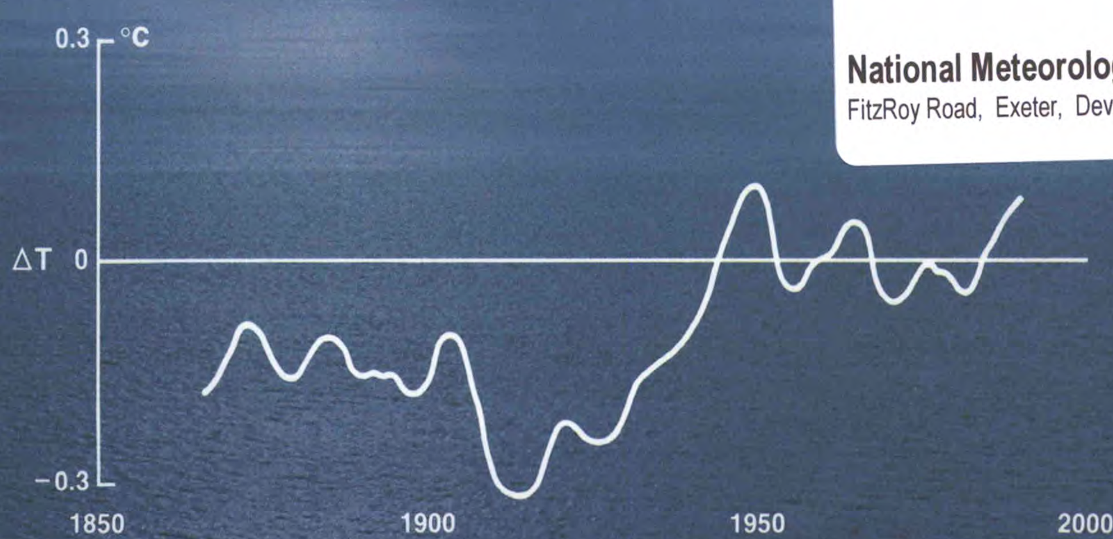
The Met. Office

ANNUAL REPORT 1988



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Meteorological Office
Annual Report 1988

Presented by the Director-General
to the
Secretary of State for Defence

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The front cover shows a graph of sea surface temperature anomaly (°C) averaged over the globe (the anomaly with respect to the 1951–80 mean). The background photograph is by courtesy of Mr R.K. Pilsbury.

Contents

Foreword by the Director-General

Early in the year there was a great deal of public interest in the publication of two reports on the violent storm which swept southern England on 15/16 October 1987. The first report, by the Meteorological Office, described the storm in detail and the reasons for the failure of the computer models at the time to describe it in an adequate manner. A number of recommendations were made, in particular, ones concerning improvements in the observation system, in the numerical models themselves and in the ways warnings are issued both to the general public through the media and to the emergency services. The second report, commissioned from Sir Peter Swinnerton-Dyer and Professor Pearce by the Secretary of State for Defence, concluded that no blame could be attached to any individual for the forecasts at the time of the storm; it endorsed the need for adequate observations and computer resources and also made a number of recommendations regarding the training of forecasters. The Secretary of State for Defence accepted the recommendations of both reports; all of them have been, or are in the process of being, implemented.

In co-operation with Spaceward Microsystems Ltd versatile computer graphics have been developed for the presentation of weather information and forecasts on television. This project, known as Weather in Vision, has already had success; a contract has been placed for a new TV weather presentation with ITN, and others are in the pipeline.

In Aberdeen the Meteorological Office has moved from the airport to a Weather Centre in the commercial sector of the city. It was opened in November by Lord Trefgarne at a ceremony which drew a lot of local interest. Forecasting services at Heathrow were moved during the year to Bracknell and integrated into a newly styled Central Forecasting Office. A better, more efficient, service can thereby be provided with some savings in staff and therefore at a reduced cost to the Civil Aviation Authority and hence to the airlines.

In the new Central Forecasting Office provision has been made for many more computer terminals through which the forecaster can access and interact with a wide range of computer products. Units known as Outstation Display Systems for the presentation of data and forecast products have been installed at further Defence outstations where the forecasters much appreciate the increased capability the units bring.

Automation is also moving apace in the observation field. Forty-seven automatic weather stations distributed around the country are regularly reporting. A semi-automatic weather station is in an advanced stage of development with the object of improving the efficiency of the taking of observations, releasing some staff time for other purposes.

The radar network, which is an invaluable tool for short-range forecasting, was further extended during the year with the opening of the Lincoln radar on 13 September. Installation work is in progress on the sites for new radars in South Wales and Dorset.

Towards the end of the year there was an increase in political interest worldwide in climate and climate change, and in particular in the possible impact of man's activities (for example an increased greenhouse effect because of the burning of fossil fuels or changes in the ozone layer because of the release of chlorofluorocarbons). In November, I attended the first meeting of the Intergovernmental Panel on Climate Change, in Geneva. I was asked to chair a working group on the scientific assessment of the likely climate change next century, to report to the Panel and then to the United Nations before the end of 1990. To organize this international scientific assessment I have set up, with support from the Departments of the Environment and Energy, a small team at Bracknell. Important contributions to the assessment will come from work in the Office on the analysis of trends in observations and from the Office's climate prediction model.

Proposals have been made to grant the Office Executive Agency status on 1 April 1990. Because of its international and Defence responsibilities it is expected that the Office will remain within the Ministry of Defence. However, a better financial and management framework will be set up for the Office programme involving clearer customer–supplier relationships.

Functions of the Meteorological Office

The Meteorological Office is the State Meteorological Service. It forms part of the Ministry of Defence and is at present administered by the Air Force Department. The Director-General is responsible to the Secretary of State for Defence, through the Under Secretary of State for Defence Procurement, for the supply and support of meteorological services.

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, atmospheric electricity and ozone, in the United Kingdom and at certain stations overseas in support of the above services.

(d) The collection, distribution and publication of meteorological information from all parts of the world; maintenance of the National Meteorological Library.

(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 UN 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 programmes.

Meteorological Committee

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 1988:
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Members:
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Mr J. Wilson
*Mr R.L.L. Facer (Deputy Under-Secretary of State (Personnel and Logistics))
*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); alternate, Group Captain A.M. Bowman
Secretary:
*Mr P. Fraser (Secretary, Meteorological Office)
**ex officio*

The Committee met four times in 1988

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 programme.

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Professor H. Charnock, FRS
Members:
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Professor B. Hoskins
Dr J. Woods
*Dr D.N. Axford (Director of Services, Meteorological Office)
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*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)
*Captain A. Morrice, RN (Director of Naval Oceanography and Meteorology)
*Dr V.G. Roper (Head of Electro-optics and Microwave Group, Royal Signals and Radar Establishment)
Secretary:
*Mr C. Kilsby (Meteorological Office)
**ex officio*

The Committee met three times in 1988

Introduction

As the State Meteorological Service of the United Kingdom the Meteorological Office is a source of weather and climate data. The latest information from weather radars and satellites, together with observations from manned and unmanned sites both at sea and on land, is used in the preparation of weather forecasts. At the Office's Headquarters in Bracknell, forecast weather patterns at several levels in the atmosphere and for the whole globe are generated three times a day using numerical models of the atmosphere and its circulation, while other models are used to predict such things as local weather patterns, state of the sea, and tidal surges. Experienced weather forecasters assess the output from these models and interpret it into the form required by the Office's various customers: Defence, civil aviation, industry, commerce and the general public.

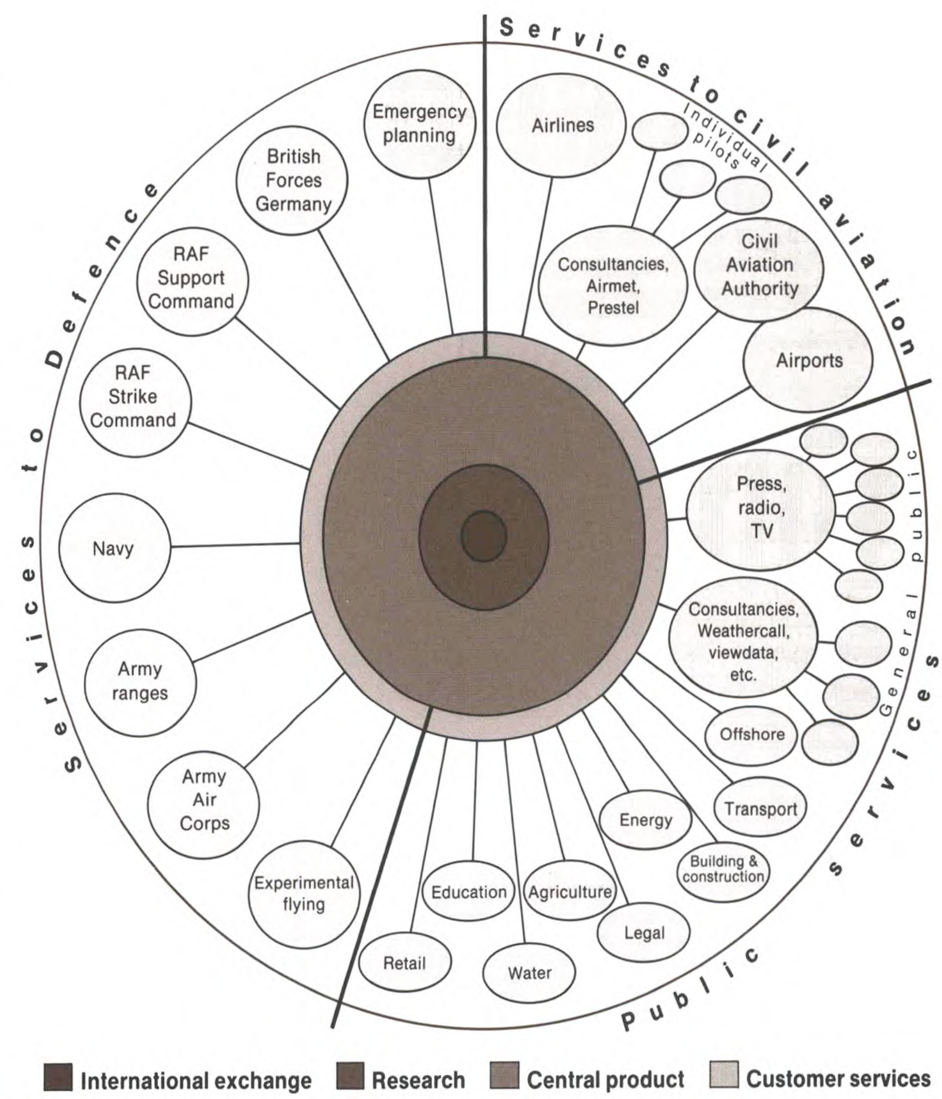
Forecasts and other weather information for Defence are provided by Office staff who work on RAF stations both at home and abroad and at some Army Air Corps bases and trials establishments. The Naval Headquarters at Northwood is also supplied with forecasts.

Bracknell is a World Area Forecast Centre for civil aviation and as such provides global forecast information to most of the major airlines some of whom receive it direct into their own computers. Low-level forecasts are also provided for general aviation.

Industry and commerce receive forecasts and historical climate information on a repayment basis. Efforts are being made to make both present and potential customers more aware of the influence of weather on their operations. The farming industry is catered for by local Weather Centres and also by Office staff working with the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food.

Forecasts for the general public are available through the media and also from the 14 Weather Centres distributed around the country.

This year the main part of the report describes the wide range of incoming observations, particularly those from satellites, and the use of Information Technology in disseminating them and providing forecasts. There are sections on the services provided to customers, training given by the Office, and its international and UK commitments. Another section describes the central forecasting operation; this together with the observations are the key activities on which the output of the Office depends, while research and development, also described in some detail, provides a vital support. At the beginning and end of this report are sections on the administration and finance of the Office. In the diagram below of Office activities area is roughly proportional to resources.



Meteorological Office organization

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    DR Met O
    A Gilchrist MA
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      DD Met O(D)
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      - **Met O 9** Special Investigations — **AD Met O(SI)** N Thompson PhD
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    - **Met O 10** Personnel Management — **AD Met O(PM)** A I Johnson BSc ARCS
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    D N Axford PhD C Eng FIEE
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      - **Met O 8** Forecasting Products — **AD Met O(FP)** A J Gadd PhD
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    - **Met O 17** International and Planning — **AD Met O(IP)** S G Cornford MSc
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*Individual merit †Special appointment

Observations

For forecasting and many other purposes the meteorologist needs quantitative descriptions of the atmosphere. This demands regular, reliable and accurate measurements of pressure, temperature, wind, cloud, precipitation and visibility.

No single observing method is capable of providing all the data required and a series of monitoring networks of different types, using different techniques, has been established. Most observing locations in these networks are manned, but automatic data-gathering systems are being used to provide data from remote areas. Such systems are also used to obtain some data from locations not continuously manned.

Some elements can be measured automatically and easily, for example temperature; others such as cloud cover or precipitation type require human judgement. Technology is being developed to automate even these observations, but it is unlikely that the whole observing process will be completely automated in the next 10–20 years.

Many measurements are made *in situ* on ships, aircraft, buoys and balloons as well as the familiar installations at airfields, coastguard stations and the like. However, increasing use is now made of remote-sensing techniques, usually by sensing electromagnetic radiation that has been emitted, scattered or absorbed by the atmosphere or ocean. Satellite sounding and weather radar are notable examples of the technique.

Surface observations

A network of 30 'key' observing stations with a spacing of less than 150 km is needed to define the broad weather patterns over the United Kingdom. These stations are manned by professional meteorologists who make measurements every hour. However, local small-scale detail is also needed, and this demands observations from a denser network. A further 53 sites are manned by the Office; there are 47 synoptic automatic weather stations (SAWSs) and 124 locations are manned by auxiliary observers, such as lighthouse keepers, coastguards, and private individuals. Their contribution is vital, and considerable effort is expended upon recruiting and assisting these observers to maintain their observing programme. There is great variability in the type of site, and liaison staff work closely with observers to achieve good instrument exposure and high standards of observing.

Instruments used in the international intercomparison of visibility measurements at RAF Finningley

Reductions in manpower within organizations traditionally providing auxiliary observers have increased the requirement for automation. SAWSs provide basic measurements of air temperature, humidity, pressure, and wind. Work to improve the SAWS system software has continued, making it possible to add further sensors for the measurement of hourly rainfall, surface and soil temperature, maximum and minimum air temperature, wind averaged over 1 hour, global radiation, cloud base and visibility.

A semi-automatic station (SAMOS) has been developed that uses the same sensors as a SAWS but also accepts input from an observer when available. At other times, the system reverts to automatic operation. Thus a limited observing programme can continue where sites are not manned during weekends or the 'silent hours'.

All observations made by auxiliary observers are scrutinized at 'parent' stations during transmission to the communication centre at Bracknell. To maintain the accuracy of observations while reducing the level of manual scrutiny, software has been developed that allows a microcomputer at an auxiliary station to check, code and transmit surface observations entered at the keyboard. Because safety of life may be dependent upon the observations it is essential to preserve the integrity of observational practices, and to regulate the introduction of automation. Standards for writing the validating software used in association with surface observations have, therefore, been specified and enforced. A similar effort has been invested in specifying maintenance standards for the associated electronic hardware.

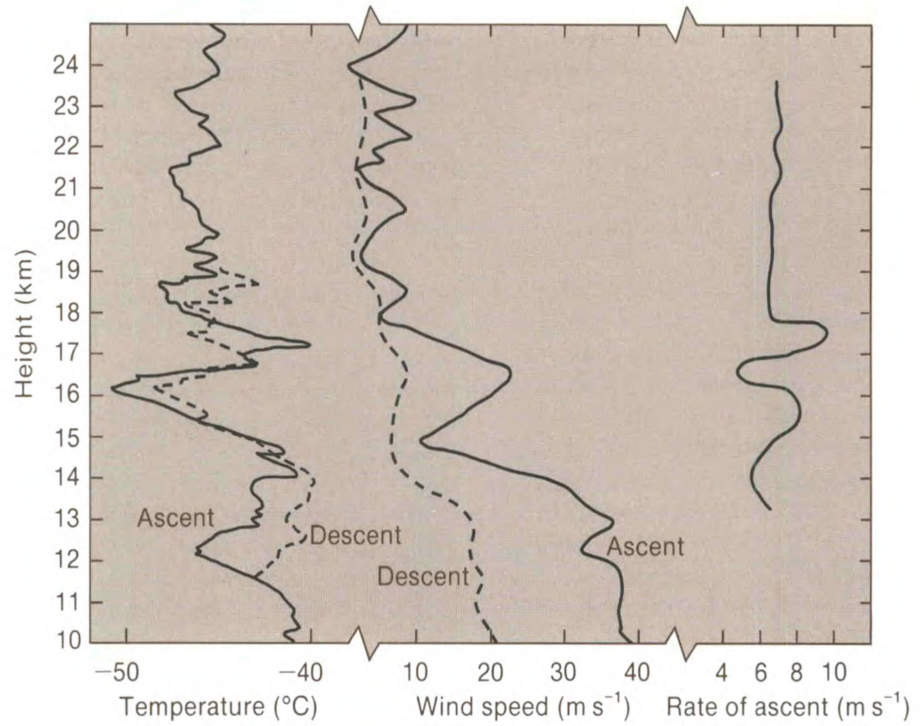
Other surface observing networks satisfy specific needs:

- Observations alongside major roads and from road surface sensors are used in forecasting conditions hazardous to motorists, especially fog and ice. The co-operation of road maintenance staff in providing this information is gratefully acknowledged.

- Measurements of global and diffuse short-wave radiation are made at 14 Meteorological Office stations, and 23 co-operating stations measure at least the global component. Procurement action is in hand to re-equip the Office stations with a new and up-to-date data-logging system.

- Routine measurement of total ozone amounts using the Dobson spectrophotometer is carried out at three stations — Lerwick (60°09′N, 01°09′W), Bracknell (51°23′N, 00°47′W), and St Helena (15°56′S, 05°39′W), and assistance is given for similar measurements at Singapore (01°20′N, 103°53′E) and Mahé Island (04°41′S, 55°32′E). Instruments are being refurbished to bring all these stations up to the full operational standard required for accurate and reliable observations of this very important atmospheric constituent.

An extensive database for climatological and advisory services is regularly updated with observations from most synoptic stations, 55 being designated as Principal Climatological Stations. These are supplemented by data from 484 voluntary Ordinary Climatological Stations and daily rainfall data from a further 4800 sites; the Meteorological Office is extremely grateful for the dedication, commitment and skill of those who assist in this way.



Orographically forced gravity waves in the stratosphere over eastern England as detected by a radiosonde launched from Shanwell at 1127 GMT on 25 July. Waves of this amplitude are rarely observed in summer-time but in this instance are associated with a depression to the north-west of Scotland which gave rise to hourly mean surface winds of 25 m s^{-1} on Cairn Gorm.

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

- Software for a SAWS to convert ceilometer data into information on both cloud height and cloud amount, in a form useful to the forecaster, is being tested in the field.

- An international intercomparison of visibility measurements sponsored by the World Meteorological Organization (WMO) Commission for Instruments and Methods of Observation is being hosted by the Meteorological Office at RAF Finningley. This intercomparison will help to identify visibility sensors suitable for SAWSs and SAMOSs.

- An intensive programme of visual observations and data logging associated with the visibility trial is being used to evaluate a device that is intended to differentiate automatically between different types and intensities of precipitation.

- A trial of automatic observation coding and transmitting software is in progress.

- Installation of SAMOS equipment at Bristol Weather Centre has begun.

Procurement action continued for new systems and some entered service:

- A further 17 runway cross-wind resolvers were obtained to supplement the 28 delivered in 1987.

- Action commenced for the purchase of a number of digital anemograph logging equipments. These use a design developed by the Meteorological Office.

Merchant ships are the main source of surface weather observations from the oceans. More than 520 vessels and oil rigs make up the United Kingdom Voluntary Observing Fleet, part of a WMO scheme incorporating 7200 ships of 49 nations. Observations from all parts of the world are transmitted in coded form by radio and telex to reach National Meteorological Centres via coast radio stations. Increasing use of the Meteorological Observing System for Ships (MOSS) ensures more regular and timely receipt of the data by means of automatic transmission via geostationary satellite. The observations are keyed to a computer terminal by the observer thus facilitating the provision of much needed observations. Twenty ships are now fitted with MOSS and 99% of their transmitted data were found to be correct; a further ten MOSS equipments have yet to be installed on ships.

Ocean Station Vessel (OSV) *Cumulus* made regular surface and upper-air observations at station 'Lima' in the North Atlantic at position 57°N, 20°W in accordance with obligations undertaken under the terms of the North Atlantic Ocean Stations Agreement. Norway and the USSR each operate a North Atlantic station. In August OSV *Cumulus* carried out a successful rescue of two airmen who had ditched their small aircraft when they ran out of fuel whilst flying from Greenland to Iceland. Under the auspices of the WMO Voluntary Co-operation Programme (VCP) a meteorologist from the Kenyan Meteorological Service embarked on a 5-week voyage as part of his training.

For forecasting over and around the United Kingdom detailed, regular observations are required from the surrounding seas. Experience and experiment suggest that a network of 9 key stations, reporting every 3 hours, and about 30 secondary stations, reporting less frequently, will meet the need in a cost-effective manner. To date, 6 key stations and 23 secondary stations have been established on fixed buoys, light-vessels and oil and gas platforms. One key station was destroyed with the tragic loss of the Piper Alpha oil platform.

- Support for the COST-43 (European Co-operation in Science and Technology) Atlantic drifting buoy programmes continued. Six buoys were launched and a further ten procured. A buoy purchased by the Irish Meteorological Service and designed to measure wind speed and direction has been modified to overcome rotational problems due to wave action.

- The data buoy ODAS 452 at 61°36′N, 13°24′W, a joint project between the UK and Icelandic Meteorological Offices under COST-43, continued to provide useful information from the data-sparse area to the north-west of the United Kingdom. Unfortunately it suffered sensor failure after nearly 12 months' operation and was replaced in August by a similar buoy, ODAS 451, which continues to operate successfully.

- The ODAS 20 data buoy, moored in the southern North Sea at 50°20′N, 02°20′E, operated successfully until it suffered damage from unusually large waves in the spring. It was redeployed late in the year.

- Under an agreement between the United Kingdom and France the 'Bosco' data buoy ODAS R1 was moored at 51°N, 14°W. Initial problems with the European satellite (Meteosat) communication link were cured by changing the design of the aerial.

- The data buoy ODAS 1 was successfully launched in September at a key station (48°05′N, 08°90′W). This buoy is the first to provide measurements of significant wave height and period in addition to the usual observations of pressure, temperature and wind.

- The first installation of a marine automatic weather station on an automated light-vessel was completed at Smith's Knoll in November. This system is unique in the marine environment in providing visibility measurements. A second system will be installed on the Channel light-vessel early in 1989.

- A contract to supply three deep-ocean data buoys to a new design has been let. The first of the buoy hulls was delivered in December.

Upper-air observations

Upper-air measurements of geopotential, temperature, humidity and wind continued to be made routinely from eight radiosonde stations in the United Kingdom, from Gibraltar, St Helena, Mt Pleasant in the Falkland Islands and from OSV *Cumulus* while on her 33-day round voyages between station 'Lima' and Greenock.

A contract was placed for the supply of radiosonde ground stations, to replace the existing Mk 3 systems in the United Kingdom and the radiosonde equipment at Gibraltar. The replacement programme is planned to take place towards the end of 1989.

In parallel with the replacement of the main UK radiosonde network, progress has been made towards the purchase of boundary-layer radiosonde systems. Eight ground stations are being obtained for siting at locations where measurements of geopotential, temperature and humidity up to about 5000 m could usefully supplement the main network data. The boundary-layer systems will be operated by staff at synoptic offices to meet local forecasting needs.

A trial was carried out during the summer to compare wind profiles from two acoustic sounders, kine-theodolites and radar tracking of balloons. The results are being analysed and a report prepared.

Office staff continued to co-operate with those of several other National Meteorological Services in the provision and operation of Automated Shipboard Aerological Programme systems, making upper-air soundings from the decks of merchant ships plying transoceanic routes. The systems, housed on board the MV *OOCL Challenge* and the MV *Canmar Europe*, are operating well.

Office staff are playing a major role in the WMO procurement of aircraft to satellite data relay systems. When the manufacturer, Marconi Defence Systems Ltd, succeeds in obtaining international certifications to fit the system to aircraft, the way will be clear for the Office to purchase 5 of the initial 13 production models. They will sample meteorological data measured on the aircraft, quality control, encode and transmit them via meteorological satellites to the ground. Two of the five have been accepted by Singapore under the terms of the VCP.

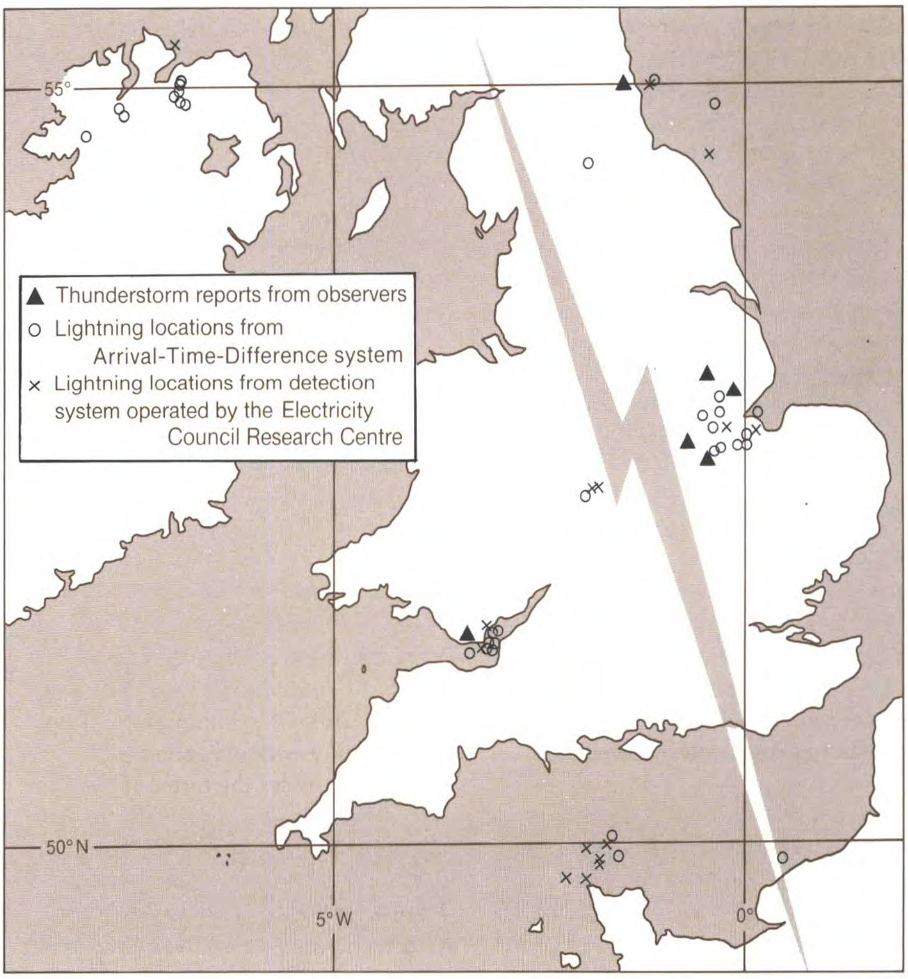
Lightning detection

The new Arrival-Time-Difference system for accurately pinpointing thunderstorm location began service during the summer with a period of intensive trial. The system has five outstations in the United Kingdom at Lerwick, Stornoway, Camborne, Hemsby and Beaufort Park, and two in the Mediterranean at Gibraltar and Cyprus. The trial revealed a combination of software, hardware and communication faults. By the end of September the system was performing much closer to its potential and it is expected that by spring 1989 the majority of existing problems will be solved.

