfall in the Sahel. *Royal Meteorological Society, London.* 18 March.
Worldwide surface temperature variations, 1984–87, in relation to El Niño, tropical rainfall and longer term trends. *2nd WMO Workshop on Diagnosis and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe/WMO Symposium on Ocean–Atmosphere Interaction Relevant to Long Range Forecasting, Toulouse, France.* 15–19 June.

PICK, D.R.
UK Microwave Programme. *Passive Microwave Observing from Environmental Satellites, Williamsburg, Virginia.* 1–4 June.
The UK Meteorological Office's report to IPOMS. *IPOMS, Tokyo.* 11–12 June.
Passive microwave radiometry from space. *Seminar MSSL, Dorking.* 5 November.

PRIOR, M.J.
Methods of assessing the exposure of buildings to rain. *School of Architecture, University of Manchester.* 26 January.
The derivation of driving rain testing conditions from meteorological data. *CIB Symposium on Building Climatology, Moscow.* 14 May.

READ, P.L.
Phase-space analyses of rotating baroclinic waves. *Clarendon Laboratory, University of Oxford.* 27 November.
The atmosphere of Venus. *Royal Astronomical Society Discussion Meeting, London.* 11 December.

RIDDAWAY, R.W.
Modern methods of weather forecasting. *Lancaster Engineering Society.* 15 September.

ROACH, W.T.
The radiative importance of atmospheric gases: an overview. *Royal Meteorological Society, London.* 21 October.
The Meteorlogical Research Flight — its history, role and work. *Royal Meteorological Society, Scottish Centre.* 13 November.

ROSS, G.H.
An updateable Model Output Statistics scheme. *WMO Workshop on Significant Weather Elements Prediction and Objective Interpretation Methods, Toulouse, France.* 22–26 June.

ROWNTREE, P.R.
Progress and future in modelling the climate system with general circulation models. *IUGG General Assembly, Vancouver.* 19 August.
Modelling the climatic impact of changing concentrations of radiatively active gases. *Royal Meteorological Society, London.* 21 October.

ROY, M.G.
Weather observing on Scotland's Arctic mountain tops. *Royal Scottish Geographical Society, Edinburgh.* 4 November.

SHAW, D.B.
The weather package; distance learning techniques in meteorology. *WMO Symposium on Education and Training in Meteorology with Emphasis on the Optimal Use of Meteorological Information and Products by all Potential Users, Shinfield Park, Reading.* 14 July.

SHAWYER, M.S.
Meteorlogical aspects of drainage design. *Planning, Transport Research and Computation Co Ltd Course on Flood Estimation for Drainage Design, Institution of Civil Engineers, London.* 18 May.

SHEARMAN, R.J.
UK specialised marine meteorological services. *WMO Symposium on Education and Training with Emphasis on the Optimal Use of Meteorological Information and Products by all Potential Users, Shinfield Park, Reading.* 13–18 July.

SHUTTS, G.J.
Orographic gravity wave drag and barrier effects. *Royal Meteorological Society, London.* 18 February.
Two lectures: (1) Quasi-inertia waves in the lower stratosphere, (2) The representation of mesoscale phenomena in balanced models: forecasting the quasi-equilibrium dynamics. *European Geophysical Society Meeting, Strasbourg, France.* 9–14 April.

SINGLETON, F.
International meteorological information. *Forum of the Reinsurance Offices Association, London.* 21 July.

SLINGO, A.
The effect of cloud radiative forcing on the Community Climate Model. *National Center for Atmospheric Research, Boulder, Colorado.* 13 January.

SMITH, F.B.
Chernobyl — the radioactive plume and its consequences. *16th International Technical Meeting, CCMS NATO Conference, Lindau, Federal Republic of Germany.* 6–10 April.
2nd International Environmental Chemistry Congress, Salvador, Brazil. 16–18 September.
Air pollution meteorology. *MSc Course on Radiological Protection, University of Surrey.* 12, 19, 26 February.

SPACKMAN, E.A.
Weather and spray-occasions 1986/7. *BCPC Herbicide Review, Agriculture House, Knightsbridge.* 20 October.
Sprayer work days. *Institution of Agricultural Engineers Specialist Group on Machinery Management, London.* 7 December.

STARR, J.
Effect of June weather on Welsh agriculture. *BBC Radio Wales.* 1 July.

STUBBS, M.W.
Operational models and numerical forecasts. *WMO Seminar, Bangkok. 23–27 November.*
Weather forecast by satellite. Institution of Electrical Engineers, Croydon. 18 March.

TABONY, R.C.
Wind information from the Meteorological Office. *British Wind Energy Association, East Kilbride.* 17 December.

TAMLYN, J.
My work in the Met Office. *BBC Radio 1 'Janice Long Programme'.* 14 October.

THOMAS, J.P.
Operational applications of remotely sensed microwave data in the Meteorological Office wave models. *Rutherford Appleton Laboratory.* 24–25 March.

THOMSON, D.J.
A stochastic model of the motion of particle pairs, with an application to the behaviour of concentration fluctuations in decaying grid turbulence. *6th Symposium on Turbulent Shear Flows, Toulouse, France.* 7 September.

TURNER, A.B.
Meteorology for health physicists. *AERE, Harwell.* 9 June.
Meteorological aspects for hazardous materials course. *Home Office Fire Service College, Moreton-in-Marsh.* 21 January, 23 September.

WARD, M.N.
Statistical prediction of seasonal rainfall in the Sahel and other tropical regions. *2nd WMO Workshop on Diagnosis and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe/WMO Symposium on Ocean–Atmosphere Interaction Relevant to Long Range Forecasting, Toulouse, France.* 15–19 June.
Predictability of seasonal rainfall in the Northern Nordeste region of Brazil. *International Geographical Union Study Group on Recent Climatic Change, Sheffield.* 25–27 August.