Observing system performance

Before operational use meteorological instruments are tested to ensure 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

Comparison of thunderstorm locations using three different techniques on 1 September 1600–1700 GMT



a total of 50 ships recruited by the USA, Canada, France, The Netherlands, the Federal Republic of Germany and the United Kingdom contributing to the scheme. Nine UK ships trading across the North Atlantic have agreed to provide extra information. Data returns already show promise of achieving the ultimate aim of determining whether and to what extent instrument exposure introduces systematic biases in marine data. The project is designed to continue into 1990.

Doppler acoustic sounder used in the wind-finding trial at Larkhill

ultimately it is performance in the operational environment that matters. When in operational service, further 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 received at Bracknell facilitates several quick-response actions: chaser messages are sent to request missing data; maintenance staff are informed of instrumental and communication problems; 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 (such as drifting buoys and shipborne radiosondes) and of automatic stations.

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

- Statistical analyses of the differences between observed values and computer-analysed values of a variable, as well as field trial results and maintenance reports, detect basic deficiencies in system software and hardware. 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 internationally.

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

- Quarterly reports on North Atlantic drifting buoys 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.

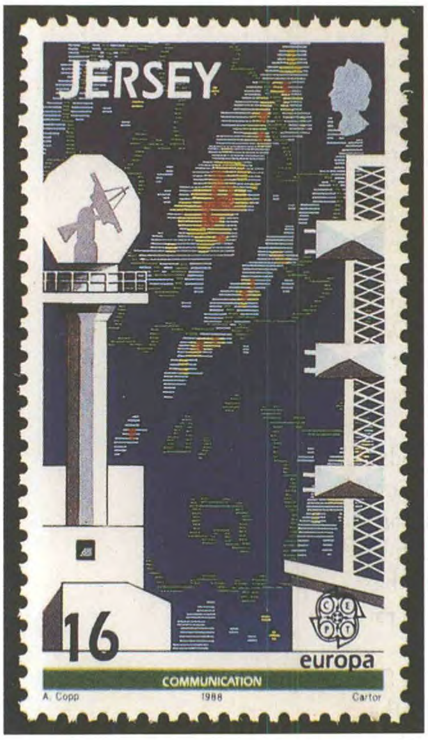
A major international project, the Operational World Weather Watch Systems Evaluation — North Atlantic, commenced in 1987. European and North American countries are jointly assessing in detail the cost and performance of land, marine, airborne and space-based observing systems and of their communication links to each participant. At the same time numerical forecasting centres are carrying out studies of the impact of observations reported by various systems on both the analyses of present weather conditions and on forecasts.

A new WMO project aimed at improving the accuracy of weather data collected from merchant ships gained momentum during the year. The intention is to have

Use of radar

The weather radar network continued to provide 'real-time' precipitation data over England, Wales and Ireland at 15-minute intervals to forecasting offices. The same data are also provided, on a repayment basis, to Devon County Council and nine of the ten Water Authorities to assist in their day-to-day operations. Pictures derived from the network were introduced into the BBC TV forecasts on a regular basis.

During the year the new weather radar at Ingham became operational. The Meteorological Office, Anglian, Severn-Trent and Yorkshire Water Authorities with support from the Ministry of Agriculture, Fisheries and Food jointly funded this radar sited just north of Lincoln.

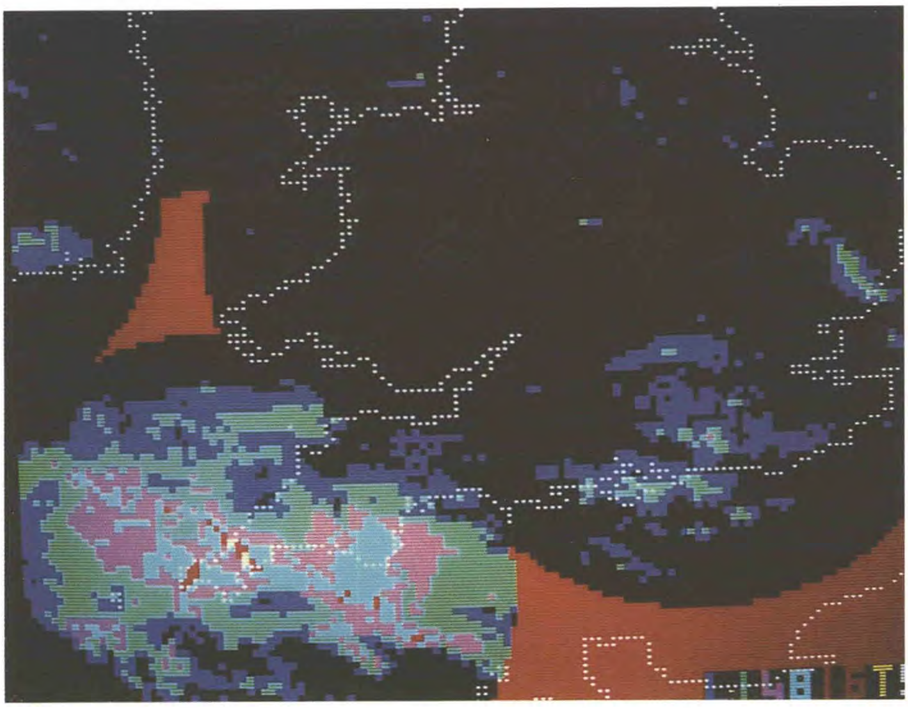


The Meteorological Office is grateful to the States of Jersey Department of Postal Administration for permission to reproduce Jersey's 1987 'Europa' stamp on the theme 'Transport and Communications' featuring the airport's weather radar and ILS installations with a background showing a computerized rainfall display

The installation of a radar at Crug-y-gorllwyn in Dyfed is well advanced and this system should be operational in the early part of 1989. The Welsh name of this site is particularly appropriate meaning 'look-out point'. This system has been funded by the Meteorological Office together with the Welsh, Wessex and South West Water Authorities, and Devon County Council.

Further systems are planned for north Devon and Dorset but both projects have been delayed by problems in obtaining local planning consent. The Dorset radar will replace the poorly sited Upavon system and the Devon radar will provide coverage of the flood-prone rivers of Dartmoor, Exmoor and the Somerset Levels. Warnings given by the South West Water Authority of the

Floods in Truro on 11 October at 1615 GMT (Photograph by courtesy of South West Water)



Radar rainfall picture at 1300 GMT on 11 October. The area of rain that caused the floods in Truro is indicated over south-west England.

floods in Truro in October demonstrated dramatically the importance of weather radar in areas of such small steep catchments and emphasized the potential value of these two radars.

The States of Jersey are installing a weather radar on the south-west corner of the island. The Meteorological Office is assisting this project and the data will be included in the UK composite images. Agreement has been reached with the Scottish Development Department to install three radars in Scotland in the early 1990s. These are likely to be sited in the vicinity of Glasgow or Edinburgh, in the Buchan region, and on one of the Western Isles.

Archived radar data are provided, on a repayment basis, to a large number of customers. This work is underpinned by the continuing development of the system by which hourly and daily totals of rainfall are archived for each 5 km square within a 210 km range of every radar in the UK network. The radar measurements are adjusted by using daily rainfall totals observed by a network of rain-gauges and these adjusted values are also archived. In addition, the composite radar images produced from the radar network every 15 minutes are now also archived. These data enable the quantitative performance of the radars to be monitored and assessed, both by individual case-studies of chosen rainfall events and by studying statistical comparisons with measurements from the climatological network of daily gauges. A study of ways of optimizing radar rainfall measurements at ranges of greater than 75 km from the radar has commenced in partnership with the Lincoln Weather Radar Consortium. Further collaborative work is being undertaken through joint funding with the North West Water Authority of a University of Salford post-graduate student who is investigating the use of radar data for real-time hydrological forecasting. Further research is being co-ordinated by the Natural Environment Research Council Committee for the Hydrological Uses of Radar Data on which the Office is represented.

Updated depth–frequency relationships of 1-hour duration rainfall over the United Kingdom have been produced using a much more extensive set of rain-gauge data than was available at the time of the Civil Engineers Flood Studies work in the early 1970s. While this work generally confirms the earlier results, there is strong evidence of systematic periodic variations. Studies continue of sub-hourly depth–frequency relationships using a blend of radar and rain-gauge data.

As well as being used for the analysis of rainfall totals and consequent river and stream flows, radar data have been used in studies of the effect of rain on microwave communication links and in studies of the wet deposition of pollutants. The data have also been used to provide evidence in court cases to supplement conventional observations and to provide information on probable rainfall between gauges.

Satellites

Special topic

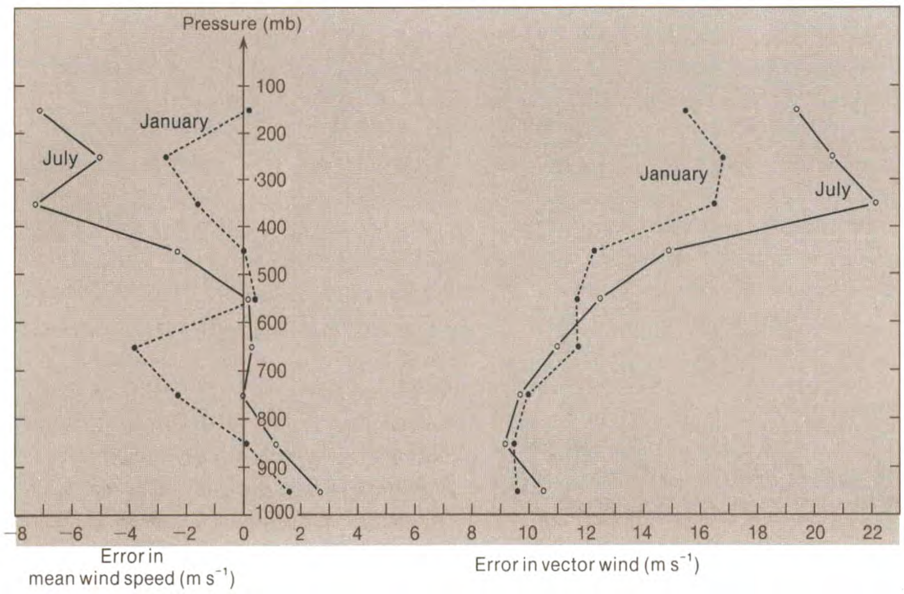
Since the first meteorological satellite was placed in orbit in 1960, satellites have become essential tools for operational meteorology as well as for research. Geostationary and polar-orbiting satellites together constitute an integral part of the global observing system co-ordinated by the World Meteorological Organization and known as World Weather Watch. Currently operational systems providing data of direct interest to the United Kingdom are the geostationary satellite Meteosat, built by the European Space Agency (ESA) but operated on behalf of the European National Weather Services by EUMETSAT, and polar orbiters operated by the United States National Oceanic and Atmospheric Administration (NOAA) and by the United States Defense Meteorological Satellite Program.

Since the late 1960s satellite-generated cloud pictures using visible and infra-red wavelengths have been provided on a routine basis to forecasters. However, it is only within the last 10 years that digital data from polar-orbiting satellites (850 km altitude), and from the geostationary satellite Meteosat (36 000 km altitude), have become regularly available. Much effort has been devoted to procedures for processing these data to provide soundings of temperature and humidity through the depth of the atmosphere, comprehensive images of clouds, their temperatures, and characteristics of the surface of the earth.

In the early 1960s a Satellite Meteorology Branch was formed within the Office, but the subject has grown and during 1988 the main activities were split: the Remote Sensing Instrumentation Branch is concerned with new instrumentation opportunities and their likely impact, while the Nowcasting and Satellite Applications Branch is concerned with the subsequent processing, interpretation and exploitation in forecasting systems.

Operational use of satellite information

Two NOAA polar-orbiting satellites, one overhead during the forenoon and one during the evening, carry infra-red and microwave radiometers that produce imagery and soundings four times a day. The imagery provides information on cloud distribution and the Television Infra-Red Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) radiance data give vertical profiles of temperature and humidity through the atmosphere. The TOVS data are received in Washington, and processed in near real-time to give soundings, known as SATEMs, over the globe with a sampling interval of 500 km. Some countries, including the United Kingdom, can receive the SATEMs with a closer sampling interval of 250 km, but lateness of receipt impairs their operational utility. Cloud imagery is also obtained globally from Meteosat and four more geostationary satellites operated by other nations. The images are obtained at frequent intervals enabling wind patterns to be inferred from cloud displacements. The resulting 'cloud track winds' are available from Washington and are used as input to the Meteorological Office global version of the numerical weather prediction (NWP) model at 850 and 250 mb, roughly 5000 and 35 000 feet above ground level. They are particularly useful over the tropics where conventional observations are sparse.



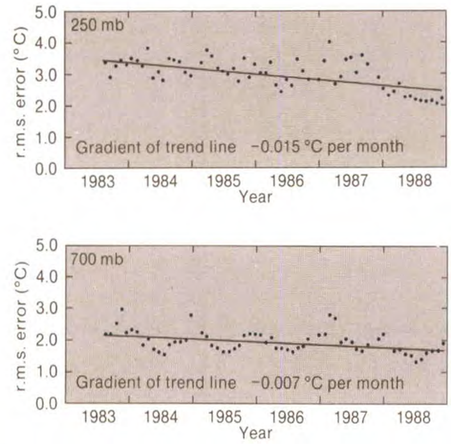
Mean wind speed errors and root-mean-square vector wind errors for January and July 1988 determined from tracking cloud elements between 20°N and 50°N from Meteosat images. Errors are expressed in terms of differences between observations and background wind fields derived from the coarse-mesh numerical forecast model.

To speed up the acquisition and use of soundings from the NOAA satellites, local-area data are received directly at Lasham, Hampshire. The satellite radiances are converted to atmospheric profiles by a 'retrieval' or 'inversion' process involving the manipulation of radiative transfer equations. Software to carry out this task has been implemented at Bracknell on a VAX 11/750 computer. The total processing system, known as the Local Area Sounding System (LASS), provides data in a timely fashion over the North Atlantic and Europe for use operationally in the NWP model data assimilation software suite. The current LASS uses a background field from the numerical model as a first guess on which to base further interactive calculations. The software is known as the Forecast First Guess system. The LASS and SATEM soundings have comparable errors, with a standard deviation of typically 2.5–3.0 dam for the 1000–500 mb thickness.

Some of the sounding data from the NOAA satellites, covering the range 1–100 mb, are obtained from a three-channel infra-red radiometer developed by the Meteorological Office and known as the Stratospheric Sounding Unit (SSU). In all, nine flight models have been procured and prepared for flight by the Meteorological Office. Since the launch of the first SSU in October 1978, a continuous global archive has been maintained providing material for studies of the middle atmosphere. The last SSU will be launched in 1992.

Forecasters use satellite images to identify and analyse different kinds of cloud systems and to predict their movement and development. At outstations, satellite images are found to be particularly suitable for the identification and short-period prediction of localized weather, such as thunderstorms, squall lines and fog. The main source of operational satellite imagery, the AUTOSAT computer system at Bracknell, became operational during 1980. The inputs to this system are mainly analogue data streams. Satellite images from AUTOSAT are broadcast to forecasters on a dedicated facsimile network that currently serves 45 stations within the United Kingdom as well as the Central Forecasting Office (CFO). In addition to this hard-copy output, a graphics display monitor and terminal linked directly to AUTOSAT are available to forecasters in the CFO. Facilities are available to select any image held within the AUTOSAT computer and display it on the monitor. Temporal sequences of images from geostationary satellites are also available. At remote stations that cannot easily be connected to the network inexpensive stand-alone receivers are used. These allow the reception of the analogue data and give output on to graphics monitors.

Since 1979 digital cloud imagery from Meteosat has been received at a Primary Data User Station for use in an operational interactive processing system for blending Meteosat data with radar rainfall patterns. The spatial



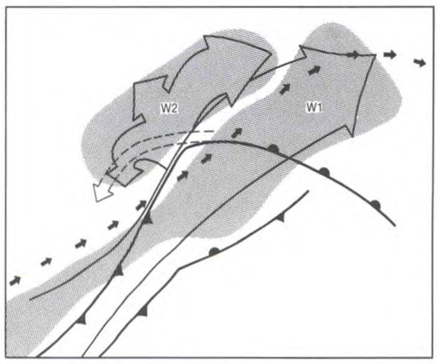
Comparison of retrieved temperature LASS profiles with those from radiosondes. To ensure that the radiosonde provides an acceptable estimate of the true state of the atmosphere for the retrieval, the separation between the radiosonde and the satellite retrieval is not allowed to exceed 150 km in space and 3 hours in time. The plots show monthly root-mean-square (r.m.s.) values at two levels.

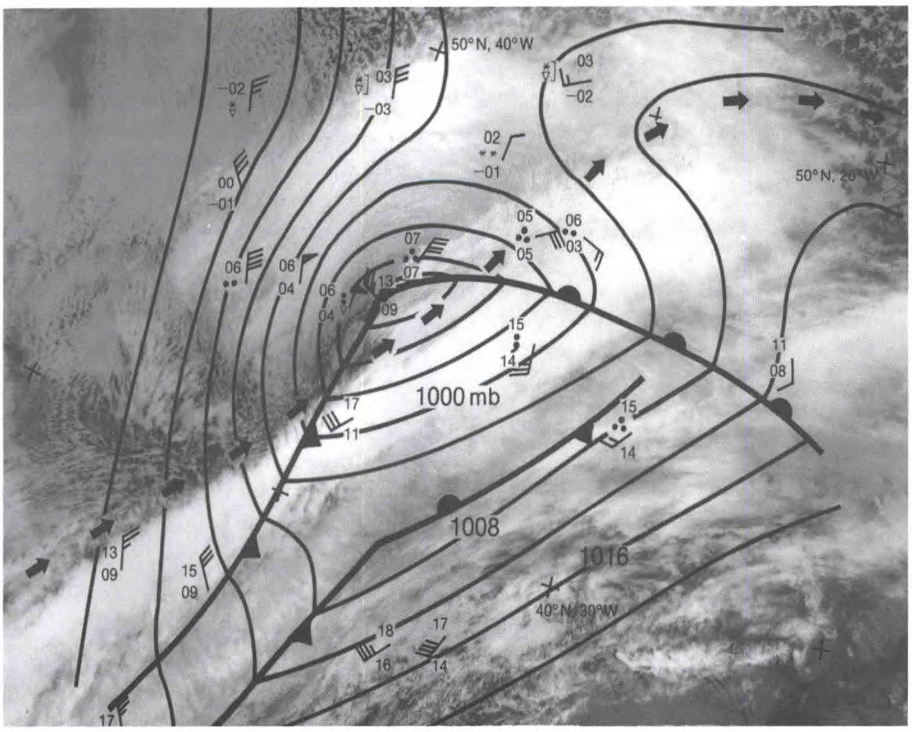
coverage provided by the UK weather radar network is insufficient for a 3-hour extrapolation forecast, even for areas well within radar range, and so the Meteosat imagery is used to infer probable areas of precipitation outside the area of good radar data coverage. During daylight hours a combination of data from visible and infra-red channels is used. The system is operated by a forecaster using a menu-driven work station with touch-sensitive screens. The first stage of the half-hourly operational cycle involves additional corrections being applied to the radar data and the resultant quality-controlled picture is disseminated routinely to users. The forecast is produced by advection of the combined radar and satellite precipitation field at its recent velocity. A significant advance during the year has been the increase in spatial resolution of the forecast output from 20 to 5 km to match the resolution of the input data, without a significant increase in processing time. The enhanced resolution allows the inhomogeneous nature of rainfall fields to be depicted more clearly in the forecast.

Current developments

The satellite soundings produce an improvement over the forecast model background field. The impact is considerable in data-sparse areas but in parts of the northern hemisphere rich in radiosonde observations the improvement is small. Until recently, profiles retrieved from TOVS sounding data have been used in NWP in a rather simplistic manner being treated in a similar way to radiosondes but assigned a lower weight because, when considered as profiles, they have higher errors than radiosondes.

It is now coming to be accepted that this is an inappropriate way to use the satellite data and one which can degrade an otherwise good analysis; the TOVS measurements are of radiance, not temperature, and they should be treated accordingly. Over the last 3 years, research has proceeded on more direct ways to use radiance data in NWP analysis. The technique, essentially, is to use 'first guess' temperatures to compute radiances which are then compared with measured radiances, the



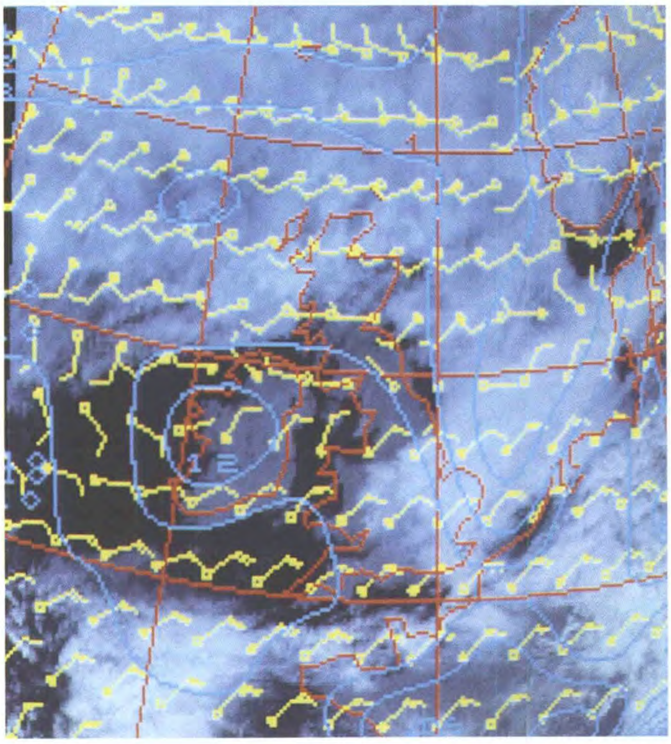


NOAA-9 infra-red image for 1721 GMT on 30 January south of Greenland showing a cloud signature that often precedes the very rapid deepening of a depression. (The central pressure subsequently fell by 25 mb in the next 12 hours.) The large canopy of cloud (shown white) is penetrated by a cloud-free wedge lying close to a very strong upper jet stream (arrowed). The cloud forms by ascent of air in two 'conveyor belts', W1 and W2 (see schematic), associated with the frontal systems. The heaviest rain falls from W2 as it ascends very rapidly over the more intense northern frontal zone. (Photograph by courtesy of University of Dundee) differences being used to modify the first guess temperatures. The assimilation of radiance data is thus treated as part of the NWP analysis and not as a separate temperature retrieval phase followed by analysis. Hence it is planned that the satellite data processing and NWP analysis will be drawn together and integrated within the operational computer system. A modular approach will be used to enable the procedure developed for TOVS soundings to be extended to handle the new advanced TOVS data when they become available in the early 1990s.

Satellite imagery is the only source of data (except for radar imagery which has limited coverage) with a resolution comparable to that of the Meteorological Office mesoscale model and is thus well suited for the initialization of mesoscale features. Meteosat infra-red imagery currently used in the Interactive Mesoscale Initialization procedure provides direct information on humidity fields from locations of clouds. The main effort to develop effective use of imagery within this procedure will be the exploitation of conceptual models to help forecasters to understand the images and use them together with conventional observations in the model initialization process.

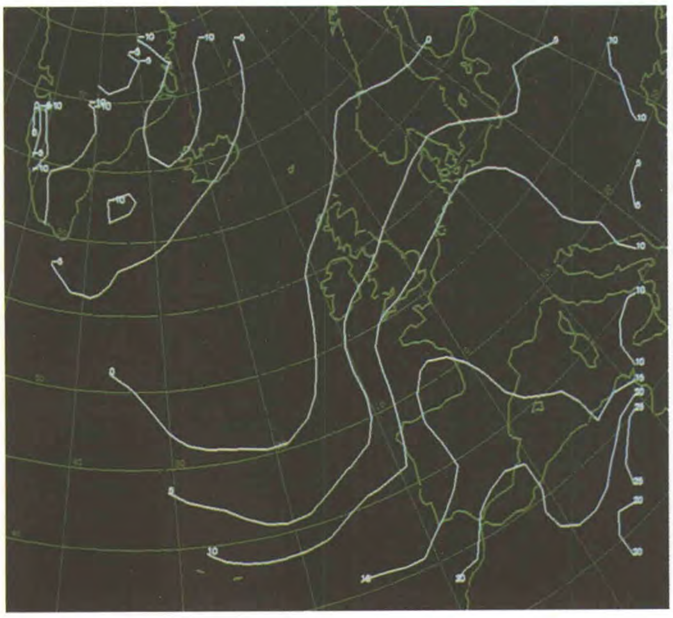
Analogue facsimile formats, as in AUTOSAT, suffer from poor quality of the processed images, uncertainties in the interpretation of image brightnesses, and high cost. Moreover, the analogue data streams have less spatial and radiometric resolution than the digital equivalents and contain little information for calibration purposes. To solve these problems AUTOSAT-2 is being developed. This will generate a variety of meteorological products from the digital data streams available from both polar-orbiting and geostationary satellites. These products will include accurate determinations of surface and cloud-top temperatures, the detection of fog by day and night, and also quantitative products for the mesoscale model including albedo, cloud type and amount, and temperature. AUTOSAT-2 will be located at Lasham where the raw data are received. The Weather Information Network will provide forecasters at outstations with the images on video work stations.

Clouds result from the physical and dynamical processes over a wide range of scales but the observed patterns need to be interpreted within the context of other observations, numerical model products, and conceptual models. Procedures for doing this are to be laid out clearly and training provided. An imagery interpretation manual that gives more dynamical insight than existing manuals is being written. The efforts of meteorologists in Europe and the USA are being co-ordinated by means of workshops at the Meteorological Office College and an editing committee consisting of research workers and forecasters within the Office.

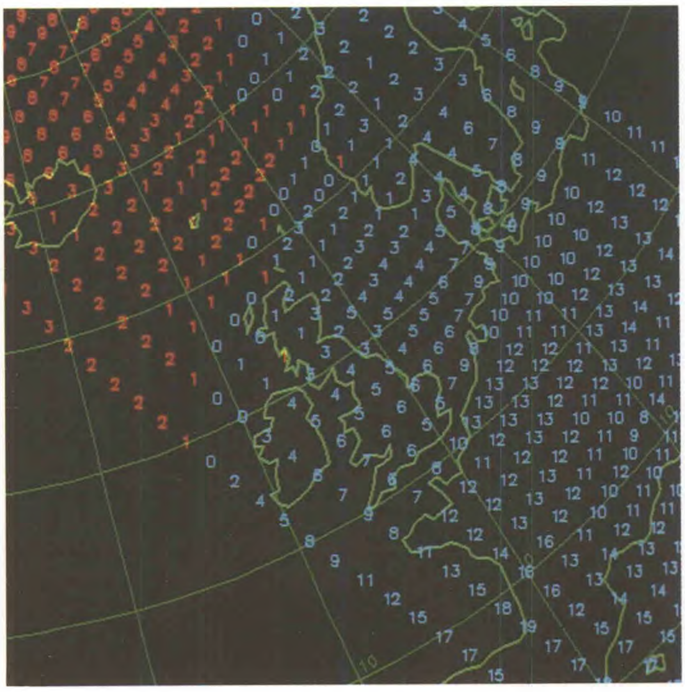


Visible image from Meteosat for 5 April together with 10 m winds (yellow), 1.5 m temperature contours (blue) and geographical information (red). The wind and temperature data were obtained from the Meteorological Office's fine-mesh numerical weather prediction model and combined with the Meteosat image using the HERMES system.

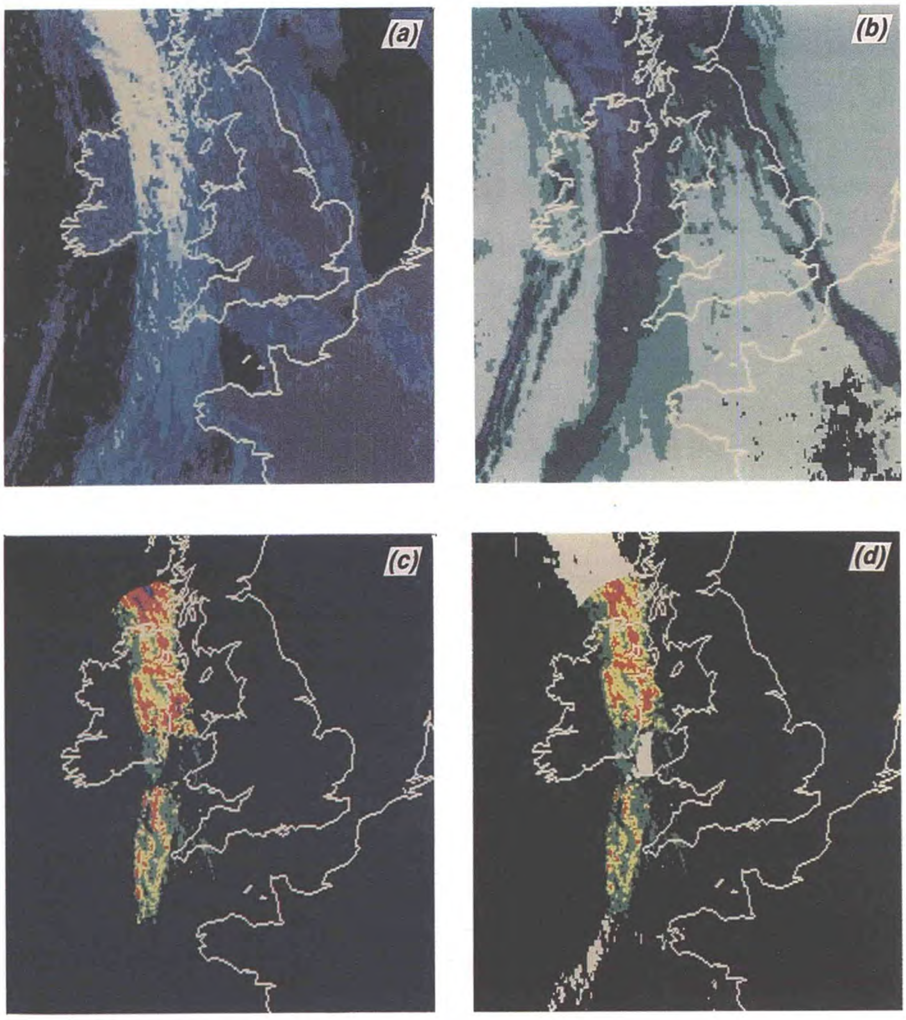
LASS temperature field and spot temperature values at 850 mb for the evening of 15 October 1987



Isotherms derived from three successive passes of NOAA-9 showing the tight thermal gradient between warm air over Biscay and cold air over the eastern Atlantic prior to the storm of October 1987



Temperatures (°C) for the 1820 GMT pass of NOAA-9 showing the high spatial density of information available from the satellite (negative values in red)



Figures (a), (b) and (c) show the basic data sources used by the FRONTIERS system to produce analyses of precipitation. Figure (a) shows a visible image from Meteosat at 1530 GMT on 8 August, (b) the corresponding infra-red image and (c) the precipitation detected by the UK weather radar network. The final precipitation analysis for the same time as deduced from the radar and satellite data is shown at (d).

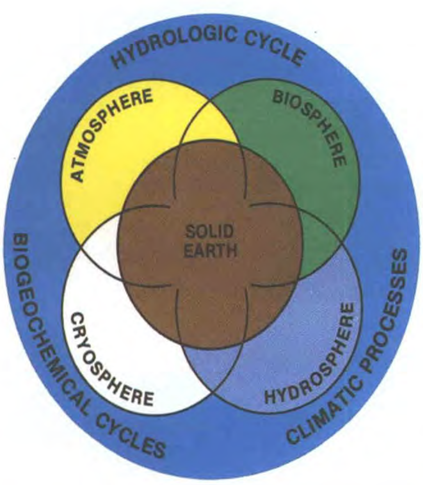
The future

During the next decade further sources of satellite data will become available. Of particular importance is Meteosat Second Generation (MSG) which is likely to provide multi-spectral high-resolution imagery and a limited sounding capability from geostationary orbit. It is planned to launch the last of the current series of Meteosat operational satellites in 1990 and MSG-1 in late 1994 although some slippage is likely.

The NOAA polar-orbiting satellites to be launched during and after 1993 will carry the Advanced Microwave Sounding Unit (AMSU). The AMSU, a 20-channel self-calibrating microwave radiometer covering the frequency range 20–190 GHz, will replace the four-channel Microwave Sounding Unit (MSU) used to give the TOVS data on the existing NOAA satellites. Under cloudy conditions it should provide temperature soundings superior to those from the current MSU. Indeed the quality of these advanced TOVS soundings under many cloudy conditions should be comparable to that achieved in clear conditions with the present TOVS. AMSU will also provide the capability of measuring water vapour profiles between 300 mb and the ground. In addition these sounders should allow the identification of rain cells and an indication of their intensity. The resolution, 45 km for the temperature channels and 15 km for the precipitation and humidity channels, will be good enough to provide useful image products.

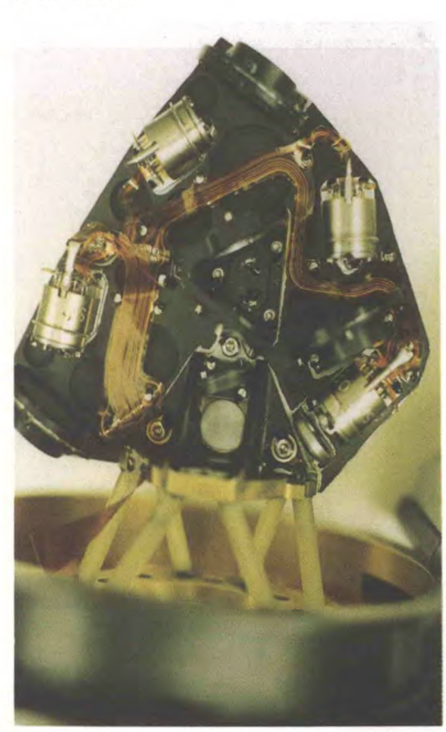
The procurement of AMSU is divided between NOAA (AMSU-A, the temperature channels) and the Meteorological Office (AMSU-B, the humidity channels). A development model of the AMSU-B critical microwave receiver, constructed under an industrial contract, is under assessment and tenders have been invited for the construction of the first three flight models. The Meteorological Office has also initiated a scientific programme aimed at understanding the radiometric and spectroscopic aspects of AMSU-B. The basic microwave properties of water in its three phases are being measured in the laboratory and an aircraft radiometer is being fitted to the Hercules aircraft of the Meteorological Research Flight (MRF) for airborne trials. These measurements will assist in generating and evaluating the retrieval algorithms needed to interpret the AMSU-B data.

The Upper Atmosphere Research Satellite (UARS), due to be launched in 1991, will provide atmospheric data above the troposphere, including regions known to be susceptible to change by external agents. It will measure 16 chemical species as well as temperature and wind over a period of around 18 months. A senior member of the Office is one of the NASA-designated Principal Investigators for theoretical studies. The Meteorological Office already undertakes daily analyses of the



The Earth Observing System (By courtesy of NASA)

The ATSR flight model focal plane assembly showing the four detector channels which are cooled to 80 K



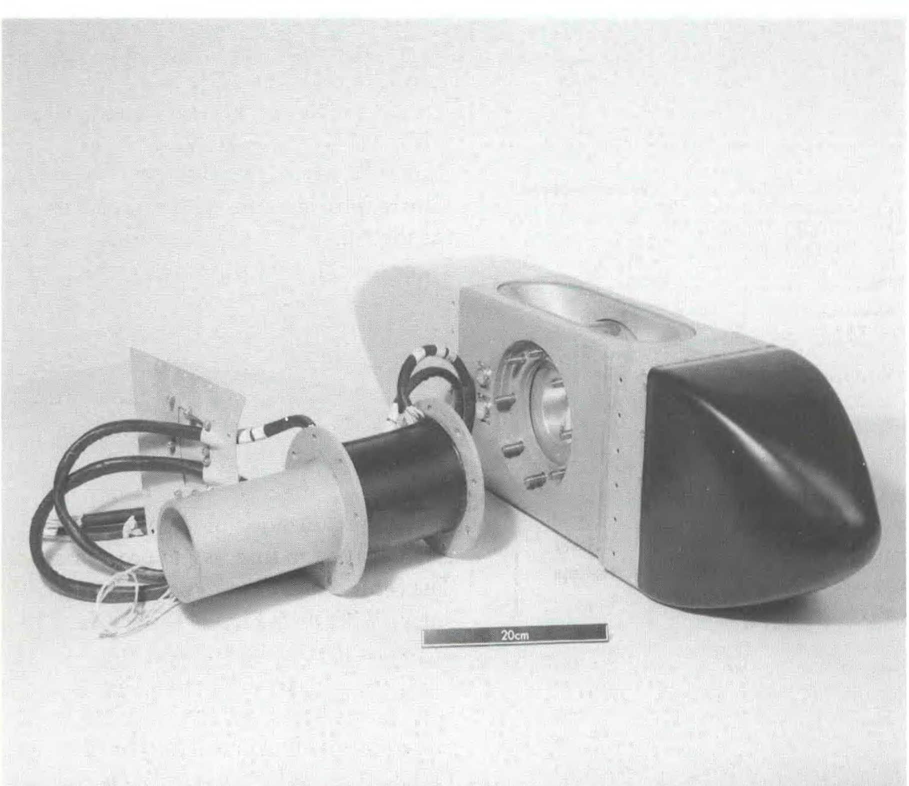
stratosphere using data from SSUs. These will be provided in near real-time to other UARS investigators for use as corroborative data. UARS data will be received via a transatlantic telecommunication link provided by NASA for experimental use as input to the operational data assimilation scheme. Information gained about the composition and behaviour of the stratosphere and mesosphere will be used in diagnostic and modelling studies. Details of the photochemistry will be examined by studying changes taking place along trajectories of air movement.

The European Remote-sensing Satellite ERS-1, due to be launched in 1990, will carry a number of instruments for making measurements at the ocean surface. The main interest to the Meteorological Office is in the measurement of waves, surface wind, and sea surface temperature. Wave height information will be provided by a radar altimeter, and surface wind by measuring the radar back-scatter of the ocean surface at three azimuth angles over a 500 km wide swath. The surface wind speed and direction at 50 km intervals can be derived from these measurements to an accuracy of $\pm 2\ m\ s^{-1}$ (or $\pm 10\%$) using fields from an NWP model to provide a first guess in a similar way to the current temperature retrieval system. Both the wind and wave data will be used as input to the operational weather prediction and wave models. The data will be assimilated with other conventional data in a way that prevents imbalances between the different data sources. Sea surface temperatures will be provided by an instrument known as the Along Track Scanning Radiometer (ATSR) for which the Meteorological Office has supplied the detection package to the main contractor, Rutherford Appleton Laboratory. The ATSR will have an accuracy of 0.3 K which is better than that of currently available instruments and is important for studies of the relationship of sea surface temperature anomalies to weather and climate.

Finally, the Meteorological Office will have a role in major new programmes taking satellite meteorology into the next century. The Earth Observing System is the name given to the NASA component of an ambitious project in which the space agencies of the USA, Europe and Japan (NASA, ESA and NASDA) are co-operating to provide a set of 'state of the art' observations over a decade aimed at describing the atmosphere/ocean/cryosphere system and its climatology. To achieve this, long-lived polar orbiters are proposed with individual payload capabilities of about 2 tonnes (the present operational meteorology package has a mass of 500 kg) and power capability of several kilowatts. The first NASA platform is due for launch in 1995 and is to be followed by another NASA platform, an ESA platform and a NASDA platform during 1997. The payloads are being co-ordinated to provide a coherent set of observations from the mesosphere down to the surface over the whole spectral range from visible to microwave. They will include limb and nadir sounders and use active as well as passive techniques. New instruments, such as the Atmospheric Infra-Red Sounder designed to provide temperature soundings with improved vertical resolution, and the Laser Atmospheric Wind Sounder to give global wind measurements in three dimensions, are likely to provide further research opportunities for Meteorological Office scientists. Data from these instruments and others currently being considered will contribute to the further understanding of atmospheric dynamics and atmospheric chemistry. A new programme, the Global Energy and Water Cycle Experiment, part of the World Climate Research Programme, depends upon data to be acquired from satellites during 1995–2000.

National and European co-operation

Satellite meteorology and space applications in general are in a state of ferment nationally and internationally. Programmes are too wide-ranging for any group to undertake in isolation, and the work in the Meteorological Office has to be seen as part of a collaborative network. An important national link is between the new Remote Sensing Instrumentation Branch and the British National Space Centre (BNSC) through its Director of Projects and Technology. This Branch, now located at the Royal Aerospace Establishment, Farnborough, can benefit from proximity to the BNSC Space Facility and the MRF Hercules to be used to flight-test satellite instruments. International links in satellite meteorology are both bilateral with other National Meteorological Services and through membership of ESA and EUMETSAT. Major issues now being discussed of particular importance for operational weather forecasting include the nature of Meteosat Second Generation and of the polar-orbiting satellite programme.



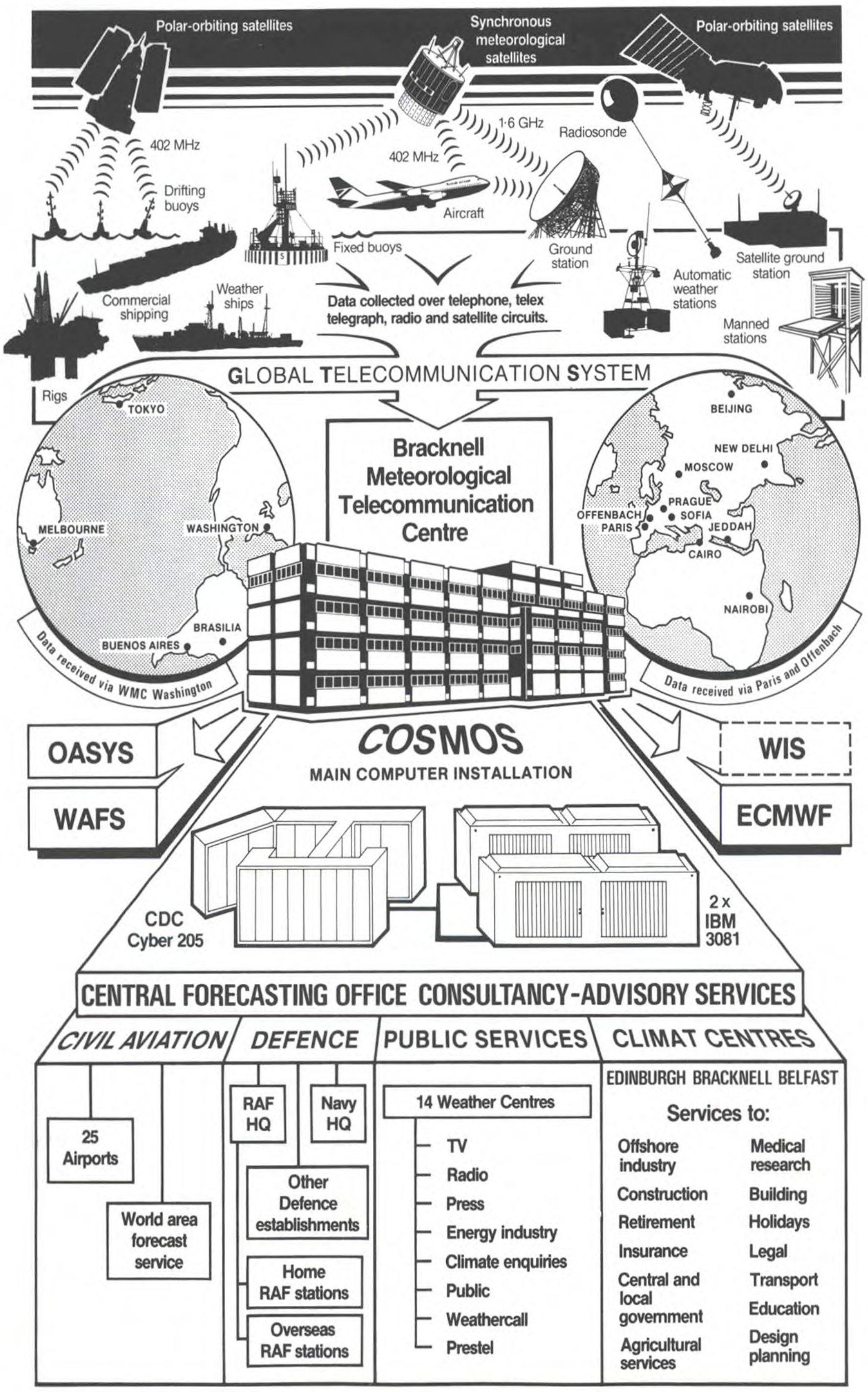
Scanning system housed in a pod and the mounting pylon for the Microwave Aircraft Radiometer Scanning System. This is mounted outside the MRF Hercules with the left-hand flange bolted to an aperture in the side of the aircraft and the pod cantilevered off the right-hand flange. There are two similar viewing ports on the pod which permit the collection of radiation in sequence from above and below. This radiation passes down the centre of the pylon to a two-channel radiometer mounted inside the aircraft. Calibration targets are mounted inside the fibreglass cones shown at each end of the pod.

The exploitation of information systems

Special topic

Information is the essence of weather forecasting. There are few other disciplines where the perishability of data and the products derived therefrom provide such an incentive to exploit the available technology in computing and communications, referred to collectively as Information Technology or IT for short.

Even in areas where limited lifetime is not the dominant factor, such as research and services based on climate data, the quantity of data and the need to ensure quality and availability demand the exploitation of IT. Indeed the world meteorological community in general and the Meteorological Office in particular have long been leaders in exploiting new methods of communication, automated or otherwise, and all levels of computing from calculators to supercomputers. It is only comparatively recently that IT has been considered by the Meteorological Office for support to management and administration but rapid progress is now expected in this field as well.



Global observing and collecting system, UK automated processing system, forecasting and consultancy services

Support for forecasting

Modern weather forecasting is inseparable from the technologies of computing and communications. Observations of the atmospheric state must be gathered, stored, and processed and the results disseminated according to tight schedules. The only way in which the current demand for meteorological forecast services can be met cost-effectively is by the application of extensive automation. The role of the forecaster may have been changed as a result of automation, but it has been by no means eliminated. A complex interaction between the forecaster and the supporting IT systems is necessary so that the best level of performance in the provision of services to customers can be achieved

The Meteorological Office's forecasting organization is divided between the Central Forecasting Office (CFO) at Bracknell and outstations around the United Kingdom and with RAF units overseas. The typical outstation has a localized function, supporting the RAF or providing commercial services in a region of the United Kingdom; a few outstations also have specialized functions, as at Headquarters RAF Strike Command (providing guidance to other forecasting outstations in the Defence area) and London Weather Centre (providing forecasting services for the North Sea). As described in detail in the section on central forecasting, the CFO is responsible for monitoring the running of the numerical weather prediction (NWP) models (for NWP see Box 1) and other centralized forecasting services. Since forecasting is the primary business of the Office, it is not surprising to find that the history and present organization of IT in the Office is closely tied to forecasting processes. The central mainframe computing complex (COSMOS) and the central telecommunication facility (AUTOCOM) are co-located with the CFO in the Richardson Wing of the Headquarters building at Bracknell. Outstations with specialized functions are supported by their own computer

1. Numerical modelling

A range of numerical models are used in the Meteorological Office in support of weather forecasting and research. Indeed, their use has become so prevalent that the ability to run these models is essential for the execution of the routine forecasting role of the Office.

It was the mathematician L.F. Richardson who, in the early part of this century, proposed the use of numerical methods to solve the mathematical equations that describe the physical and dynamical laws which the atmosphere obeys. Although this initial attempt at numerical weather prediction (NWP) was unsuccessful, because of inaccuracies in the computational method adopted, it nonetheless set a framework for later developments at a stage at which the necessary calculations could be completed sufficiently quickly for some useful guidance in forecasting the weather to be gained.

The formulation of models used for NWP has always been constrained by the computing technology available. In particular, the two main limitations are the speed of processing that can be achieved and the size of main memory that is available for storage of the variables used in the model. The ability of the computer industry to construct computers with greater power has been closely related to the development of the underlying technologies of electronic circuits. The last 30 years have seen the progression of electronic devices from thermionic valves, through transistors, integrated circuits and large-scale integrated circuits, to very large-scale integrated circuits that can incorporate tens of thousands of electronic switches on a single piece of silicon, colloquially known as a 'chip'. These advances have not only enabled much more powerful processors to be designed and built but have also allowed much larger main memories to be provided at an economic cost. Early computers used magnetic cores as main storage and this technology has now been completely replaced by the use of semi-conductor methods. The general trend in computing power is illustrated opposite. The first machine installed in the Meteorological Office was a Ferranti Mercury computer and this was capable of 3000 floating-point multiplications per second. This can be compared with the performance of the Control Data Corporation ETA10, installed in the middle of 1988, which is capable of achieving peak processing rates at least a million times faster than the Mercury.

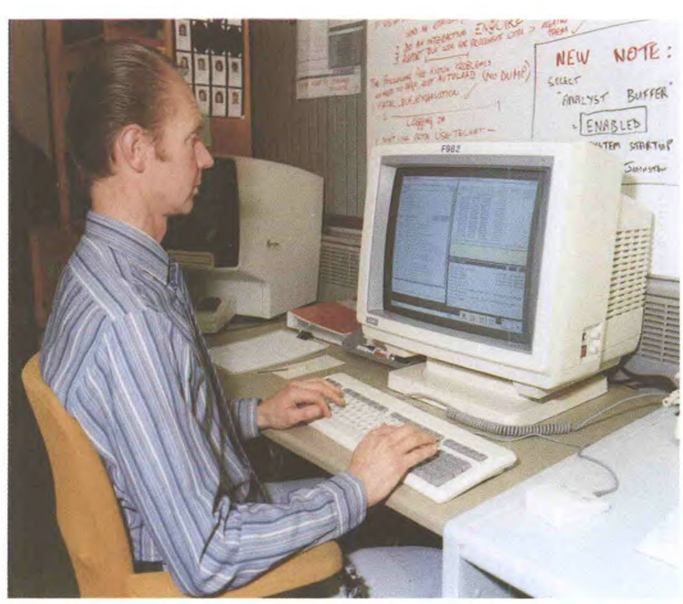
The developments in NWP have progressed step by step with the available computing technology. Numerical forecasts began to be run on an operational basis at Bracknell in 1965. The model used at that time represented the vertical structure of the atmosphere by storing variables at only three levels. The mathematical formulation was simplified to reduce the number of calculations to be made. In 1972 a completely new model was introduced. This was based on the fundamental physical and dynamic equations of the atmosphere, sometimes known as the primitive equations; the vertical structure was represented by computing the basic variables, such as pressure and wind speed and direction, at ten levels in the atmosphere. In 1982 a 15-level version of the model was introduced and was subsequently extended to cover the whole globe rather than part of the northern hemisphere as previous models had done.

Numerical modelling is a technique which is being increasingly used for research, as well as for weather prediction. Models have been developed specifically to study the effect on climate of changes in atmospheric composition. Much impetus was given to this work in the early 1970s with the studies of the effect on the ozone layer of supersonic aircraft flying in the stratosphere. More recently, other studies have been made into the impact on the ozone layer from man-made compounds and into the impact of increasing concentrations of carbon dioxide — the so-called greenhouse effect. As with NWP, the provision of improved computing facilities allows a direct increase in the complexity of models used for research and, hence, an improved understanding of the impact of man's effect on the atmosphere.

systems and the other outstations in the United Kingdom are equipped with a variety of microcomputer-based systems. All these locations are linked by dedicated meteorological telecommunication services.