WHITE, G.D.
Meteorology for health physicists. *AERE, Harwell.* 9 June.

WHITE, P.W.
Advances in numerical weather prediction. *Department of Physics, University of Edinburgh.* 26 January.
The Meteorological Office's meso-scale model — parametrization of physical processes. *US Army Atmsopheric Sciences Workshop on Mesoscale Meteorology, Risø National Laboratory, Roskilde, Denmark.* 14 May.
The use of supercomputers for atmospheric modelling. *Seminar on Supercomputers and Parallel Processing – Applications and Future Trends, Royal Garden Hotel, London.* 9 November.

APPENDIX III
PUBLICATIONS

Publications prepared by the Meteorological Office are either published and sold by Her Majesty's Stationery Office or are produced as departmental publications and sold directly, by the Meteorological Office. A catalogue containing all current titles is available on request. More extensive details of HMSO publications (only) are contained in HMSO Sectional List 37.

The titles that follow are those completed during 1987; those handled by HMSO are marked with an asterisk (*). The final numbers, within brackets, are International Standard Book Numbers (ISBN), which provide positive identification of items that bear them.

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Annual Report on the Meteorological Office 1986 (0 11 400353 X)*
Meteorological Office Almanack 1988 (Leaflet No. 11) (0 86180 221 7)
Monthly Weather Report, introduction 1986 (0 11 727957 9)*
Monthly Weather Report, annual summary 1985 (0 11 727918 8), 1986 (0 11 727958 7)*
Snow survey of Great Britain 1985/86 (0 86180 214 4)

Quarterly

*The Marine Observer**

Monthly

*Meteorological Magazine**
*Monthly Weather Report**

Note: Many Weather Centres produce meteorological summaries and statistics on a variety of time-scales. Details are given in *Publications obtainable free from the Meteorological Office* on request.

Serial

Climatological Memorandum No. 135: *The Climate of Great Britain: London* (rev) (0 86180 224 1)
Scientific Paper No. 41: *The Meteorological Office operational numerical weather prediction system* (011 400354 8)*

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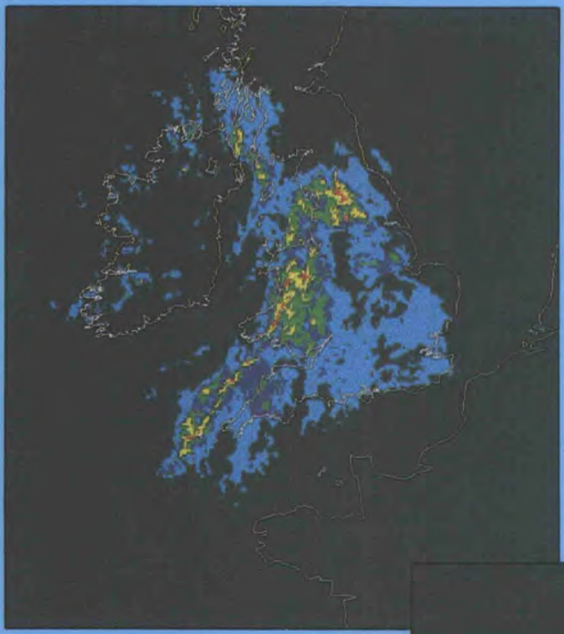

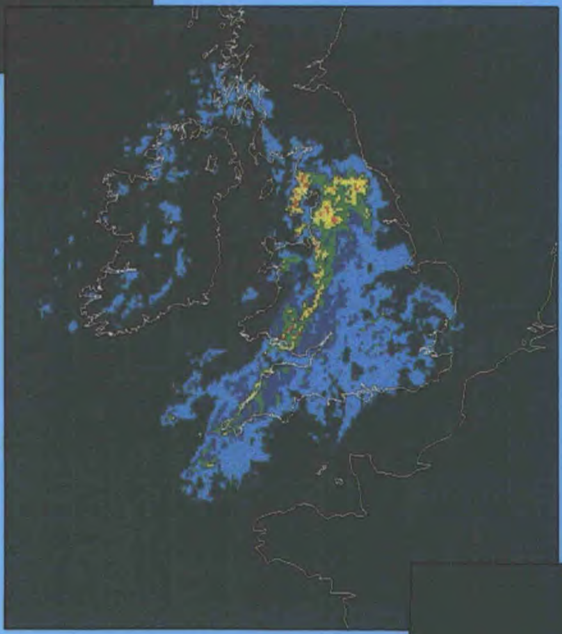

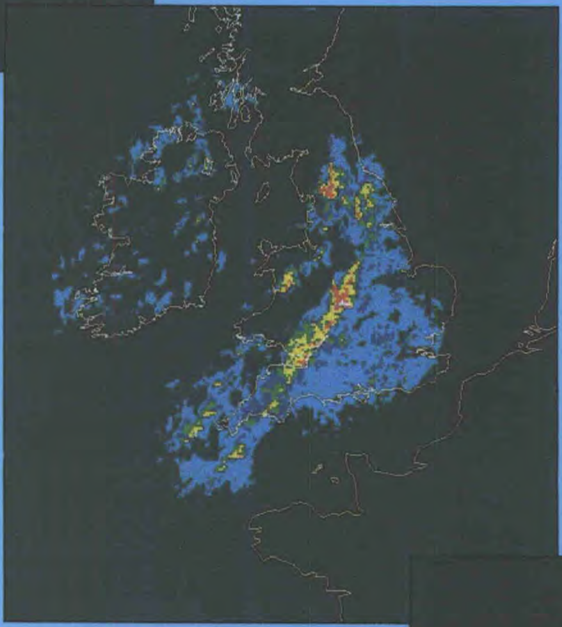

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