The first step in the process of forecasting is the making and gathering of observations. Many instrument systems now incorporate IT elements, from the single-board computers in automatic weather stations to the very powerful systems needed to process the voluminous digital data streams from satellite-borne instruments. Observations made world-wide arrive at Bracknell over the Global Telecommunication System (GTS), part of the World Weather Watch programme of the World Meteorological Organization. (See Box 2 for description of automated data acquisition.) The data are passed from AUTOCOM into COSMOS for use in NWP and other aspects of support to the CFO, and are also distributed to outstations. Imagery from polar-orbiting and geostationary satellites is obtained via the ground station at Lasham, Hampshire and processed by the AUTOSAT computer system at Bracknell into the formats required by forecasters; some digital-image products are also passed to COSMOS. A second-generation, all-digital system, AUTOSAT-2, is being implemented at present. This new system will process the data at Lasham and distribute large quantities of imagery to COSMOS (for the CFO and for incorporation into products for customers) and to computer-based display systems at outstations. Another system, RADARNET, processes radar imagery into standard formats and distributes these to the CFO, COSMOS, outstations and customers.

Colour graphics display in use in the Central Forecasting Office



Operating the ETA 10

The use of graphics by meteorologists began long before the use of computers, and some products (e.g. aviation significant weather charts) are still hand drawn. However, the vast majority of graphical output is computer-generated from observations or NWP results, either as hard copy or to be viewed on colour visual display units (VDUs). This has eliminated a great deal of manual labour since the days when every forecasting office had to employ staff to plot charts. Automated plotting of charts is very cost-effective but has not changed the forecasters' job very greatly; they may get neater charts more quickly but they still pick up a pencil to analyse the chart. Some forecasting tasks, particularly in the CFO, require interaction between man and computer. The first application of such interactive systems, now in use for over a decade, was quality control of data and initial-guess fields for NWP. More recently, some specialized interactive procedures have been introduced in the CFO. FRONTIERS is a system which uses a mixture of automatic and interactive graphical techniques to 'clean up' radar images and merge them with satellite imagery. The analysis scheme for the mesoscale NWP model (expected to become operational soon) has been designed from the outset to use interactive techniques because the particular problems of working on this scale could not be overcome by conventional techniques within the tight schedule imposed on the analyst. Graphics is an area which is still developing (see Box 4). It is dependent partly on the available technology and partly on the evolution of techniques which are found to be effective in the demanding environment of a forecasting office.

2. Automation of data acquisition

From the late 1970s steady progress has been made with implementation of automated observing systems and there are now some 47 systems at remote sites on land and also systems on buoys, light-vessels, oil rigs and platforms in the seas surrounding the British Isles. Observations from these stations and from about 200 manned observing sites in the United Kingdom need to be collected and distributed with minimal delay.

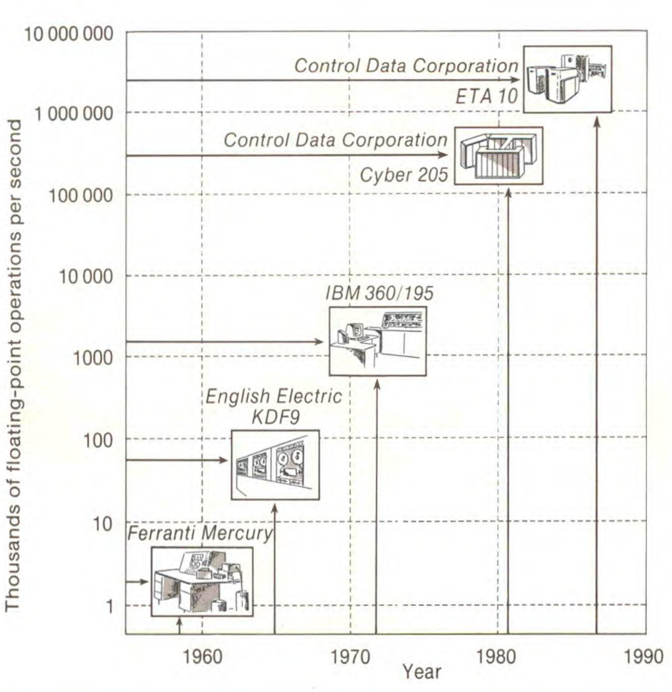
Microcomputer systems known as AUTOPREP are used at ten regional offices to collect the individual reports into bulletins for transmission to the automated telecommunication centre (Met TC) at Bracknell. From the early 1970s a phased programme for automation has been implemented to handle the national collection and dissemination of these data as well as the international exchange of data world-wide over the Global Telecommunication System.

Improved efficiency of the global network gained from automation in many countries has resulted in a steady increase in the volume of data received, and the implementation of satellite-based observing systems has contributed further large amounts of data for exchange.

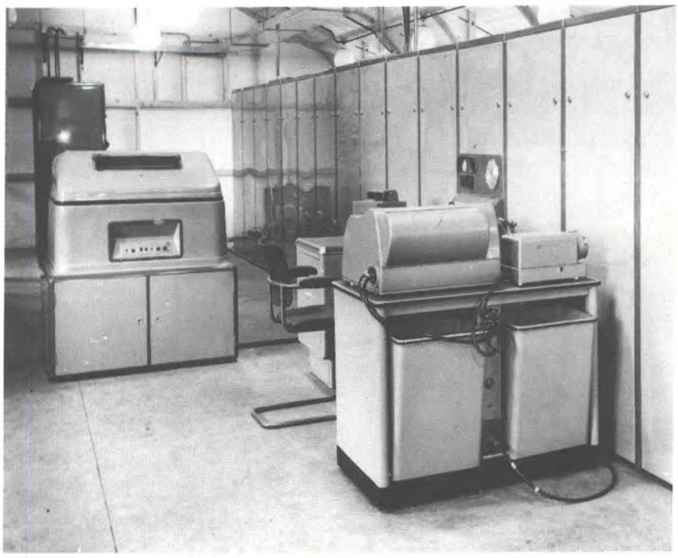
The present AUTOCOM (Phase IV) message-switching system, based on Tandem computers, was brought into service in 1985 and has been enhanced during the year to cater for the growing traffic. This system provides effective international data exchange at high speeds using international standard telecommunication procedures and protocols.

In the next few years the system will be expanded to provide the main central node of the Weather Information Network which will provide high-speed collection and dissemination of observational data, forecast products and radar and satellite imagery to sophisticated work stations at all forecasting offices throughout the United Kingdom. It is planned to use the most modern data-handling and data-management standards for these purposes including the message-handling service procedures laid down in the X400 standard and a high-speed local area network connection to link AUTOCOM to the COSMOS data-processing systems.

At the present time the typical outstation forecaster receives data and products by a variety of means. Alphanumeric data and messages are broadcast from AUTOCOM in a teleprinter format; plotted and forecast charts are disseminated from a dedicated computer system named AUTOFAX either as analogue facsimile or in digital form to drive a printer; satellite imagery is broadcast from AUTOSAT to a modified facsimile receiver. All these devices generate reams of paper — the first thing to catch the eye of a visitor to any forecasting office. The forecaster may also view radar images on a dedicated colour VDU. Many forecasts are distributed using telex or similar means; the forecaster prepares text using a word-processor linked directly to the telecommunication system. (Not many years ago, a teleprinter operator would have transmitted the messages from the forecaster's script; word-processing techniques have now completely eliminated this intermediate task.) To prepare the forecasts, textual and graphical, for road conditions, another microcomputer system is used. Despite these advances some graphical products will continue to be produced by hand and then distributed using facsimile.



The Ferranti Mercury computer



Processing speed of computers used in the Meteorological Office shown against year of purchase

3. Data management

Even before the advent of modern technology, weather observers generated large quantities of data. A visitor to the Office's technical archives in Bracknell (or to the smaller archives in Edinburgh and Belfast) can inspect many series of observation registers, autographic records and charts going back into the last century. Earlier this century, selected data were punched onto cards for electro-mechanical processing and subsequently these cards became the foundation of computer-based climatological records.

The introduction of automated systems led to rapid growth in the volume of data which are generated and also in those which need to be processed and stored. In particular, the results from NWP (see Box 1) and from remote sensing (see section on satellites) have come to dominate the real-time flow of data over the computer networks that are being designed and implemented by the more advanced National Meteorological Services.

Fortunately there are characteristics of these data which can be exploited in the design of systems. Forecasts and image products are highly perishable and can be discarded within a few hours. At the other extreme, observations that have value for climatology are retained permanently.

The principal databases are maintained on COSMOS. The Synoptic Data Bank (SDB) holds observations gathered in real time to support NWP and other forecasting applications; data in the SDB remain on-line for only a few days. The Climatological Data Bank (CDB) is formed from the SDB and other sources of observations, following careful quality control; the bulk of the information is held on magnetic tape, with back-up copies kept remote from the main storage area. Both the SDB and the CDB were designed in the early 1970s and were advanced in concept for their time. Thanks to the changes in technology and in patterns of usage (e.g. the commercial exploitation of the CDB), these major systems now need to be redeveloped. This may involve the use of new digital storage technology (e.g. optical disk) but the unique and irreplaceable nature of the CDB dictates a conservative approach.

The Office also uses commercially available software for database management, particularly for administrative applications but also for those scientific projects which involve complex data structures. Design of these databases uses the Structured Systems Analysis and Design Methodology which is now widely used in government departments.

All the data collections within the Office are subject to the Public Record Acts; the Data Management and Review Board advises on the policy for selection, care and disposal of these records, taking account of scientific and public interests, both under the Acts and more generally.

It has long been evident that there is a pressing need for a more integrated, computer-based environment to support the three stages of work: acquiring and presenting the meteorological data, adding value through the exercise of the forecaster's skill, and forming and transmitting the products required by the customers. The Office has developed a strategy for achieving this integration, known as the Weather Information System (WIS). WIS has two main components, WIN (Weather Information Network) and ODS (Outstation Display System). WIN will use digital communication techniques to interconnect sources of meteorological data and products (mainly at Bracknell), the outstations and the dissemination channels to customers. ODS will receive data from WIN, make them readily available to the forecaster and pass customized products back to WIN for onward transmission. Although plans are still being developed, some steps towards implementation of WIS have been taken. An initial version of ODS is installed in 19 forecasting offices (mainly at RAF units) and is supplied with data over an interim digital network shared with the RAF. The use of digital techniques for chart dissemination has proved successful and extension of this method (about four times faster than facsimile) to more outstations is planned. The next version of ODS will include much improved graphical facilities, but many of the desired features must wait for the full implementation of WIN.

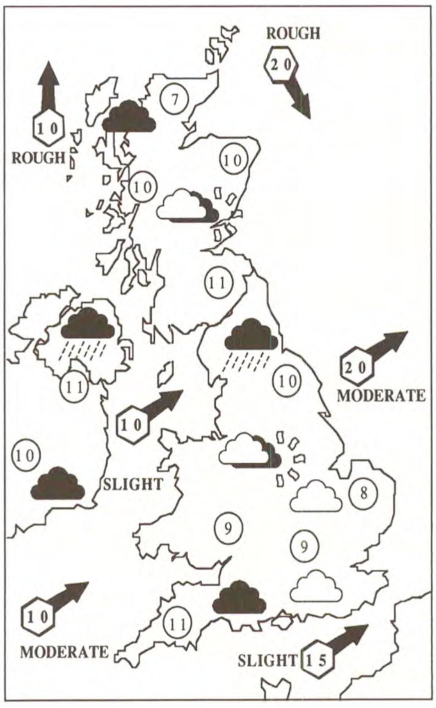
It is important to give the forecaster the best possible tools for the vital job of adding value to the automated products, but the ultimate test is the benefit derived by the customer. In some areas of business there is a danger that shortcomings in product design or delivery, or failure to respond to a changing requirement, may lead to failure to capitalize on the quality of the science and IT systems evident within the Office. An increasing amount of effort will need to be directed to the problem of getting the right product to the right person at the right time, particularly by electronic means. The great potential of IT in this area is illustrated by the preparation of graphics for television weather presentations; here the skills of the meteorologist, broadcaster and technologist have come together with impressive results. For some tasks, off-the-shelf solutions work well; standard desktop publishing equipment is being used successfully to generate the graphics for weather forecasts that appear in some of the national newspapers. The extension of computer-based techniques from the forecaster to the customer has arrived.

Services to management and administration

In commerce and industry the most common application of computing is to support functions such as accounts, personnel records and payroll. The Office has relied for many years on central facilities in the Ministry of Defence to meet these standard business needs. In the last decade, however, new requirements have arisen for detailed management information, covering a wider range of topics particularly in response to greater delegation of authority and the growth of commercial activity outside the well established aviation sector. Managers who are responsible for providing a particular service must have good information about their customers, the cost of supplying products and the revenue earned; without such information, they have no firm basis for marketing activities such as product definition, pricing and promotion.

To meet the needs of both commercial activities and internal project costing, a facility known as MAIS (Management Accounting and Information System) has been developed over the past 8 years. MAIS uses proprietary database management software (see Box 3) and runs on COSMOS. The introduction of

Forecast issued to the Guardian for publication on 30 December



MAIS in a scientific culture has not been straightforward, and there are areas, such as stock control and expenditure monitoring, which are still largely manual in operation; nevertheless, MAIS has played an important role in preparing the Office for greater administrative and financial autonomy in the near future.

In recent years the advent of cheap software packages running on microcomputers has transformed business computing practice. Many staff within the Office use these packages for preparation of reports, budgets, etc. This has been beneficial in terms of personal productivity but fails to realize the greater potential which shared access to information brings. An effort is therefore being made to define an integrated system which will provide these standard business applications. The first stage of implementation will include facilities for senior managers and their secretaries, staff engaged in the planning and control of commercial services, and key support staff. The system will extend across those sites in the Bracknell and Reading area where Headquarters units are located, thus overcoming some of the problems of geographical separation.

Another long-standing problem has been the inadequacy of telephone services at Headquarters. A number of piecemeal solutions have been patched onto the original Private Automatic Branch Exchange (PABX) in order to circumvent shortcomings, but total replacement was clearly needed. A new exchange, based on the latest digital-switching technology, was installed late in 1988, and will be brought into service early in 1989. By means of small satellite exchanges these facilities extend to four other sites in the Bracknell area occupied by the Office. The new PABX is also capable of switching computer data, but priority in the coming year will be given to the introduction of voice telephony services.

4. Man–machine interface

Over the years since computers were invented, there has been an evolution of the way in which human beings interact with computers — the so-called 'man–machine interface'. The interface needs to allow two-way communication; it is necessary for instructions and possibly data to be provided to the computer and the computer needs to provide the results back to the user.

In the early days of computing, it was necessary for instructions to be provided to the computer in its own language, that is, machine code. Since then the methods used for providing these instructions, or programming, have evolved through the use of assembly-level languages to high-level languages. FORTRAN is a high-level language which is particularly suitable for scientific work and is the major programming language used in the Meteorological Office. More recent developments include fourth-generation languages which for certain types of work enable very high programming productivity to be achieved. The trend is therefore clear: machines are becoming easier to program but at the expense of more machine resources being required to translate the program into a form on which the computer can act directly; in many cases the resultant code runs less efficiently.

The human brain is able to assimilate an enormous amount of information if it is presented in a suitable form. Graphical or pictorial formats are especially suitable and have long been in use in the meteorological context in the form of the traditional plotted weather charts. There has, therefore, been a marked trend for data generated by computers to be presented in graphical forms, both on paper and on VDUs.

The technology of graphical VDUs has been evolving and, particularly over the last 8 to 10 years, there has been a rapid improvement in the facilities available at a given price. In designing an application for a graphical VDU, the following characteristics need to be considered: the resolution of the screen, the number of colours which can be displayed, the speed at which a picture can be drawn, and the speed at which data can be passed from the main computer to the VDU. Another important factor relevant to the design of an interactive application is the mechanism by which the user can provide information back to the computer; possible methods are use of a touch-sensitive screen on the VDU, light pen, data tablet or 'mouse'.

To achieve the best results from the Office's IT systems, continuing progress has to be made in improving the man–machine interface. There have already been major improvements in the hardware and software that provide this interface and in the ergonomic concepts which are used as a basis of the interface design. Developments of the kind described are expected to give many benefits in forecasting and research at the Office.

Facilities for research

The developments in IT over the last 20 years have been crucial to the great strides made in research in meteorology in the Office. It is now possible for complex experiments to be mounted and pursued to a successful conclusion, with large quantities of data being recorded, analysed and interpreted.

Many modern instruments incorporate IT for automatic or semi-automatic operation. In addition, the use of digital recording equipment allows more data to be captured, with improved accuracy. It also facilitates the preparation of the data for further processing.

IT also makes feasible a limited amount of data processing and display of results in real time. Although the data will be more thoroughly and rigorously analysed later, this 'instant' feedback can be extremely helpful in controlling any particular experiment. For example, the Hercules aircraft of the Meteorological Research Flight uses an on-board computer-controlled display for rapid feedback and this allows the flight plan of the aircraft to be modified in the light of measurements already made, thus helping to ensure that the maximum benefit is gained from each hour of experimental flying.

In any experimental study, the analysis and interpretation of the collected data are important steps. To aid human interpretation, it is often necessary to present the data in a graphical form, the display being generated invariably by machine (see also Box 4).

Experimental work is often designed to test some kind of theoretical model of the phenomenon being studied. Numerical models are frequently used to simulate the particular meteorological phenomenon, whether it is the development of clouds or the generation of ozone in the stratosphere. Increasingly, projects involve greater co-operation between the Office's scientists; also, for some applications, it may be necessary to transfer data between dedicated minicomputer systems used for research or to COSMOS or other operational facilities. The Central Data Network (based on Ethernet, a commercially available communication system) is being developed to provide the necessary infrastructure to support these activities, thereby avoiding a proliferation of point-to-point links.

Climate modelling and long-range forecasting are major research projects which depend heavily on the Office's supercomputer (see Box 1).

Commercial services

The use of IT has enabled a range of commercial services, which could not have been provided otherwise, to be developed and sustained. Some services currently provided would not be possible

Equipment used for Weather in Vision

at all without the use of IT, for example the Weather in Vision service; others would not be economic without IT because of the manual effort which would otherwise be involved. In some cases the application of IT is essential in the transmission of the product to the customer, as well as in the initial generation of the product.

Civil aviation is one of the Office's biggest customers. As a World Area Forecast Centre the Meteorological Office is committed to the provision of global forecasts of upper-air winds and temperatures every 12 hours. IT is used in every part of this process: the basic information is generated by the global NWP models (see Box 1) which run on the Cyber 205 computer; this information, which is used for flight-planning purposes, is then converted into the required code form for distribution automatically using telecommunication techniques. The whole process is completed without any manual handling of the data.

The oil industry is another area in which the Meteorological Office has been successful in selling its services and which rests heavily on IT. Many of the forecasts required by oil companies concern the low-level winds and state of sea in the vicinity of their rigs and platforms in the North Sea. These elements are forecast directly by the operational forecast models and, by appropriate interpolation to the geographical position of an individual rig or platform, the required forecast can be produced. Forecasters monitor the information produced from the models and provide values for all elements not directly generated by the models. Another service which depends on output from the forecast models is Metroute — the service for shipmasters which includes guidance on navigation so as to avoid bad weather.

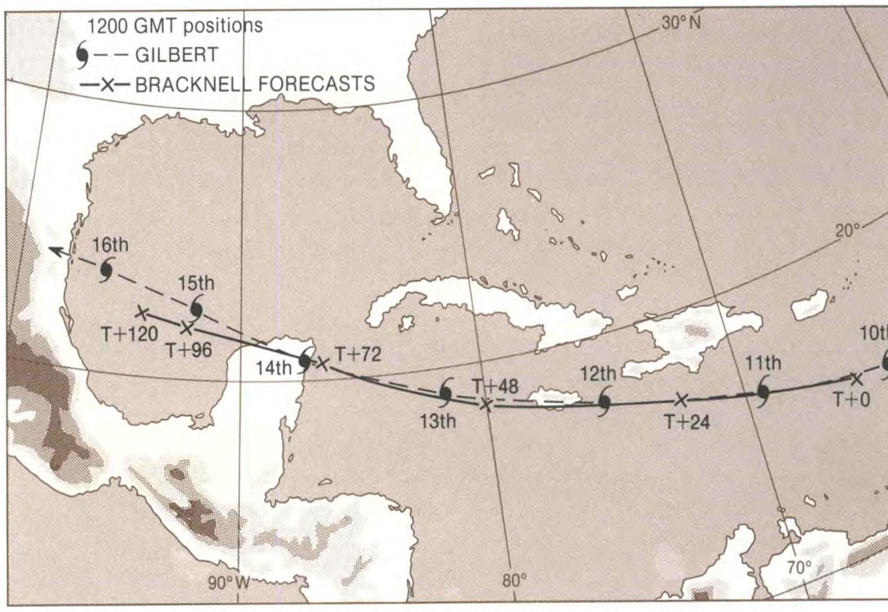
The Open Road service, provided by Weather Centres for local authorities, is an example of a service which relies on IT at the outstations. Each Weather Centre has a personal computer which runs a program that simulates the heat flow to and from the surface of roads. Forecasters provide a range of information for the model, such as forecast cloud amount, and the model predicts the temperature of the road surface at certain fixed locations in the area of responsibility of the local authority. This advice is passed to these authorities and assists in the decisions on whether or not to grit the roads.

The Meteorological Office receives a very wide range of climatological enquiries. With the extensive use of IT it is now possible to answer many of these enquiries over the telephone, whilst others can be processed in a few hours. This ability rests on the essential data being held on a computer in an easily retrievable form (see Box 3) and the existence of a standard set of programs to extract and process these data.

Display of RAF colour states on ODS

Central forecasting

The Central Forecasting Office (CFO) at the Meteorological Office Headquarters in Bracknell is the National Meteorological Centre for the United Kingdom and as such provides guidance to all other meteorological offices which serve Defence, civil aviation, shipping, central and local authorities, commerce, industry and the general public. The CFO is also a Regional Specialized Meteorological Centre for the World Meteorological Organization (WMO) and has accepted responsibility accordingly for supplying specified products to other National Meteorological Services throughout Europe, and in other Regions on request. Products available from Bracknell under these arrangements are designed to assist in the event of a nuclear accident in the European Region, in the provision of marine services, and in forecasting for the tropics. The CFO also acts as a joint World Area Forecast Centre and Regional Area Forecast Centre for the International Civil Aviation Organization, and is a Weather Analysis Centre for NATO. For convenience the Office's ship-routeing service, Metroute, the Storm Tide Warning Service, and the editors who maintain weather services on the various forms of videotex, are also located in the CFO, but these are described in the section on services.



Global model 120-hour forecast of the track of Hurricane Gilbert from starting conditions 1200 GMT on 10 September and the actual track taken by the hurricane

Refurbishment and redesign of the CFO

In March, as part of a rationalization designed to achieve more efficient use of resources, the CFO took on the role of Principal Forecasting Office (PFO) for civil aviation in the United Kingdom, requiring the transfer of forecasters from London/Heathrow Airport to Bracknell. The influx of more staff and their wider responsibilities required a complete redesign and refurbishment of the CFO. This has been accompanied by the introduction of new facilities designed to assist forecasters in their assimilation of information and issue of guidance. New air-conditioning was installed and false floors were fitted to accommodate extensive cabling for the additional VDUs and word-processors which form part of the new facilities.

The analysis forecast system

At any one time 14 forecasters are on duty, roughly divided into three teams for separate but mutually supportive tasks:

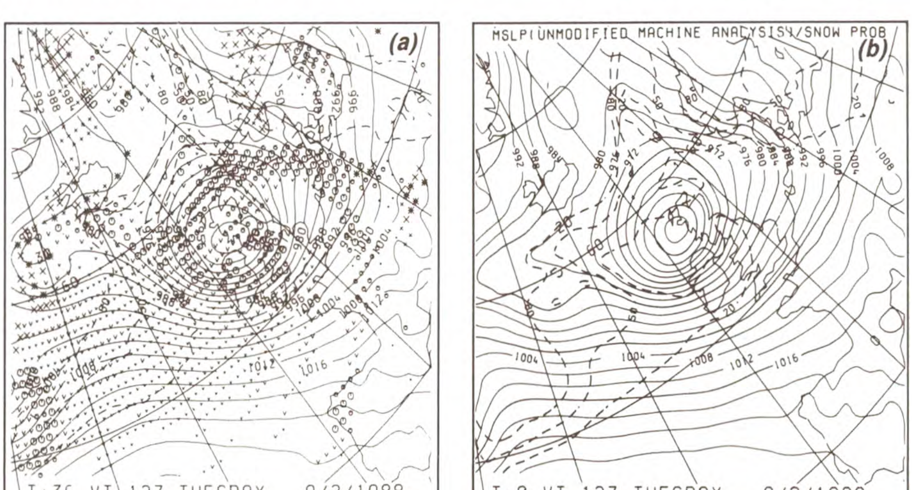
- Data-monitoring and analysis fine-tuning for the numerical weather prediction (NWP) models.

- The generation of central guidance, public services and warnings.

- The provision of services to civil aviation.

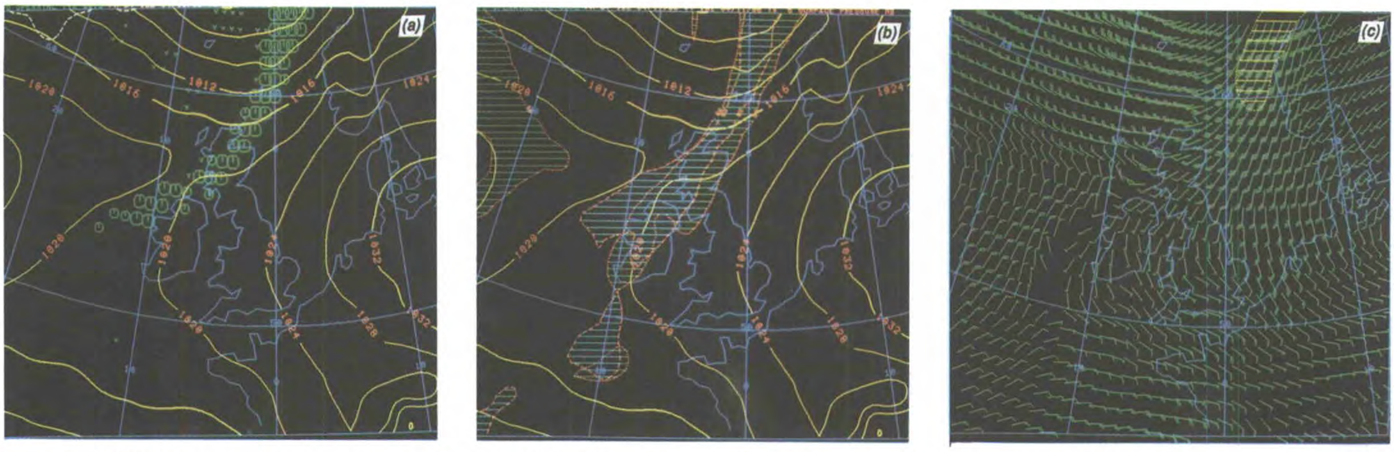
A so-called 'Chief Forecaster', who leads the central guidance team, has overall responsibility.

On 9 February an intense depression moved across Scotland and many places experienced severe weather and very strong winds. The fine-mesh model forecast pressure for 36 hours ahead (a) is shown alongside the verifying analysis (b).



The data-monitoring and analysis team are responsible for ensuring the quality of data which provide the initial conditions for the NWP models. This may entail scrutiny and acceptance or rejection of individual weather reports, or creation of 'bogus' reports based on the forecasters' interpretation of satellite images in an otherwise data-sparse part of the globe.

In essence, the NWP models predict the future state of the atmosphere, given these initial conditions. Two versions are used operationally; both have 15 levels in the vertical but differ in their horizontal resolution and coverage. They are described in more detail in the section on forecasting developments, but the global NWP model currently has grid points spaced at intervals of 1.5° in latitude and 1.875° in longitude.



Examples of NWP fine-mesh forecast of instantaneous rainfall intensity (a), two levels of relative humidity (representing cloud) in mid troposphere (b) and surface wind at each model grid point (c) ((a) and (b) superimposed on surface pressure)

Forecasts to 6 days ahead are computed twice daily, from 0000 and 1200 GMT initial conditions derived from data which arrive at Bracknell by 0320 and 1520 GMT. Predictions to 36 hours ahead are available by 0415 and 1615 GMT and to 6 days ahead by 0500 and 1700 GMT.

The regional fine-mesh NWP model currently has its grid points spaced at intervals of 0.75° in latitude and 0.9375° in longitude. It covers the region bounded by 30–80°N and 80°W–40°E. At the lateral boundaries of this region the model takes information from the global model. Forecasts to 36 hours ahead are computed twice daily, from 0000 and 1200 GMT initial conditions derived from data which arrive at Bracknell by 0200 and 1400 GMT. Results are available in the CFO before 0300 and 1500 GMT respectively. During the year a third daily run of the fine-mesh model was introduced to make optimum use of regional data generated between 0300 and 0600 GMT.

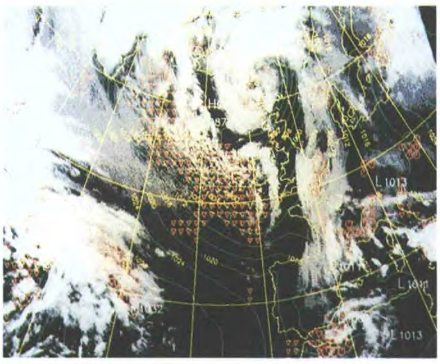
The surface winds from the NWP atmospheric models are used to drive global and regional sea-state models, which hindcast and then predict the surface wave energy spectrum at each grid point. The global sea-state model has the same resolution as its atmospheric counterpart and produces forecasts to 5 days ahead twice daily. 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. Its formulation includes shallow-water effects.

The key tasks of the forecaster are those of assessment and interpretation of NWP output, and the issue of guidance based upon the result. To assist with this each forecaster has a VDU, which accesses the Office's main computer facility, COSMOS. This enables forecasters to view both raw and processed data, satellite imagery and NWP forecast products on their screens, usually much earlier than hard-copy charts can be made available. Word-processors are used to prepare and forward descriptive forecast guidance for onward transmission to users.

New ways of exploiting the VDUs to help forecasters with their tasks are continually being developed. A major development in data display occurred towards the end of the year when it became possible to superimpose on the screens NWP data and products upon satellite imagery. This technique allows forecasters to assess the accuracy of the NWP analysis more thoroughly and more efficiently than before and to take corrective action more quickly.

Improved services

As experience grew, increased use was made of the FRONTIERS output during the year. Forecasts of rainfall distribution in hourly steps up to 6 hours ahead are prepared every half hour by the FRONTIERS operator. This information is included, when appropriate, in the very short-period forecasting guidance issued to the dependent forecasting offices around the country.



Example of NWP forecast data superimposed on satellite image

The global capability of the CFO received wide recognition during the year. The skill of the operational global version of the NWP model in predicting the track of tropical cyclones for periods 2 to 5 days ahead proved to be at least as good as and often much superior to other more traditional techniques in use. The track of Hurricane Gilbert, which caused severe damage in Jamaica, was well forecast as shown on page 17. The skill of the model is due partly to intervention techniques applied by forecasters in the CFO to ensure that there is a good representation of the position of tropical cyclones in the analysis. The CFO depends greatly upon receipt of tropical cyclone advisories from local Tropical Cyclone Warning Centres for this purpose; in return the Bracknell forecasts are relayed through the Global Telecommunication System to the national centres for their local guidance.

The daily input to the BBC World Service by a forecaster in the CFO continued throughout the year. Letters received by the Office and the BBC indicate that this is a very popular broadcast. Accurate and up-to-date reports on the unusual weather events that occur were particularly well received.

Requests for international services from the CFO grew considerably during the year. Several companies dealing in the commodities market took forecasts, on a repayment basis, for parts of the world where agriculture and horticulture take place on a large commercial scale. Short-period forecasts and comment on the Sudan flooding were provided on request and daily briefings on the weather near Mount Everest were given to the British Expedition. In each case it was found that meaningful forecasts could be produced from the model output with skilled forecaster interpretation.

Civil aviation

Civil aviation is the largest single civil user of the output of the Meteorological Office. The continuing improvement in the 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 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 in the United Kingdom. The role of the Meteorological Office is to provide professional advice to the CAA and to provide meteorological services according to its stated requirements on a repayment basis. The greater part of these costs, about £18 million this year, are recovered by the CAA as part of the *en route* charges levied on aircraft that use the air navigation services within UK airspace.

International responsibilities

The organization of meteorological services for international 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 number of flight levels, twice per day, for 12, 18, 24 and 30 hours ahead. These forecasts, the direct output of the 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 National Meteorological Services and airports within the region. Four airlines (British Airways, Scandinavian Airlines System, Japan Air Lines and Pan American

Airfield warnings board in the CFO

Airways) accept the global grid-point data directly from Bracknell for use in computerized flight planning. Two airlines (Lufttransport-Unternehmen of the Federal Republic of Germany and Sterling Airways of Denmark) take 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 Inc. These companies provide the data either in their original form or processed as flight-planning information to most of the major operators world-wide.

Computer-derived equivalent tailwind components are available also. These cover most of the well used air routes in an area from Canada in the west to India in the east. Such products enable the on-the-ground flight-planning time to be greatly reduced. Another advantage to the customer is that a denser array of forecast points is utilized than in the coarser grid for global use. Eight air-tour operators and smaller commercial operators from England, Sweden and Spain are currently taking the service.

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. Considerable progress has been made in computer-generated significant weather forecasts and further work is being carried out. 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 Group is also considering whether forecasts should be issued more frequently and in greater detail than at present.

Although ICAO and the World Meteorological Organization 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. A number of air-tour operators send AIREPs from data-sparse areas directly to Bracknell, post-flight over SITA communication channels. These currently total about 300 per day. One or two companies will introduce new-generation aircraft to their fleet in the next year or so and discussions are taking place on ways and means of retrieving data automatically from them.

National responsibilities

In March the Principal Forecasting Office for civil aviation at London/Heathrow Airport closed and all the forecast functions were transferred to the extended and refurbished Central Forecasting Office (CFO) at Bracknell. Although this was a major task the move was completed on schedule with little or no interruption to the services provided. This move followed an in-house feasibility study, and leads to more efficient use of manpower, accommodation and other resources. Late in the year the forecasting office at Aberdeen Airport was closed and the aviation forecasting tasks were transferred to Glasgow and Aberdeen Weather Centres.

The CFO serves as a Meteorological Watch Office (MWO) for the Shanwick Oceanic Control Area and the London Flight Information Region. 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. Glasgow Weather Centre has a similar responsibility as an MWO for the Scottish Flight Information Region.

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 are expected which could be a hazard to the safety of aircraft during landing and take-off or when parked on the ground.

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.

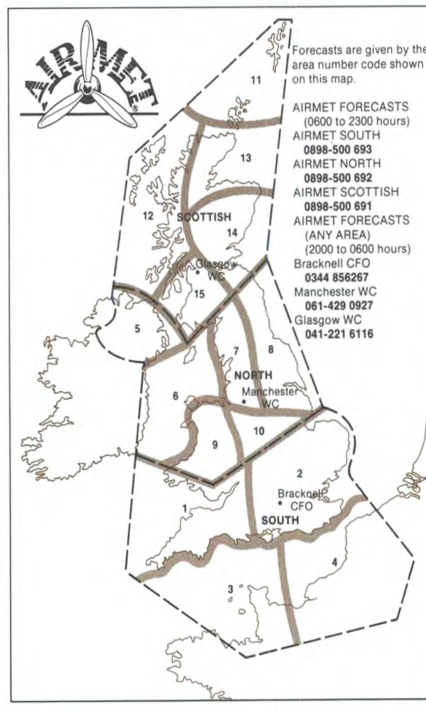
Forecast minimum pressure values are prepared every hour in the CFO for 20 Altimeter Setting Regions over and around the United Kingdom. They aid the safe clearance of high ground by low-flying aircraft and the safe vertical separation of aircraft.

The Meteorological Office, on request from the Aircraft 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. Sadly, this facility has been exercised on several occasions during the year, notably in connection with the destruction of the Pan American Boeing 747 at Lockerbie.

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 CFO 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 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 special service introduced by the CAA after protracted consultation with user organizations.

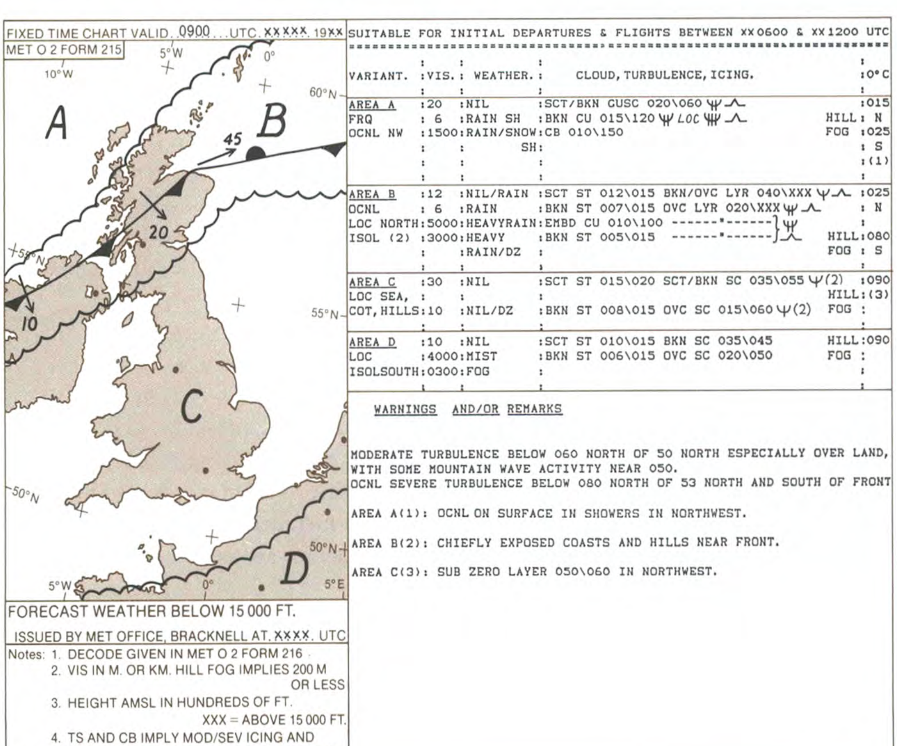
The service, Airmet, provides forecasts for three regions covering the United Kingdom and near Continent, each region subdivided into areas. The forecasts describe the general meteorological situation and give details of the weather, cloud, visibility, freezing level, upper winds and temperatures, airframe icing and any warnings that may be in force. They cover a period of 8 hours and include an outlook for a further 6 hours. 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 previously prepared.

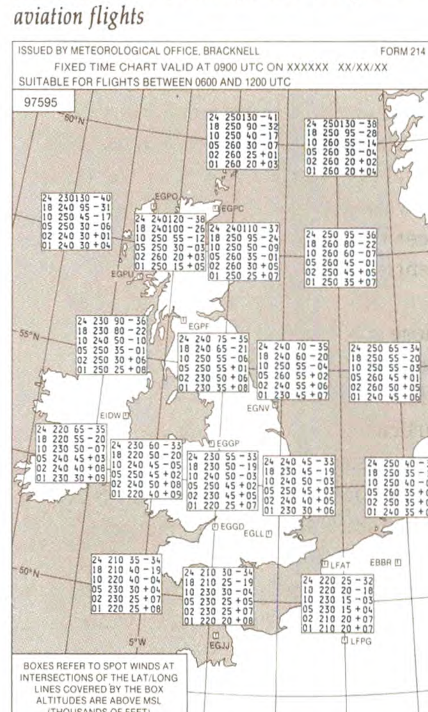


Airmet forecast areas

Special forecasts are prepared for the helicopter operators that support the offshore oil and gas industry. Forecasts for operations over the Irish Sea and the southern North Sea are prepared in text form at Manchester Weather Centre, those for the northern North Sea in chart form at Glasgow Weather Centre.

Examples of charts issued for low-level general aviation flights





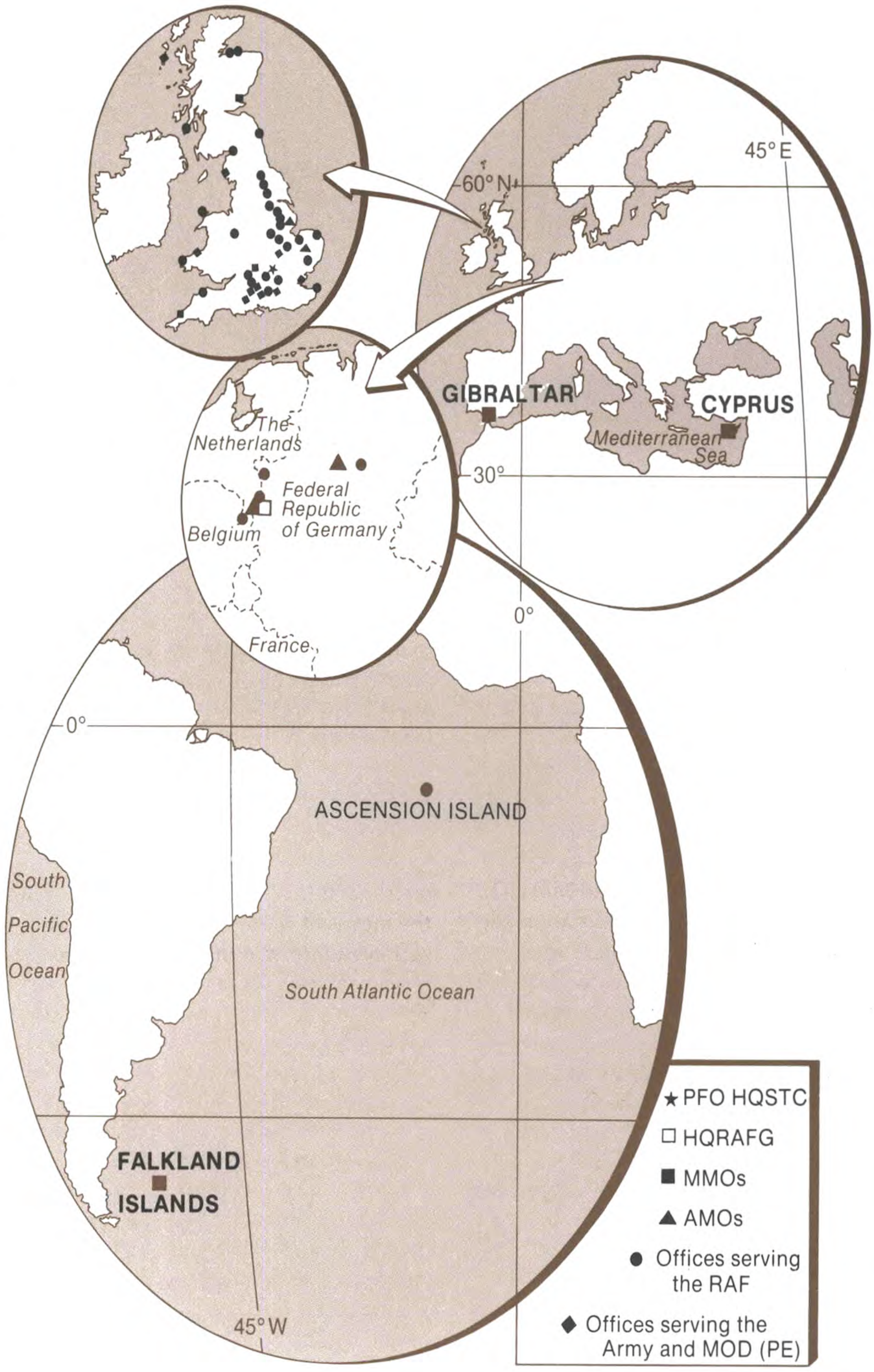
Defence

Almost exactly 25% of Office manpower provide direct support for Defence. Staff are based at military headquarters and outstations both in the United Kingdom and overseas, and at Ministry of Defence (Procurement Executive) and Army trials establishments in the United Kingdom. The great majority are employed at operational flying stations where they maintain a continuous weather watch and brief aircrew and operational staff as required. RAF, Royal Navy and Army Air Corps aircrew are also taught the essentials of aviation meteorology by Office forecasters at a number of airfields. Manning levels are kept under continuous review; during the year the office at RAF Binbrook was closed when squadrons were withdrawn and at RAF Leeming forecasters were re-introduced when operational flying resumed.

The Principal Forecasting Office (PFO) at Headquarters Strike Command (HQSTC), backed by numerical weather prediction (NWP) model output from Bracknell, provides the basis for meteorological support for Defence activitites in the United Kingdom and the Federal Republic of Germany. The offices in the Mediterranean and South Atlantic function largely independently of the PFO, but are equipped for the direct reception of data from polar-orbiting and geostationary satellites; they also receive NWP output from Bracknell.

The Royal Navy maintains its own meteorological service under the Directorate of Naval Oceanography and Meteorology (DNOM) although guidance and observational and NWP data from Bracknell are routinely provided. Close co-operation is maintained with DNOM through a Naval Liaison Officer and, operationally, between the PFO at HQSTC and the Fleet Weather and Oceanographic Centre.

Close co-operation in military meteorology is maintained through the offices of other NATO nations, particularly with the German Military Geophysical Office and the Air Weather Service of the United States Air Force. Office staff, with DNOM advisers for naval aspects, represent the United Kingdom on the NATO Military Committee Meteorology Group and its Working Groups and on the Meteorology Panel of the NATO Army Armaments Group.



Meteorological offices serving Defence in the United Kingdom and overseas

Aircrew briefing

At airfields, forecasts are prepared for differing RAF operations, e.g. maritime reconnaissance, and helicopter flying. One of the most exacting forecasting requirements is that for low-level fast-jet flights over the United Kingdom, much of NATO Europe and adjacent waters. Visibility, cloud amount, and cloud height are combined to give what is known as a 'colour state' and it is the current and forecast colour states for the base airfield, diversion airfields, low-flying routes, low-flying areas and weapons ranges that largely determine a day's activities for squadrons at an airfield.

While communications to meteorological offices at many airfields have been upgraded in recent years through the introduction of Outstation Display Systems (see section on information systems), the means of making forecasts and other meteorological information available to the aircrew on the airfield has changed little over the years. Squadrons may be near enough to the meteorological office to collect charts and be briefed face-to-face by the duty forecaster but, increasingly, they are remote from the meteorological office; weather information is collected by a squadron member and a briefing is given over a 'teletalk' system. This method is not efficient and a joint RAF–Meteorological Office group is considering the introduction of a computer-based network whereby guidance would be made available to remotely sited squadrons in both

Tri-nation Tornado pilots at a weather briefing

Harrier taking off

alphanumeric and colour graphics formats. There will be many benefits, but the ability to update forecasts quickly and display them graphically will be particularly welcomed.

Mobile units

In the Federal Republic of Germany Office staff support Harrier squadrons in the field by deploying as a Mobile Forecast Unit (MFU). The MFU staff participate fully in the exercise, living at the field site and moving to another site when required. Meteorological data are received by radio, and aircrew are provided with landing forecasts and warnings, and briefings are given on the significant weather for the exercise area. Plans to improve communication facilities are in hand.

A Mobile Meteorological Unit in the field

A second MFU functions in support of 1(BR) Corps. The Senior Meteorological Officer is also the Staff Meteorological Officer (SMO), 1(BR) Corps; he provides advice to the Corps Commander and his staff on all meteorological aspects that may affect Army operations. In field exercises the SMO deploys with Corps (Main) Headquarters, and the MFU forms part of Corps (Rear) Headquarters and provides support to the SMO.

In the United Kingdom a small number of staff hold commissions in the Royal Air Force Reserve of Officers and man Mobile Meteorological Units. They are ready to mobilize at short notice to provide a forecasting service in remote areas or where normal meteorological advice is not available. The role of the Units is regularly exercised and four members participated in Exercise Bold Grouse in Denmark during September when it was assumed that the local meteorological service was unavailable.

Emergency services

In response to the events that followed the nuclear accident at Chernobyl, the Meteorological Office has been active in developing both the ability and the procedures to ensure that appropriate and timely meteorological advice is available in the event of any future emergency. Thus Her Majesty's Inspectorate of Pollution (HMIP) was assisted in the implementation of a new national radiation monitoring network known as RIMNET (Radioactive Incident Monitoring NETwork). This consists of 44 gamma radiation monitors at Meteorological Office observing stations and a further one each on Jersey and the Isle of Man. Hourly readings are taken by the observers and the data are transmitted over the Meteorological Office telecommunication network to Bracknell where they are collated and passed on to HMIP in London and Lancaster for analysis.

Considerable progress was also achieved towards an improved numerical model capable of predicting the movement and deposition of material in the event of a nuclear accident. Output from this model will be available at the Technical Coordination Centre at the Department of the Environment and will provide guidance essential for the management of any such future emergency. The Office continued to maintain and develop procedures that would provide meteorological advice in the event of nuclear and chemical accidents in the United Kingdom. The procedures are known as PACRAM (Procedures And Communications in the event of a release of RadioActive Material) and CHEMET (CHEmical METeorology).

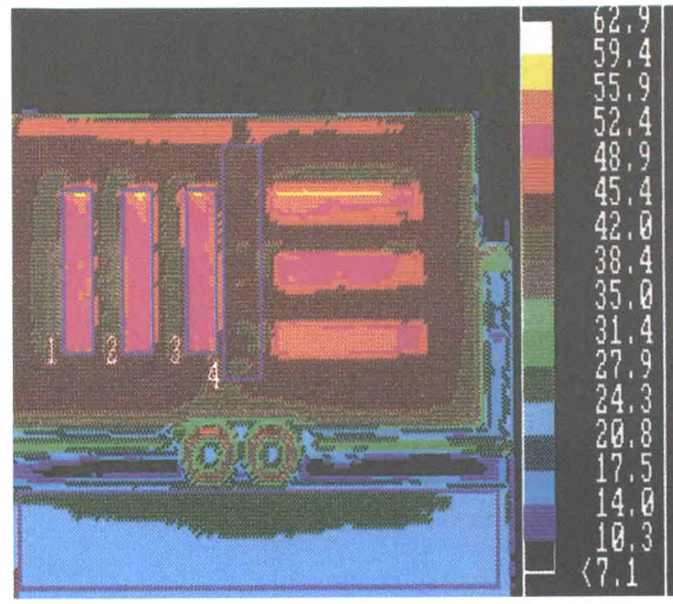
RIMNET sites in the United Kingdom. Gamma radiation monitoring equipment is shown in the background.

Development of new services

Useful progress was made in the development of techniques to forecast the presence and strength of atmospheric radar ducts. During the past year two operational forecasting techniques were made available to Defence forecasting offices:

- The first is for the prediction of surface evaporation ducts which are semi-permanent features over the sea caused through evaporation of moisture into the air. Recent trials with the Royal Navy have shown that the presence of these ducts may be forecast, since their depth and intensity depends primarily on the temperature contrast between

The instrumented target at Boscombe Down which simulates the thermal signature of a battle tank

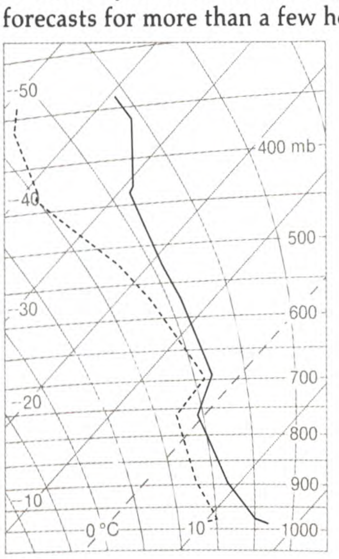


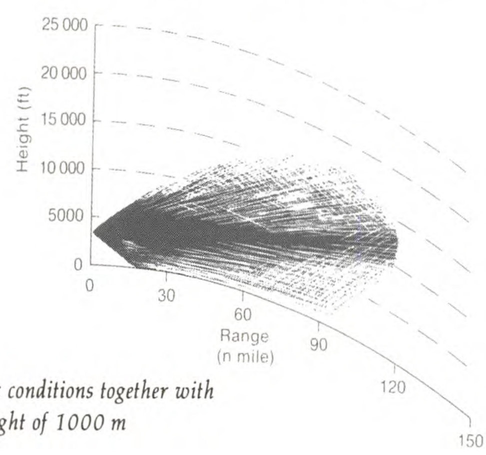
False-colour, infra-red picture of the target. The vertical scale on the right shows the range of temperatures (°C).

the sea and the air, with success, up to 48 hours ahead.

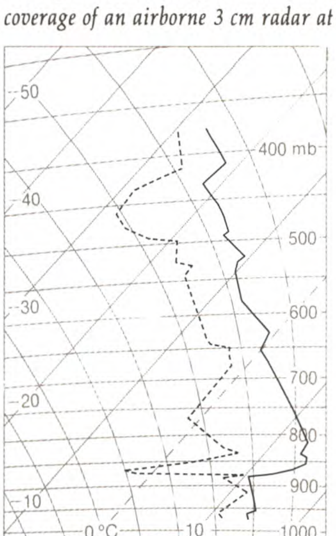
- The second is for the detection of elevated ducts. Here the spatial and temporal variations in the distribution of humidity make it difficult to produce forecasts for more than a few hours ahead but, through an understanding of the synoptic-scale processes that are the underlying cause of the ducts, forecasts for longer periods are becoming possible.

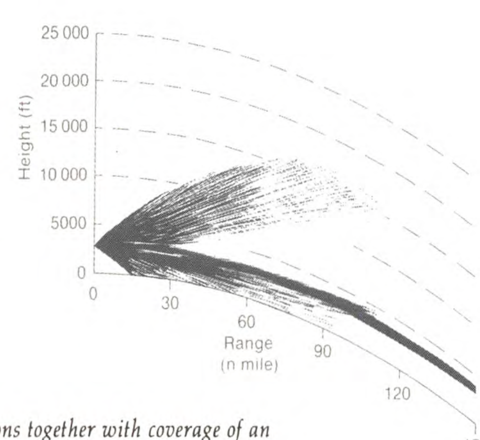
During the year work began to determine how the coverage of specific radars are affected by the presence of a duct. Under normal atmospheric conditions the coverage is as expected for rectilinear propagation but, for example, within a well developed anticyclone where there is a sharp hydrolapse the coverage is markedly different. Under such conditions part of the radar energy is trapped; in the resulting duct the radar can 'see' to unusually long distances. Above the duct, in the consequent radar 'hole', coverage is poor and targets may escape detection. Work is in hand to introduce an operational system that produces diagrams of radar coverage routinely at airfields and trials establishments.





Tephigram illustrating normal atmospheric conditions together with coverage of an airborne 3 cm radar at a height of 1000 m





Tephigram illustrating anticyclonic conditions together with coverage of an airborne 3 cm radar at a height of 1000 m (the change in radar coverage due to the presence of a radar duct and 'hole' can be seen)

Electro-optical ranging and imaging devices are coming into widespread use by both the Army and the Royal Air Force and the challenge for the meteorologist is to predict the source contrast and atmospheric transmission at the wavelengths in use. Over the past few years, computer programs have been developed that require as input forecasts of the meteorological conditions expected during the next 6–12 hours and which provide as output the parameters needed by the users of, for example, thermal imagers. A trial to determine the accuracy and usefulness of such forecasting techniques is under way at the Aeroplane and Armament Experimental Establishment, Boscombe Down. An instrumented target which simulates the thermal signature of a battle tank is used. The target, consisting of panels mounted in a background frame, is heated to give a controllable thermal contrast. Each afternoon, forecasts of the temperature of the background (grass, concrete, etc.) and of the visibility in the infra-red, are produced; during the evening and night these forecasts are compared with actual temperature measurements. The trials should help to determine the accuracy and limitations of the forecasting algorithms used.

General public

Warnings

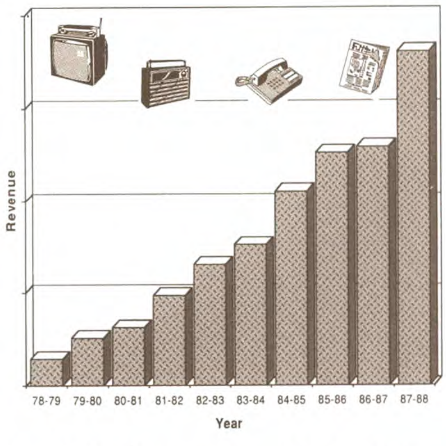
The storm of 16 October 1987 will be remembered for many years to come by those who were living in the south-east of England. Trees were still in leaf and so after a period of very wet weather the exceptionally strong winds caused widespread damage and disruption. Although many of the public recognized the inevitability of such damage given the extreme nature of the event, there was legitimate concern that the Meteorological Office had not provided warnings which properly reflected the severity and extent of likely damage. In the media 'storm' which followed closely on the event, an external review of all aspects of the Meteorological Office's role was conducted by Sir Peter Swinnerton-Dyer and Professor Robert Pearce. Although no blame was attached to any individual, this review and a parallel, internal study made several recommendations designed to assist forecasters to cope more effectively with such exceptional events. The Office has responded positively to these and action has been taken to improve the observational network in the data-sparse area to the west of the United Kingdom, to increase computer resources available to the Office and to improve the numerical models on which so much of forecasting depends. In addition, steps are being taken to improve some aspects of training and the methods used to distribute warnings to the public and emergency services.

Greater emphasis is now given to severe weather in forecasts on television and this has proved to be effective on several occasions. A major change was also made to the way the public at risk are warned of severe weather. When a high degree of certainty attaches to them, these 'Flash' messages are now issued via national and local television and radio up to 8 hours in advance of expected severe conditions. Hitherto, such messages have given a maximum of 3 hours' warning. In addition, procedures for the issue of warnings of severe weather to the emergency authorities have been reviewed. The Home Office have a co-ordinating role in this area and with their assistance it is hoped that new arrangements will come into operation in 1989.

Day-to-day services

Although it is extreme weather that captures the headlines, the British public also takes considerable interest in day-to-day weather. This is not surprising as the weather affects virtually all outdoor activities. Most people recognize that, while there is still an element of unpredictability in the very varied weather experienced in the United Kingdom, forecasts have improved noticeably in recent years. Therefore expectations remain high and the Meteorological Office attempts to satisfy that interest by providing weather information through the media — television, radio, newspapers and the telephone. The wide selection of media outlets ensures that up-to-date regional, national and international forecasts are available in styles which, hopefully, suit all tastes and the vast majority of public needs.

BBC TV Weathermen



Growth of media revenue from 1978 to 1988

Television

The Meteorological Office is involved in many of the television weather presentations on both BBC and ITV channels. The most well known of the current services is that provided by a team of five Weathermen (all of whom are from London Weather Centre) for BBC television. There are now 11 broadcasts every weekday and 3 or 4 on Saturdays and Sundays. Since early in 1985, products from the Meteorological Office numerical weather prediction models have been transmitted directly to the BBC together with satellite pictures and various other information. At the BBC, the material selected by the Weatherman is converted into graphics displays suitable for use on television. There have been continuing developments to this system and in May a number of new features were introduced. One of these was the use of weather radar data, which gives a detailed and up-to-the-minute picture of the rainfall over the United Kingdom. An animated sequence of half-hourly frames shows vividly how the rainfall areas have developed. The new graphics also include a new opening sequence, colour-coded temperature fields and moving wind arrows. In general, the viewers appreciate the changes made, but have been critical of those introduced by the BBC at the end of October. They involved a reduction to 1 minute in the length of the main 9.25 p.m. broadcast and a postponement of the 6.25 p.m. forecast by half an hour; both were rescinded at the end of the year.

Some of the BBC regions use staff from the local Weather Centre; others use prepared scripts read by an announcer. Most ITV companies feature weather forecasts in some form, but again the wide range of styles is illustrative of the different importance attached to them. Some use Office staff; others employ their own Weathermen who receive briefings, data and charts from the Office. The new satellite channels are also interested in weather presentations. That on Superchannel is sponsored by the Goodyear Tyre Company and is provided by the Weatherman from the BBC main studio.

Television companies have come to realize that weather presentations attract audiences and this has led to a much greater willingness on their part to devote time and money to improving them. With the growth of satellite channels, there are now many new and exciting opportunities. In anticipation of the demand, the Office has developed Weather in Vision — a system that enables weather information to be portrayed graphically in a variety of ways to suit the particular requirements of the individual television company. This flexible approach allows the company to choose the style and 'look' of the programme, but the information itself is fed either from Bracknell or the local Weather Centre. The system was developed in conjunction with Spaceward Microsystems Ltd.

Radio

Major changes are taking place in radio, with plans to introduce a national commercial network and a wide range of community stations. Forecasts are already provided to many local radio stations. The service varies from a brief script read by the announcer or disc jockey to a live presentation given by the local forecaster.

The national BBC radio networks all broadcast weather information supplied by the Office. The live presentations, mainly on Radio 4, are given by London Weather Centre forecasters directly from a specially equipped studio there. In recent years, broadcasts describing significant and interesting weather developments around the world have been provided for the BBC World Service. These are provided by forecasters in the Central Forecasting Office at Bracknell. Radio 648, the World Service for near-Europe, also broadcasts a daily forecast.

The Press

There have been significant improvements in the style and content of weather information in the major national newspapers. Of necessity, the forecasts are read some 12 hours or so after they have been prepared. Even so they provide an important source of information for many people. There is an increasing requirement for forecasts for other parts of the world from holiday-makers and businessmen. The opportunity is also sometimes taken to provide associated weather articles of general interest. The weather section in the *Guardian* has proved particularly popular in this respect.

Many provincial newspapers are taking more of an interest in the weather, and attractive, graphical presentations were developed for a number of these.

Some of the year's newspaper headlines

Videotex

In this country Prestel is the main videotex system available, and is provided by British Telecom. Its growth has not been as rapid as was expected at one time, but weather information continues to be one of the most frequently accessed items. The Office has over 800 pages of information. As frequent updating is required a dedicated computer system is used. Videotex systems are also used in the supply of services to more specialized customers.

Public service offices

Forecasts for the general public are issued by the 14 Weather Centres within the United Kingdom. Forecasters get to know the local weather peculiarities for their area and also the particular weather information required by their customers. National forecasts are generally issued by London Weather Centre.

In Aberdeen, a new Weather Centre became operational in September. The new premises are in the heart of the city and provide easy access for customers. The Weather Centre was formally opened on 29 November by Lord Trefgarne (Minister of State for Defence Procurement) who, in his opening address, emphasized the way in which weather information was being used for the benefit of people in Scotland.

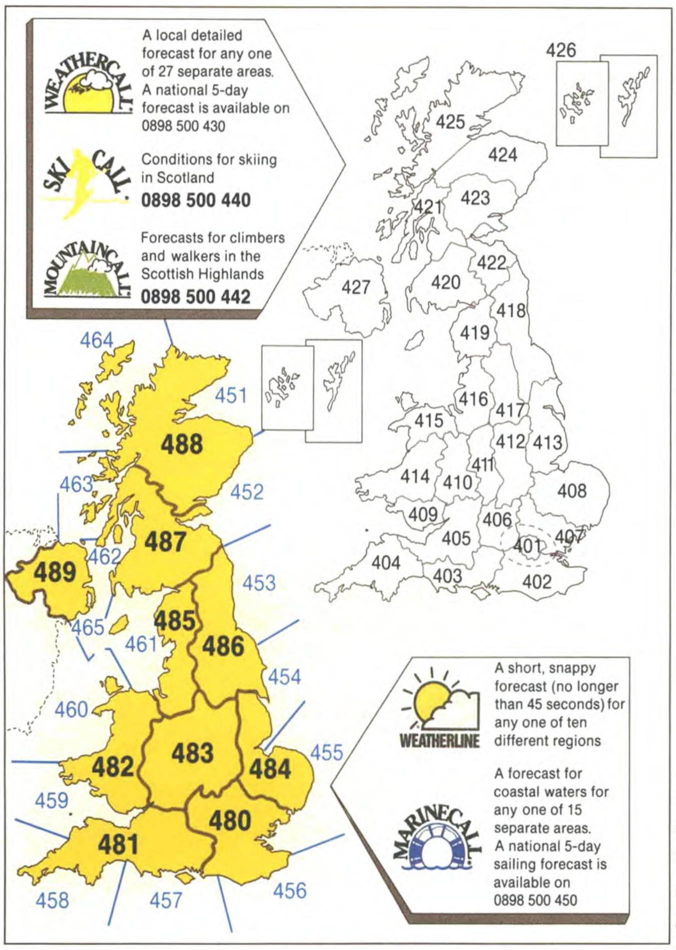
Location of public service offices

Three additional offices specialize in the supply of statistical and other information based on records compiled over many years. One is in Bracknell (for England and Wales), another in Edinburgh (for Scotland) and the other in Belfast (for Northern Ireland). The libraries and archives at these offices are open to the general public. The National Meteorological Library and Archives at Bracknell between them contain one of the most comprehensive collections of meteorological literature, photographs and climatological data to be found anywhere in the world. The collection includes rare, historical material held on behalf of the Royal Meteorological Society.

The Meteorological Office Library Accessions Retrieval System is maintained as an on-line computer

Lord Trefgarne opens Aberdeen Weather Centre (Photograph by courtesy of Aberdeen Evening Express) bibliographic catalogue available internationally via the European Space Agency's Information Retrieval Service. The database now contains more than 176 000 references to meteorological literature. A catalogue of the archive holdings of original records is also being compiled on computer and Part 1, listing observation registers from England and Wales, was released in October.

Telephone



Telephone services available by dialling 0898 500 followed by the appropriate three-figure code shown on the map

Current telephone services allow highly automated access to local, up-to-date, and if necessary specialized, forecasts whenever the user needs them. The Office provides such forecasts for a range of activities in collaboration with Telephone Information Services Ltd through the premium-rated service network. Call charges — 38p per minute (peak and standard rates) and 25p per minute (evenings and weekends) — are the same from anywhere in the country, the exact cost depending on the duration of the call. The services that are available are shown above. The discontinuation by British Telecom of the weather guideline service (provided by the Office for over 30 years) made the above services particularly important.

Industry and commerce

The Meteorological Office offers a wide range of services on repayment to industry and commerce. During recent years a positive effort has been made to develop a market-led approach to their provision. This has resulted in a number of specific, positive benefits to both the Office and its customers:

- Services on offer have increased in number and become more customer-oriented.

- The revenue from such services has grown considerably — about 13% in real terms in 1988.

- Those engaged in development, promotion and provision of such services have benefited from the discipline of working closely with their customers.

- It is believed that many customers now have services which are more closely tuned to their needs.

More generally, the focus on the needs of the customer has contributed to a tighter planning process and something of a change in the culture of the organization. Thus the current Meteorological Office marketing plan is a more systematic, co-ordinated and thorough approach to the provision of repayment services than any of its predecessors; it sets out medium- and long-term targets for each market sector together with comprehensive proposals to achieve them. A 2-year programme of basic commercial training continues with the aims of increasing the commitment of staff to customers and improving their commercial skills.

As these skills have become more widespread and the understanding of markets has grown, so the promotional activities of the Office have become more effective. This can be seen in:

- Improved targetting of brochures, advertisements and exhibitions to specific market sectors and for specific groups of products; promotional literature has concentrated on the benefits that services can deliver.

- The general promotion of the Office has been conducted in a much more systematic and pro-active fashion than in the past.

During 1988 the work of the Graphics Studio has reflected, both in volume and graphic content, the growing importance of the Office's commercial involvement and public image projection. Projects ranging from desk-top publishing designs of weather symbols and charts for Press agencies to window dressing of eye-catching seasonal topics at London Weather Centre were completed, and work associated with both direct and indirect sales required the production of videos, posters, hand-outs, brochures, advertisements, visual aids and artwork for tendering contracts, year planners and even tea cloths.

Of the 15 exhibitions mounted, 5 have featured agriculture, sailing and offshore industries, and commerce, whilst the remainder have concentrated on meteorological services and the promotion of good public relations.

Agriculture

Agriculture in the United Kingdom faces major changes as policy-makers within the European Economic Community strive to reduce both food surpluses and environmental pollution.

Turnip moth caterpillar on a potato tuber. Agrometeorologists within ADAS use temperature and rainfall data to provide an index of egg development and caterpillar survival.

Forecast, warning and consultancy services for agriculture are issued from Weather Centres to various farmers and businesses. Emphasis is placed on services which allow farming operations to be completed efficiently — with a minimum of waste and duplication — and effectively — to maximize the quality of products. A trial forecasting service tailored to the needs of a farming co-operative was provided. If successful, it is planned to extend the concept to other agricultural and horticultural co-operatives.

The Agricultural Development and Advisory Service (ADAS), the Ministry of Agriculture, Fisheries and Food's advisory arm with which Office agrometeorologists have for many years been associated, reduced the number of its regional agrometeorology units from six to five. The closure of the Reading unit in June represented the first stage of a rationalization that will reduce substantially the amount of in-house meteorological support available to ADAS staff.

Despite the changes, the units answered over 2000 enquiries and were involved, like the parent section at Bracknell, in various farming activities.

- Trials of a forecast of day-to-day changes in the quality of grass cut for silage were co-ordinated by staff of the Bristol unit. In addition, forecasts of 7-day accumulated temperature, used as a guide to time the application of fertilizer in the spring, were issued via *Farmers Weekly* magazine and, before its demise, Farmlink, the videotex system.

- The Office is able to provide advice on the application of weather data to crop processes; cereal growth has received particular attention. A trial of forecasts of weather favourable to potato blight was extended in 1988 to the whole of the United Kingdom.

- Irriguide, the ADAS irrigation advisory service continued to expand its customer base, mainly in horticulture but also in arable, grass and amenity management (e.g. golf courses). The service contributed to pest prediction schemes for lettuce, raspberry and field vegetables, which are dependent upon temperature and rainfall information.

Land transport

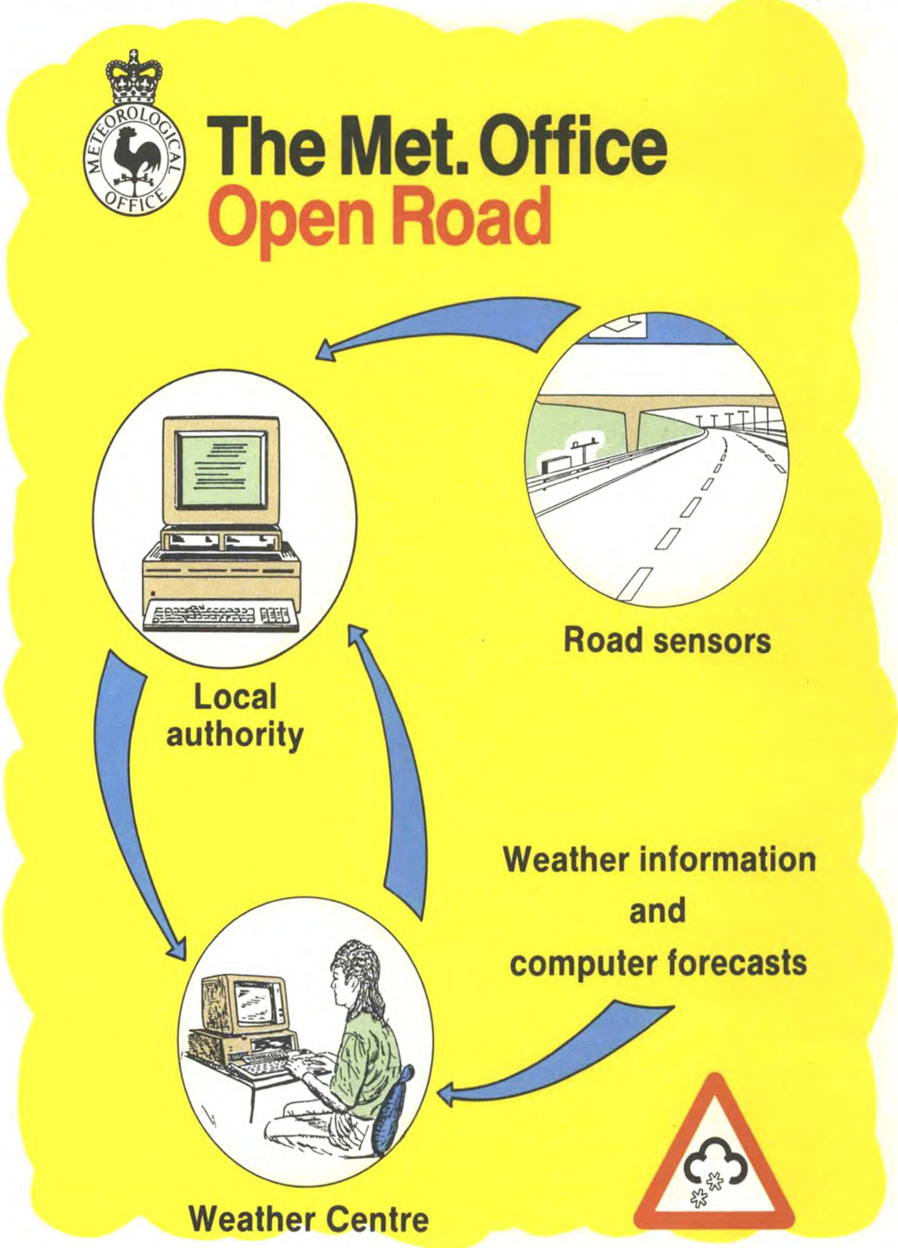
Since the launch of 'Open Road' at the end of 1986 an increasing number of local authorities have used the service, allowing them to be better prepared for dealing with hazardous winter conditions, and thereby helping to keep roads clear and safe for traffic.

Open Road forecasts are based on predictions from the Central Forecasting Office at Bracknell of air temperature, wind, cloud, and precipitation and incorporate, where possible, information from sensors in road surfaces. There are a growing number being installed and they are accessed via the local authority computer work station. Each afternoon Weather Centres send detailed predictions for the coming night of road surface temperatures and wetness, and their relationship to the formation of ice, to the appropriate local authorities. In addition, up-to-the-minute rain or snowfall information can be provided from the Office's networks of weather radars, and other observing stations.

Authorities using Open Road experienced cost savings in their winter road maintenance budget. Berkshire County Council saved over £70 000 in one season and the Atkins/Maunsell Joint Venture avoided ten road salting runs on the M5/M6 Midlands link motorways around Birmingham.

A new service developed for British Rail's winter operations, 'Open Rail', was successfully launched on a national basis during the winter of 1987/88.

The Open Road system



Daily forecasts that highlight elements of weather adverse to British Rail's operation are provided for 25 areas of Great Britain (excluding Western Region); details of sea conditions and tides for stretches of rail in coastal areas are included.

There has been continued interest in assessing the likelihood of fog on existing and planned roads. A study of the M25 was carried out for the Department of Transport to identify optimum locations for fog detectors. Other detailed studies included the M6 and M54 in the West Midlands and bypass alternatives on the A6 in Leicestershire and the A34 in Berkshire.

Energy

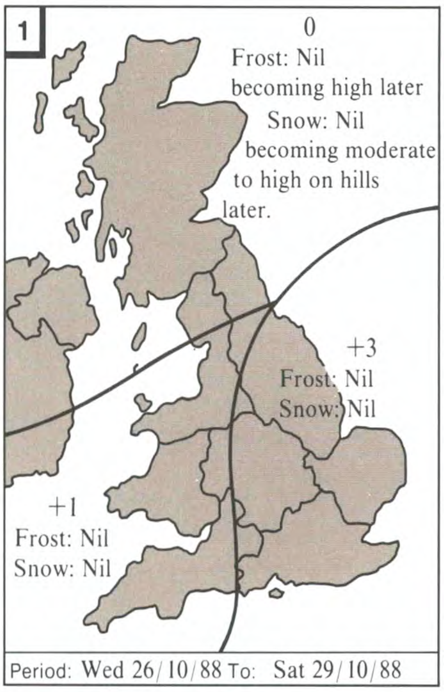
Weather forecasts are used, on a national and regional basis, by both the Central Electricity Generating Board (CEGB) and British Gas to anticipate the likely energy requirements and thus ensure that supplies can be maintained efficiently. Weather Centres issue forecasts daily, each containing quantitative information up to 36 hours ahead.

From June a new service was provided to the CEGB for all power stations in England and Wales. The service gives warning of rapid falls in atmospheric pressure that can result in the potentially dangerous release of methane gas in underground workings. Similar warning services are provided to many coal mines.

Weather information has many other uses within the energy industry. To avoid accidents the Regional Electricity Boards refer extensively to weather forecasts before maintaining installations and power lines. Weather information is provided for industrial space-heating needs, frost protection and humidity control. Electricity Boards are provided with mean temperature and wind forecasts; this information is used as a basis for remotely controlled heating systems, designed to combat hypothermia. In addition weekly temperature data are supplied to the Department of Health and Social Security; these identify the periods of severe weather when an extra fuel allowance is made available.

Retail

The Retail Unit at London Weather Centre was set up in June 1987. Parts of the retail sector are particularly sensitive to changes in the weather. Sales of salad, ice cream and soft drinks rise dramatically during a period of hot, sunny weather whilst soup, porridge, de-icer and car batteries all show increased sales should the weather turn cold and frosty. Sales figures of a particular product group are analysed and their weather sensitivity ascertained. The ability of retailers to be prepared for these changes is aided by forecasts from the Retail Unit.



Example of a forecast sent from the Retail Unit to a customer particularly interested in frost and snow

Offshore

Despite international uncertainty in the medium- and long-term price of oil, activity in the offshore industry globally shows signs of recovering from the slump of 1986–87.

There has been steady acceptance of the Office's automated graphical forecasting product which has been enhanced to include 50-metre winds, and imperial as well as metric units for sea heights. The format now represents the best way of portraying the information whilst ensuring that further information can readily be included.

It was decided in the autumn that, in addition to forecast guidance to day 5, a trend guidance to day 8 should be offered for longer-term planning.

The demand for detachment of forecasters offshore has shown signs of response to the enhanced activity in the industry. A forecaster continues to be detached permanently on Buchan Field (BP) for winter operations, and Ninian Field (Chevron) during the summer sub-sea maintenance programme which has been prolonged into the winter season.

Forecasters were also detached, often at very short notice, to various offshore locations to assist subsidiary companies involved in construction or pipe-maintenance projects, notably the Heerema/Amerada sub-sea production facility on Rob Roy and Ivanhoe Fields, and Phillips (Norway) installation work on the Edda Complex carried out by McDermott's heavy-lift vessel 'DB102'

Legal and insurance

Meteorological services and advice to the legal profession continued to grow, with increasing recognition of the availability of data and their importance in the settlement of cases. Generally, the requirement is for certified statements, or opinions related to such statements, for use by solicitors and barristers in civil and criminal proceedings.

A large number of enquiries are received from the insurance industry, concerning both personal injury and weather-related damage to property and buildings. A notable enquiry was the provision of weather data to insurers of a seaside summer show to assist them in determining whether poor attendance was due to the weather or the heart attack of the 'top of the bill' comedian.

Marine enquiries

Marine data for design and planning purposes were provided for locations as diverse as the Cook Strait, the South China Sea, the Malacca Strait, the Caribbean Sea and the South Atlantic Ocean. Closer to home, marine data were also provided to the CEGB and contractors involved in the planning stages of the proposed nuclear reactors at Sizewell and Hinckley Point.

Ongoing efforts to add to the Global Marine Data Bank were supplemented by special work for the Tropical Ocean and Global Atmosphere programme, involving the early collection and quality control of ships' observations in the tropical belt 30°N–30°S. Another World Meteorological Organization project to obtain a special subset of high-quality ships' observations, together with additional detail on instruments and exposures, also began in 1988 with the selection of nine UK merchant ships operating across the North Atlantic.

A forecast service specifically designed to help with coastal engineering operations is under development in co-operation with Hydraulics Research Ltd. Field trials were set up for the winter of 1988/89 to assess the site-specific forecasts of winds, inshore waves and water level for up to 36 hours ahead.

Requests from solicitors and marine insurers for assessments of past weather and sea conditions continue to be the most numerous of the enquiries received. These related mainly to delays, or damage to the cargo or the vessel, but a few concerned loss of life. In this latter category, there was continuing interest in the weather conditions prevailing when the *Derbyshire* was lost in Typhoon Orchid in September 1980.

Building and construction

Weather information can be used to great advantage throughout the various stages of construction projects.

A high demand for services including support for several major construction projects was maintained. These included the Sizewell B power station, the Channel Tunnel terminal and developments in London Docklands. Routine services included the provision of local 'downtimes' in *Metbuild*. The service is being extended to the sale of booklets of downtime averages, for use during the tendering and planning stage of work.

Collaborative research with the Building Research Establishment included the preparation of updated material on the loading of structures caused by wind and snow, for incorporation within British Standards Institution codes of practice.

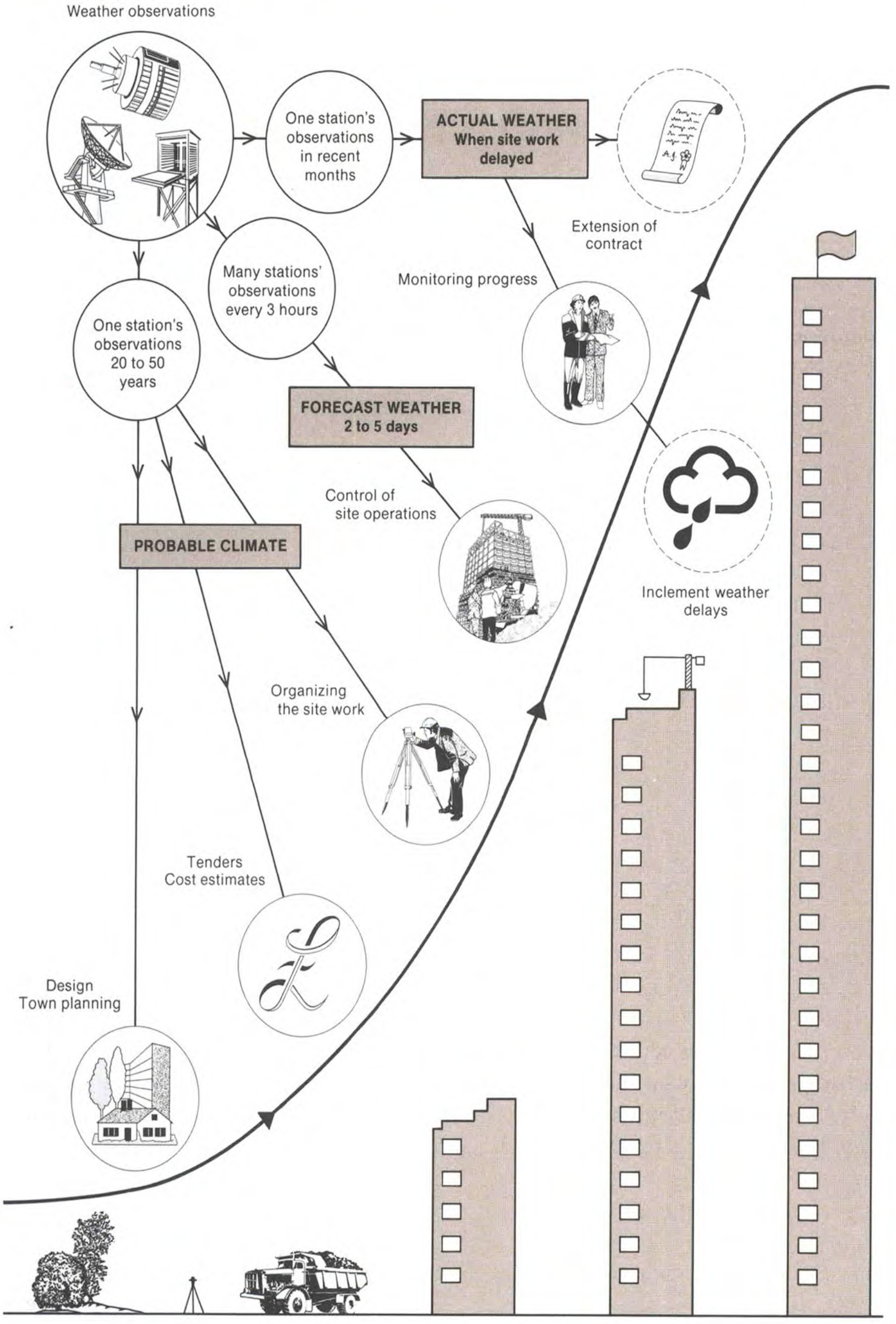
Although most services are based on the climatological database, techniques are being developed to improve the assessment of highly localized climatological features for which no direct measurements exist.

Storm Tide Warning Service

Tidal levels at 11 stations from Stornoway, Western Isles, via the east coast to Newhaven, East Sussex, continue to be monitored by the Storm Tide Warning Service (STWS). The network of gauges is in the process of modernization — the programme includes the installation of microprocessors and digital data stores at tide-gauge sites. Furthermore, the STWS is now able to monitor tidal levels at additional ports on the west coast — Ilfracombe, Avonmouth, Fishguard, Holyhead and Heysham. This information, together with tidal predictions generated from a knowledge of the astronomic tide and the actions of the weather in generating positive and negative surges, particularly in the North Sea, allows the STWS to operate a comprehensive warning service.

During the storm surge season from September 1987 to April 1988, 30 alerts were issued, 20 of these alerts later being confirmed. Danger level was exceeded on 4 occasions and the tide came to within 0.2 m of the danger level on a further 12 instances.

Meteorological information for the construction industry



Ship routeing service

Many of the ship routeing programmes were being transferred to computers towards the end of the year thus giving Metroute, the Meteorological Office's specialized routeing service, greater capacity to deal with the increased business. Vigorous sales activity produced new contracts from Shell International and Esso International, both Rotterdam based, and from Cool Carriers of Stockholm, thereby adding some 180 vessels to Metroute's clientele. The service provides guidance world-wide and makes it possible for ships to make their ocean passages in the safest and most economical manner. A service that provides advice on tropical depressions and cyclones is also under way. Other Metroute contracts include advice to yachts on passage, and for towage of oil rigs. Contracts can be tailored to clients' specific requirements and can include post-voyage analysis and performance data.

Water

Water Authorities have shared in the investment which has created the UK weather radar network and receive precipitation data from it. Such data, together with hour-by-hour forecasts of rainfall, are used to assist in the regulation of river levels, the control of sewage treatment and the support of flood warning procedures. Forecast rainfall accumulation for periods up to 5 days ahead are being provided, on a trial basis, to a few Authorities.

Numerous bodies with responsibilities for water management receive the weekly operational water balance bulletin *MORECS* (Meteorological Office Rainfall and Evaporation Calculation System.

Developments in forecasting

Automation, using computers, is essential in the Office's forecasting systems, to handle a vast volume of information about the atmosphere in a limited time. All stages rely on computers: the making and transmission of observations, their analysis into an organized representation of the atmospheric state, the forecasting of future states, and the interpretation and dissemination of forecasting products. Some aspects can be completely automated, others require skilled human intervention.

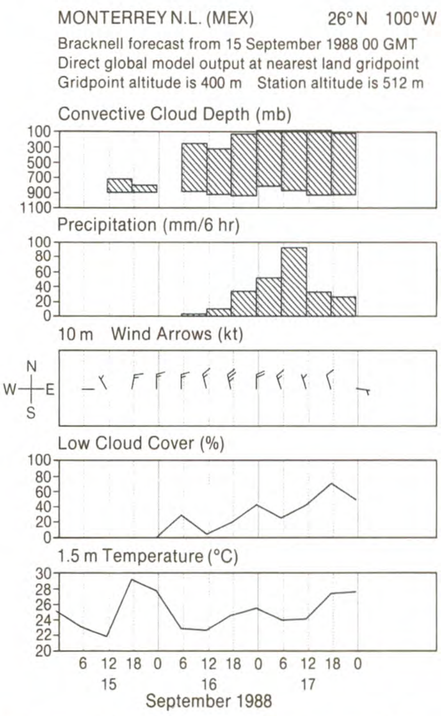
The MRF Hercules aircraft refuelling at Brest during Fronts'87. Nearby was the main field centre, linking an array of observing systems.

The heart of a forecasting system is a numerical weather prediction (NWP) model. As well as being used for the forecast stage, it is an essential component in the automatic quality control and four-dimensional assimilation of observations. Some forecast model products are used directly, whilst diagnostic output is used by forecasters in the interpretation and assessment of model forecasts.

Computer limitations restrict the accuracy and resolution with which atmospheric phenomena can be represented in a model. Since forecasts are needed for a large range of time-scales, each affected by different phenomena, a range of forecasting systems is required. Each system is based on a model that concentrates on the relevant phenomena. Effects that are at first localized can spread to influence the whole globe within a few days, so for longer time-scales global models are used. Forecasts for shorter time-scales are made using limited-area models, which allow a higher-resolution representation of phenomena that affect local weather, such as fronts and clouds. For all the models, the effects of phenomena not properly resolved and of processes too complicated to be directly modelled are represented indirectly by parametrizations relating the effects statistically to direct model variables. The parametrization relationships are based on theoretical understanding, and observational and numerical studies.

Forecast models

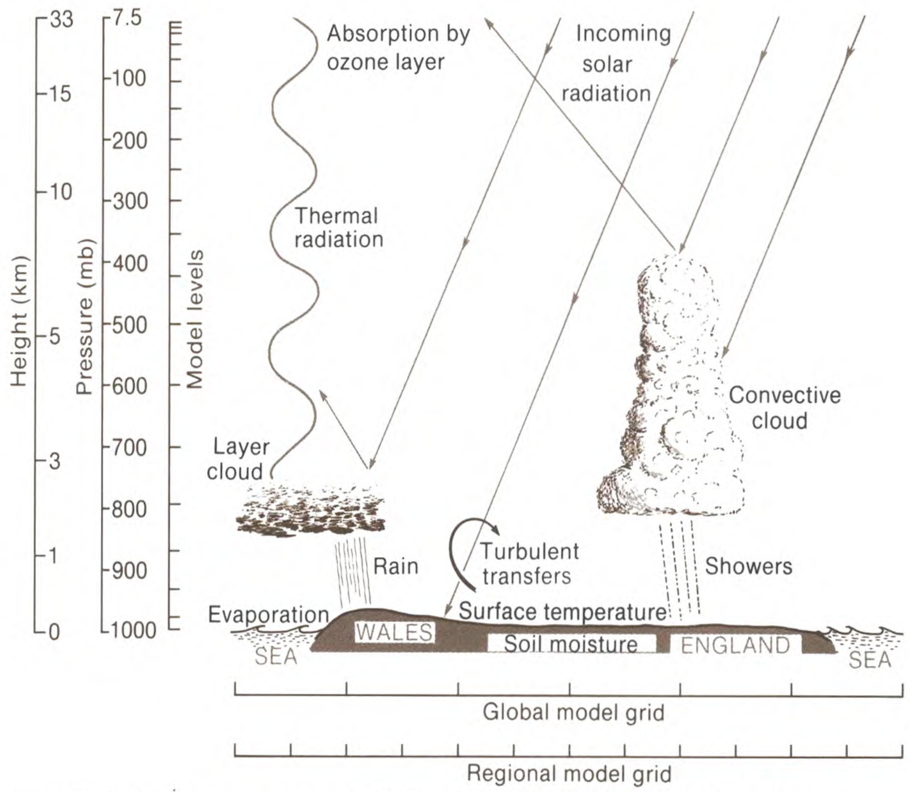
The Office is developing NWP models to satisfy the full range of forecasting requirements. To avoid duplication of development effort, two of these models are versions of the same computer code. The global model provides forecasts out to 6 days, for instance for aviation, shipping, and tourism. The regional fine-mesh model provides added detail, especially of fronts and rainfall, out to 36 hours for the North Atlantic and Europe. Enhanced versions of these models, with increased resolution, have been prepared; these will take advantage of the increased power of the ETA10 computer system (see section on information systems). The representation of the physical processes that affect the actual weather has been improved, particularly in the global model where the physical processes represented in the parametrizations have been extended to match those previously used only in the regional fine-mesh model. The detailed representation of physical processes will enable direct computer forecasts of the weather to be produced as shown in the figure left for anywhere in the world.



Direct model output forecast of surface weather, for a point near Monterrey, Mexico in the track of Hurricane Gilbert, from an experimental forecast with the global model at its current operational resolution, using the enhanced physical parametrization package. With the enhanced representation of physical processes, direct forecasts of surface weather are improved.

There have also been developments in the use of these models in the processing, quality control and analysis of observations. As the models' realism and accuracy increase, so does their utility in these tasks. The system which processes local-area satellite-sensed radiances into temperature information (see section on satellites) now benefits from a preliminary estimate provided by the regional, fine-mesh model. This allows a more accurate treatment of the non-linear relationships between temperature, humidity, and radiance. Systems for the quality control of all observations are being developed, based on knowledge of the characteristics of each observational system, forecast values, and statistics on forecast accuracy. A system for automatic quality control of ships' observations was put into operation during the year, and proved as effective as the previous labour-intensive methods.

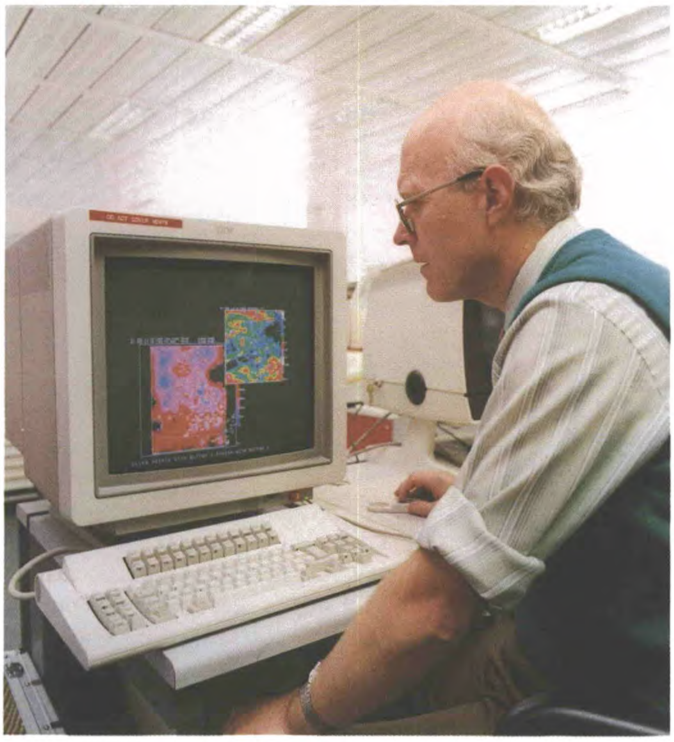
Analyses are made by combining information from current observations with that from earlier observations, updated and organized using a forecast model; this process is called data assimilation. It is done by correcting the model state (forecast from earlier observations) to bring it into agreement with current observations. These corrections should be consistent with knowledge of the general nature of the atmospheric phenomena that the model can represent; for instance, by making repeated small corrections over a period of time the assimilation method avoids very rapidly varying, and therefore unrealistic, structures. A scheme designed with more regard to the convergence properties of the repeated corrections has been developed. The new scheme has a beneficial impact on the skill of short-period forecasts, and allows greater flexibility in the way different types of observations are used, by taking account of their special characteristics. For instance, it can give appropriate weight to the temperature information from satellite-sensed radiances (see above) which already contain information from a model forecast.



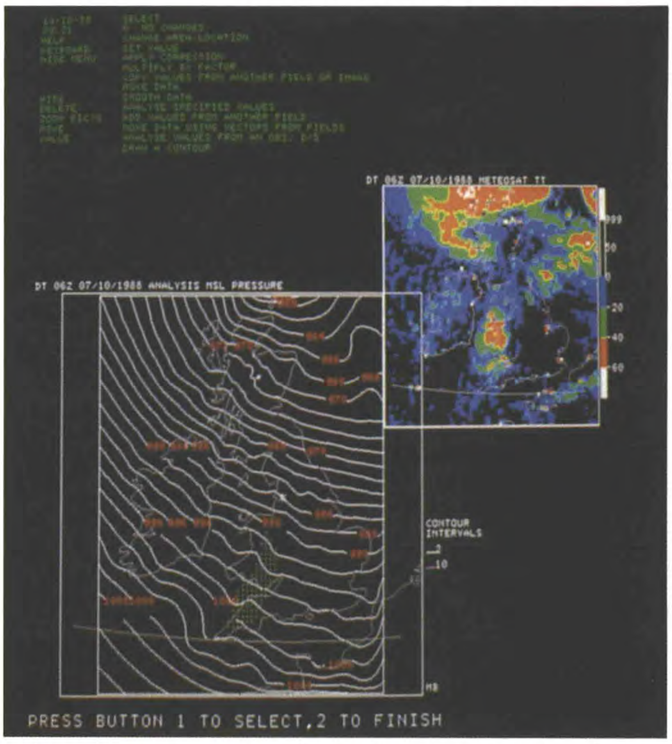
Schematic of physical processes represented in the enhanced physical parametrization package. Horizontal grid points shown are from an east–west cross-section at 52.5°N from the Irish Sea to the North Sea. Vertical levels are shown on a pressure scale which reduces the apparent physical spacing in the upper atmosphere.

For climate research and long-range forecasting another model is used (see later). Similar physical processes are represented in this model and in the global and regional fine-mesh models, as all of them now put increased emphasis on surface weather, radiation and clouds. Development of the models is therefore closely co-ordinated; the representation of physical processes in the forecast models is based on those of the climate model, and plans are well advanced for a closer unification of the computer codes. This will allow an even more effective use of research and development effort.

For short-period forecasting of the detailed weather over the British Isles, a mesoscale model with horizontal grid length of 15 km has been under development and testing for some years. The accuracy of forecasts from such a model depends crucially on the initial distribution of moisture as both clouds and vapour. High-resolution information about clouds is available from satellite imagery and weather radars. It is not yet possible to use this information routinely and quantitatively; however, under the control of a skilled analyst, it can make a valuable contribution to the initialization of the model. A system for performing the interaction was introduced into the Central Forecasting Office (CFO), for regular use by the forecasters. The interactive initialization merges data from past forecast runs, satellite and radar imagery, lightning fixes, and surface synoptic reports, to create a detailed description of the state of the



Mesoscale analyst adjusting computer analysis of cloud base. The satellite infra-red image top right is used as guidance.



Surface pressure pattern being modified by hand (analyst not shown). The pressure in the stippled area has been selected for modification in view of the information from the satellite infra-red image top right.

atmosphere over the British Isles for input to the mesoscale model. The photographs on page 31 show modifications being made to two of the key variables, surface pressure and cloud base. The analyst can use a variety of techniques to: transfer information directly from the satellite or radar picture, use freehand drawing, or fit a surface to specified points. The key variables then provide information for objective techniques which adjust the three-dimensional model fields to produce a consistent structure. Thus the insertion of a trough in the surface pressure analysis will be reflected in the upper-wind and temperature fields.

A major source of error in forecasts from the current mesoscale model is air that enters the model domain during a forecast. The properties of this air are not as well known as those of air originating within the model's area, which has had the benefit of the interactive initialization. The current boundaries just enclose the United Kingdom; the ETA10 computer will permit the area to be approximately trebled. Air crossing the boundaries of the enlarged model should not normally affect the United Kingdom within 12 hours. The ETA10 will also allow the use of an enhanced vertical resolution, giving the potential for forecasting the height of low-level cloud to the precision required by the Royal Air Force.

Many of the model developments described above were given additional impetus by the lessons learned from study of forecasts for the October 1987 storm. The revised assimilation scheme for the global and regional fine-mesh models can make better use of aircraft observations which, as in the case of the storm, do not coincide with a main analysis time. The improvements in the processing of satellite data and the quality control of ships' observations should lead to a general improvement of analyses in data-sparse oceanic areas. The enhanced resolution of the regional fine-mesh model will enable a better representation of the dynamical processes of storms such as that of October 1987. Sophisticated diagnostic methods have been developed and used to compare the various model forecasts of the October storm with detailed analyses of satellite pictures, leading to a better understanding of the cloud patterns which often presage such explosive developments.

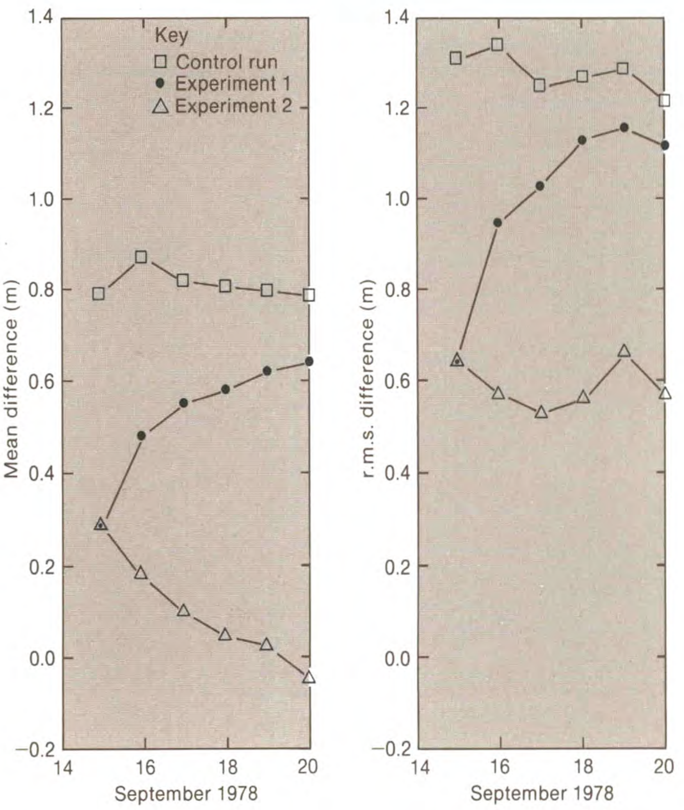
As well as NWP models the Office also runs global and regional sea-state forecast models. These have been enhanced, taking advantage of the ETA10 supercomputer. The enhanced global sea-state model uses exactly the same grid points as the enhanced atmospheric model, and thus can be driven directly by the forecast surface wind fields without interpolation. The grid points of the regional sea-state model have not been changed, however, since they are already more closely spaced than those of the enhanced regional model that provides the wind field. Both sea-state models on the ETA10 will eventually use improved spectral resolution in the representation of the wave energy at each grid point. Further research is required to determine the most effective combination of frequency and direction components for the given computing power.

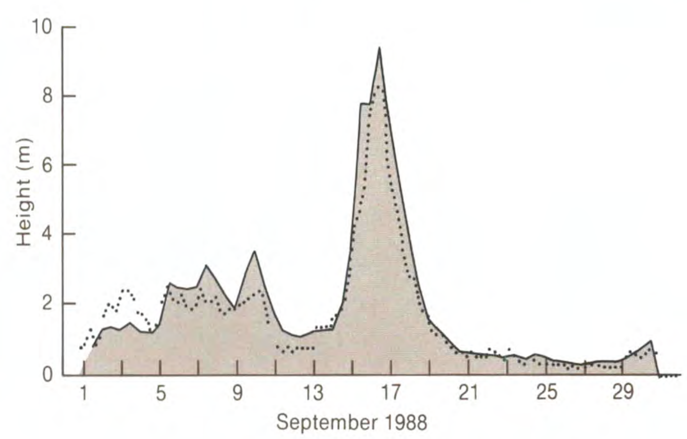
Substantial progress has been made with experiments on the assimilation of measured data into the global sea-state model. These experiments have used collocated wave height and wind speed data for a period in 1978, derived from the altimeter instrument on a satellite known as 'SEASAT'. Similar data in near real-time are expected from a European satellite known as 'ERS-1', due to be launched in 1990. The SEASAT experiments demonstrate that the assimilation technique is successful in adjusting the sea-state model to the satellite data over a period of several days; and also that, even after a single 24-hour period of data assimilation, there is an impact in the sea-state model that lasts throughout the 5 days of a subsequent forecast.

Forecasting products

A new Forecasting Products Branch was established during the year in recognition of the spread of automation throughout the forecasting activities of the Office and the increasing provision of tailored numerical model output directly to users.

The maintenance and development of the operational numerical forecasting system is, of course, the most basic requirement for the provision of forecasting products. An important development of the system occurred in February, when a new fine-mesh run, based on 0600 GMT starting conditions, was added to the daily operational



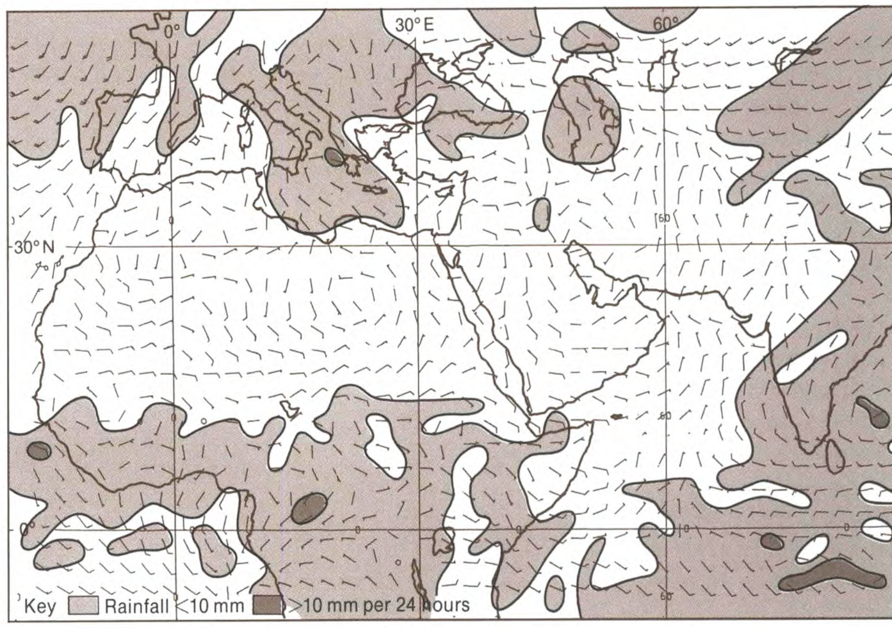


Observed (dotted line) and modelled (solid line) wave heights at a location in the Gulf of Mexico close to the track of Hurricane Gilbert

Global statistical measurements of the differences between SEASAT and model wave heights. The control run used no satellite data; in experiment 1 satellite data were assimilated for 24 hours prior to the 5-day period illustrated; in experiment 2 the satellite data were assimilated throughout.

schedule. This was in response to one of the recommendations of the reports on the October 1987 storm.

Back-up arrangements to cover a variety of contingencies are of major concern for users of forecasting products. Following a short loss of service (caused by rupture of a faulty water pipe) in March, special collaborative work has been carried out with the airlines' organization Société Internationale de Télécommunications Aéronautiques to make it easier for airlines to access the back-up global products from Washington should Bracknell ever be unable to provide a service. Back-up regional products from Paris were added to the operational system in August for use in the CFO.



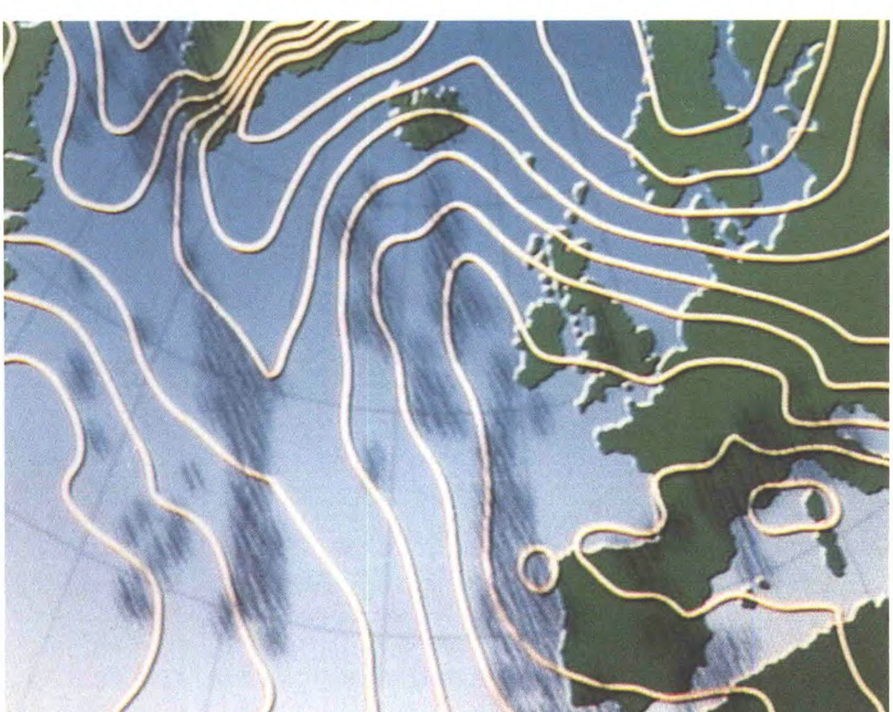
Combined rainfall and surface wind forecast for the desert locust region. The chart covers all the main seasonal breeding areas. Rainfall is necessary for locust breeding; wind strongly affects the subsequent movement.

The quality of forecasting products must be closely monitored to enable advice to be given to users and to stimulate research and development. During 1988 the quality of the products from the global and regional fine-mesh NWP models and sea-state models remained broadly as in recent years. Verification facilities have been expanded, particularly with regard to precipitation forecasts. Case-study verifications remain important and the products generated for the Gulf of Mexico region at the time of Hurricane Gilbert in September have been specially studied. The diagnosed peak wave height, for example, agreed remarkably well with data from a buoy moored close to the hurricane track.

Monitoring of the availability and quality of observations is essential for maintaining and improving the accuracy of forecasting products. Within the World Meteorological Organization context, Bracknell has been assigned the lead role in monitoring surface marine observations on a global basis.

The demand for numerical products for Defence, civil aviation, commercial and international purposes has continued to grow. A large number of digital products are now supplied directly to several RAF airfields. Since late March, numerical forecasts of wind, temperature and humidity have been supplied to the Algerian Meteorological Service to support locust control activities (see figure above). New products introduced during the year include three-dimensional air trajectory forecasts to assist with forecasting low cloud. Trajectory data have also been provided routinely to the Royal Netherlands Meteorological Institute under a special collaborative arrangement, and were provided at the request of the Overseas Development Natural Resources Institute for a period in October for an investigation of the arrival of the desert locust in the Caribbean region. Additional forecasting products are obtained through enhancement of model output by statistical methods. This approach has been extended to provide predictions of maximum and minimum temperatures for nearly 100 European stations. Results show smaller errors than 1-day persistence forecasts, even at lead times up to 4 days ahead.

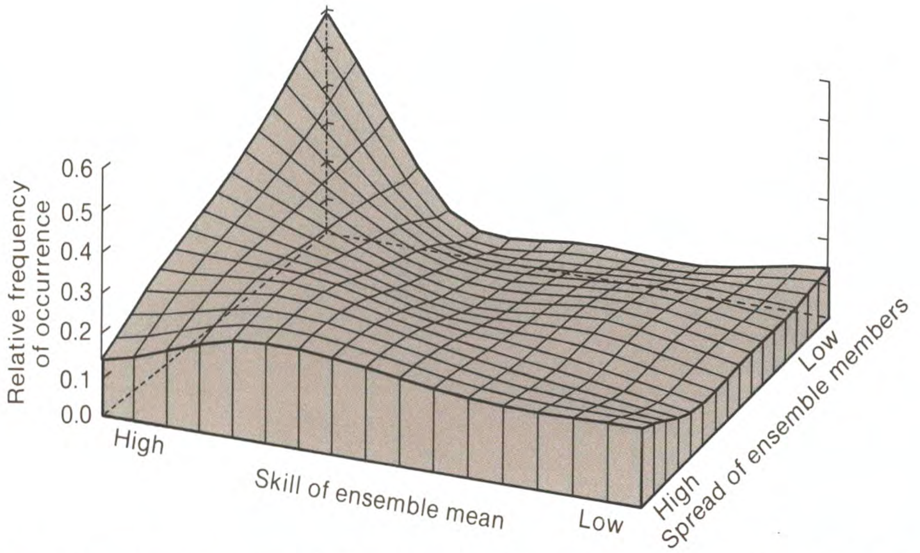
Numerical forecast of pressure and precipitation displayed directly on BBC TV



The graphical products supplied to BBC TV were considerably enhanced during the year, with new displays going live from June onwards. This work shares basic software and databases with the CFO graphics and with the Weather in Vision project.

The increasing use of numerical products at outstations is supported by software development for the local computer systems and also, this year, by the investigation of increased automation for certain forecasting services. Close technical liaison on these matters is maintained with the Directorate of Naval Oceanography and Meteorology.

Good progress has been made during the year with products that have special application to marine activities. The development phase of the North European Storm Study, a major collaborative commercial project to compute a new wind and wave climatology for the offshore industry, was completed successfully, and the production phase began. Also in the marine sector, increasing numbers of site-specific forecasts have been produced directly from the regional fine-mesh models in support of contracts with North Sea operators. Automated coastal engineering products, based on near-shore data from the sea-state and tidal-surge models (see section on central forecasting), are being developed. Products from the global sea-state model have continued to assist the Office's ship routeing service.



Ensembles of forecasts are categorized according to how different the individual members are ('spread') and how accurate the mean forecast is ('skill'). The diagram shows the frequency with which ensemble forecasts (of mean-sea-level pressure for the period 6–15 days ahead) fall into different categories of skill and of spread; it is seen that forecasts having low spread are most likely to have high skill.

Long-range forecasts

Forecasts of temperature and rainfall for the United Kingdom up to 30 days ahead are routinely prepared using two techniques to predict future mean-sea-level pressure patterns. One technique uses statistical relationships based on past pressure patterns and sea surface temperature anomalies. The other uses an NWP model, run for an extended period. Using the output from both these techniques, a final forecast pressure field is derived subjectively, and objective regression equations are used to derive temperature and rainfall.

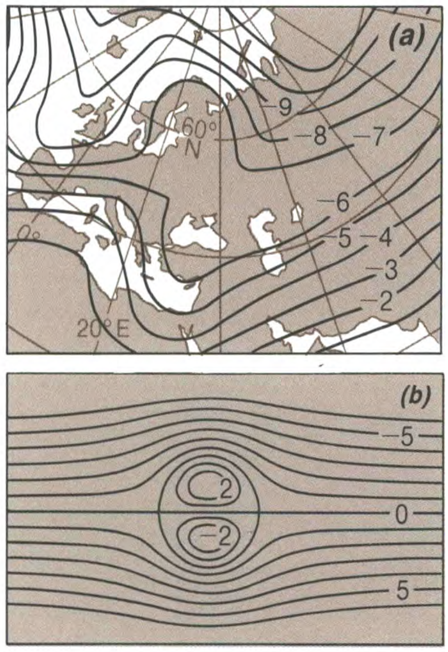
A development during the year has been the routine use of several integrations of the NWP model with slightly different input conditions to produce an ensemble of predictions. There are preliminary indications that the spread of the ensemble is related to the skill of the forecast (see figure top right); such a relationship would allow some objective confidence level to be assigned to a particular forecast.

Because the long-range forecasts have a low (but positive) skill, they are not suitable for issue to the general public. However, they can be used for decision-making by industry and commerce, and it is intended to make them available to this type of customer during 1989.

It is well known that, as well as day-to-day variability in weather, the atmosphere in our latitudes exhibits longer 'spells' of settled or unsettled weather. Theoretical work has suggested that the atmosphere may lock in to a natural 'free-mode' state which persists for some time and real synoptic situations have now been identified that exhibit some of the characteristics of these 'free-modes' (see figure right). This theoretical research may have practical application in the future in long-range forecasting; if particular states of the atmosphere can be recognized as being of low or high predictability then this can supplement the guidance provided from ensemble forecasts in deciding the level of confidence that can be placed on particular forecasts.

Clouds and radiative processes

Clouds are important features in the atmosphere; they influence the circulation because they act as local sources or sinks of heat due to the effects of radiation or latent heat. They are also regions in which much of the vertical transport of heat and momentum takes place. Many practical problems result from the effects of clouds. For example, clouds and precipitation affect the atmospheric transmission at wavelengths used for communications. Also many hazards to aviation are associated with clouds. These include icing, turbulence and heavy rainfall.



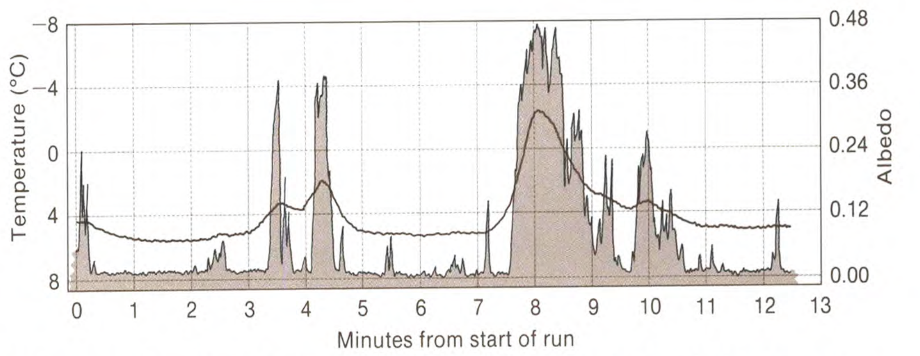
Observed mean flow at 300 mb for 20–24 October 1987 (a) has a pattern, centred on 30°E, reminiscent of the theoretical solution (b) of equations governing atmospheric flow. The resemblance between the two is confirmed by more detailed analysis.

The object of much of the work on the interaction between clouds and radiation is to understand the effects of clouds on the atmospheric energy budget; the effects are large but in most atmospheric circulation models it is impossible to predict the properties of clouds with the detail required for accurate radiative calculations. Although, as indicated in the section of the report on world climate, progress is being made in using the models to predict the cloud liquid water content, many aspects of the clouds and their radiative effects must continue to be parametrized in these models. Systematic uncertainties in the parametrizations can lead to uncertainties in climate prediction that are comparable with effects of large increases in carbon dioxide concentration. The formation and dissipation of clouds are also influenced by radiative processes so that a better understanding of cloud–radiation interaction is necessary to predict the evolution of layer cloud, especially that of stratocumulus. Improvements in such predictions are important for aviation. During the year the Meteorological Research Flight (MRF), with its research activities in the field of radiative transfer, was merged with the Cloud Physics Branch. This reorganization will strengthen the research by permitting a greater exchange of expertise in these interrelated areas.

The initial processing of data obtained during the First ISCCP Regional Experiment (FIRE) which took place in 1987 off the west coast of the USA was completed and interpretation of the extensive high-quality data set started.

The data appear to support ideas developed from earlier data gathered around the United Kingdom concerning the diurnal variation of the cloud that results from imbalance between radiative and turbulent transport processes in the cloud. Measurements of the cloud radiative properties in these experiments have enabled estimates of the 'equivalent radius' of the droplets to be obtained; this parameter is often used in parametrization schemes for numerical circulation models. On one occasion during FIRE a banded structure, due to the presence of a solitary travelling wave in the capping inversion, was observed in the cloud layer. The cause and frequency of occurrence of such events are being estimated since such features alter boundary-layer structure and vertical transport processes.

The evolution of cirrus cloud is dominated by radiative processes. Cirrus cloud also influences the radiation budget although effects are difficult to quantify because of the complex shapes of the ice crystals and the low-ice content therein. Studies of cirrus around the United Kingdom using the MRF Hercules aircraft have identified the type and number concentration of the ice crystals; the low number concentrations have been explained using a simple model of ice crystal nucleation. The radiative properties of ice crystal clouds are influenced by the orientation of the crystals. Lidar measurements of back-scatter made at the University College of Wales, Aberystwyth can detect regions where there is a preferred ice crystal orientation and such measurements are being combined with aircraft data to determine the frequency and cause of these effects.



Measurements from the MRF Hercules of the albedo (brown line) and surface cloud-top temperature (black line) obtained using a Barnes radiometer when flying over a field of small cumulus. The high values of temperature indicate breaks in the cloud layer where the surface temperature is measured. The results demonstrate the variability of cloud radiative properties which must be appropriately conveyed in general circulation models.

Experience gained during the various cirrus studies was used in the design of the International Cirrus Experiment, the observational phase of which will involve groups from the United Kingdom, France, and the Federal Republic of Germany and will take place in autumn 1989. The object is to provide a comprehensive data set on the radiative, turbulent, microphysical, dynamical and thermodynamical structure of cirrus. Observing systems will include both *in situ* and remote sensing by several aircraft including the MRF Hercules, ground-based and satellite remote sensing, and conventional sounding systems.

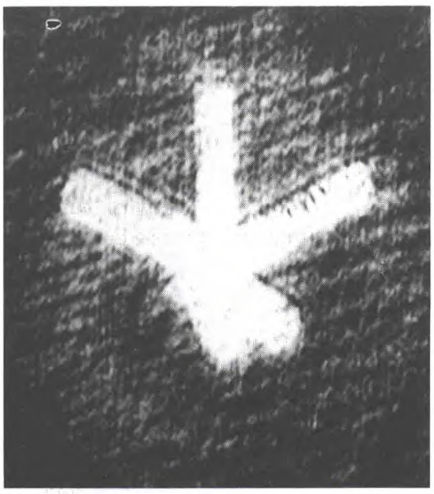
The non-uniformity of clouds in space and time gives rise to problems in the development of cloud parametrizations. Data on the radiative properties of broken cloud fields are being compared with theoretical models with particular emphasis on the role of air mass type, while high-resolution satellite imagery is being combined with *in situ* data to derive estimates of fluxes due to broken clouds averaged over distances large compared with the individual cloud size.

Atmospheric water vapour is an important source of error when deriving temperature profiles from satellite measurements, especially in regions of high specific humidity. The Hercules aircraft was detached to Dakar in July to undertake the West African Tropical Experiment in Radiation in which measurements of radiative transfer were made in regions of high humidity. A multi-channel radiometer on the aircraft was central to the success of this project. The detachment also provided data on the effects of the Saharan dust plume on radiative transfer. The data are being compared with detailed radiative transfer models, of a type used in the development of parametrization schemes, to determine whether there are systematic errors in the models.

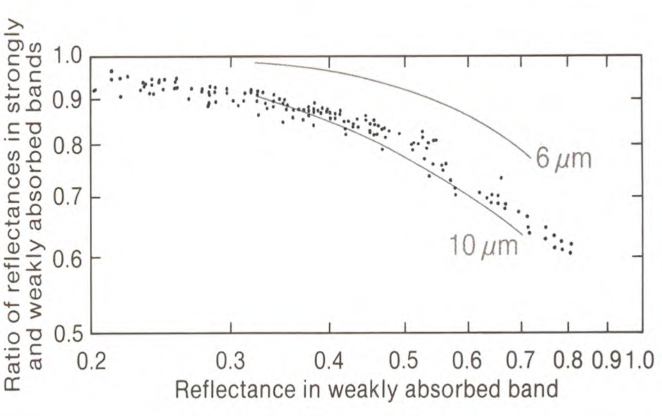
Boundary-layer processes and dispersion

Inevitably many human activities are subject to the particular influences of the turbulent air flow which occurs close to the earth's surface. The depth of this turbulent region (termed the boundary layer) varies with atmospheric static stability and wind speed, and within it fog and low cloud may form. Information on the variations of wind, temperature, humidity and visibility is required for various applications including agriculture, building, aviation and radio signal propagation. A topic of wide interest concerns the dispersion of gaseous or particulate materials within the boundary layer over a wide range of distances. The boundary layer also plays a critical role in determining the transfers of heat, moisture and momentum between the atmosphere as a whole and the earth's surface. These transfers have an important influence

Hologram of ice crystal observed from the MRF Hercules in cirrus cloud at a temperature of −41 °C. The crystal is about 0.6 mm across. The image demonstrates the complex shape of many natural ice crystals.



Comparison of reflectance of stratocumulus clouds (points), observed during FIRE, with those predicted using different equivalent radius approximations. The results are being used to test parametrizations of clouds in climate models.

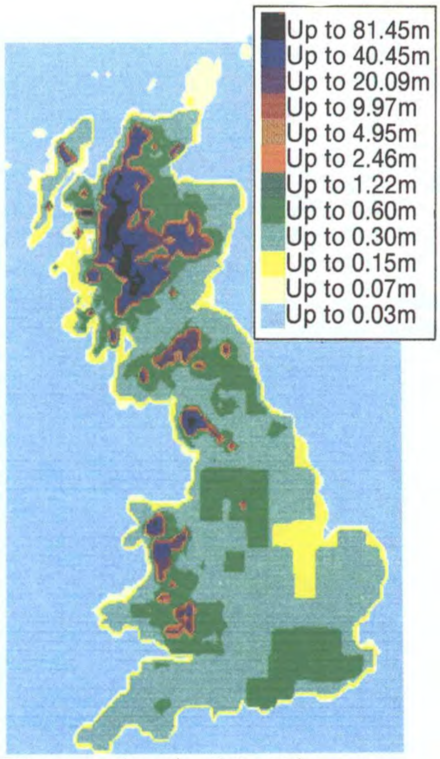


on both short-term forecasting and the longer-term predictions of climate. The Office's research programme is aimed at providing improved predictions of both the local flow features within the boundary layer and also the gross transfer properties.

The representation of the boundary layer over complex terrain is recognized to be a weakness of NWP models and the prediction of local flows in such environments. Observational and theoretical studies continue to be undertaken and progress to date shows that 'roughness length' provides a suitable description of terrain effects within boundary-layer models. In consequence a map of roughness length over the United Kingdom, based on readily available digitized terrain and land use data, has been generated (see figure right) and will be subject to tests in future field studies.

The turbulence that occurs in the vicinity of surface fronts in an active depression is of interest to aviation and its representation is important to improving weather forecast models. Observations of this turbulence were made using the Meteorological Office tethered-balloon facility from a location on the Isles of Scilly. This study formed part of the Fronts '87 collaborative field experiment (described on page 37).

The large-scale turbulent motions within the boundary layer contain most of the turbulent kinetic energy and affect the main transports of heat, moisture and momentum. Three-dimensional numerical simulation of the larger-scale motions in so-called 'large-eddy simulations' has proved to be a powerful method of providing new information on the structure of the boundary layer. Current applications include the nocturnal stable boundary layer and boundary layers with low stratocumulus cloud. The results are being used to improve the predictions of the simple models which are now employed in various applications including weather forecast models.



Effective roughness length for 10 km square areas. The map is derived from a 500 m resolution orography and a 40 km square resolution land use data set.

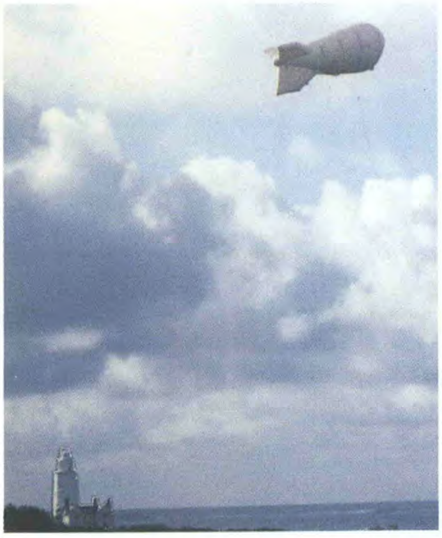
When materials disperse into the boundary layer the concentration at any location is not steady but fluctuates considerably in time. In estimating the consequences of accidental releases of toxic, inflammable, or objectionably odorous materials the magnitudes of these fluctuations are of critical importance. The Office has taken an international lead in the observation and prediction of these fluctuations. Current work is concerned with extending short-range observations at distances of about 100 m from the source of the material to longer ranges of about 1000 m.

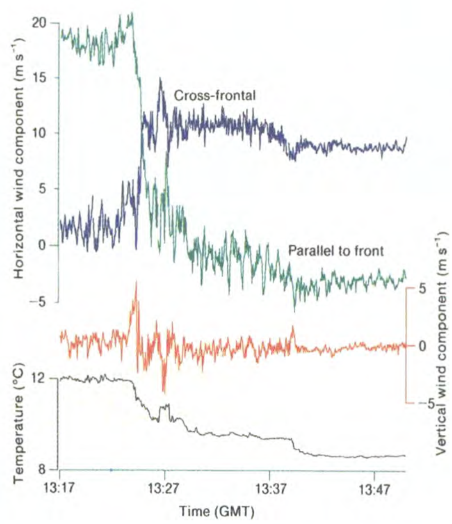
Following on from the nuclear accident at Chernobyl a National Response Plan was drawn up to deal with any further emergency of this kind. The Plan requires the development of a fast-response numerical model capable of simulating the transport, dispersion and deposition of radio-nuclides released into the atmosphere from any European installation. A fairly basic model was quickly prepared in case of further emergencies, and work is now in progress on the main model which, by the end of 1989, is expected to be in the forefront of large-scale dispersion models of its kind. The work has developed into a major collaborative project between the Office, the Safety and Reliability Directorate of the United Kingdom Atomic Energy Authority and two university groups who are carrying out supporting investigations.

The transport of material is simulated by releasing a large number of 'particles' into the model atmosphere at the site of the accidental release, and computing their trajectories using wind fields from the operational NWP suite modified by random displacements representing the influence of sub-grid-scale turbulence. To reflect various processes of entrainment and convection, material can be transferred between model levels in the three-dimensional air flow. A particularly important exchange is that between the boundary layer (which may be of varying depth depending on atmospheric conditions) and the free atmosphere above.

Work is now proceeding to represent the critical processes of wet deposition, where the radioactive plume is

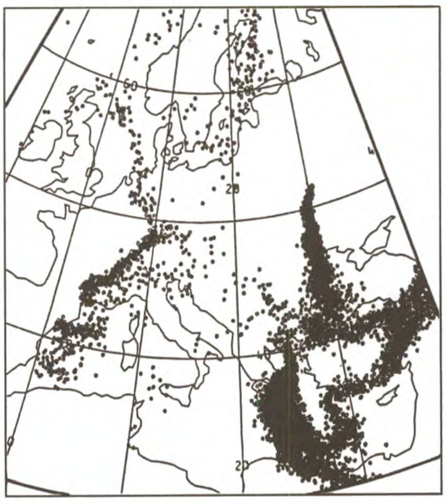
The Meteorological Office tethered-balloon facility in use collecting turbulence data over the Isles of Scilly

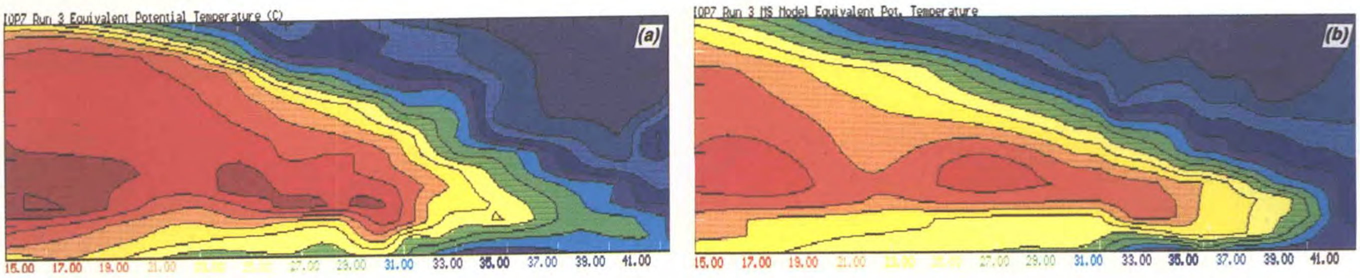




Time traces taken at 300 m from one of several probes during the passage of a sharp cold front over the Isles of Scilly on 11 November 1987

Simulation of the spread of radioactive material present in the atmospheric boundary layer from 2023 GMT on 25 April until 0000 GMT on 3 May 1986





intercepted by a rainfall system. A procedure is being developed to generate and use hourly fields of rainfall data and type derived from near real-time radar, satellite and surface observations, supplemented where necessary by NWP model products. It is intended, eventually, in the light of available radiological observations, to incorporate a facility for objective correction of both plume location and the concentrations and depositions of radio-nuclides.

Mesoscale processes

Increased understanding of the interactions between processes operating on small scales and the underlying larger-scale patterns is important for further progress in short-range forecasting. In recognition of this the Joint Centre for Mesoscale Meteorology was established during the year, bringing together observational and numerical modelling groups from within the Office with dynamical research workers from the University of Reading.

Initially a focus for the Centre's work is the analysis and interpretation of observations and model forecasts from the very successful Fronts '87 experiment of the Mesoscale Frontal Dynamics Project. This experiment, the largest such mesoscale experiment carried out in Europe to date, was mounted between October 1987 and January 1988 to study the detailed structure of cold fronts approaching the Channel.

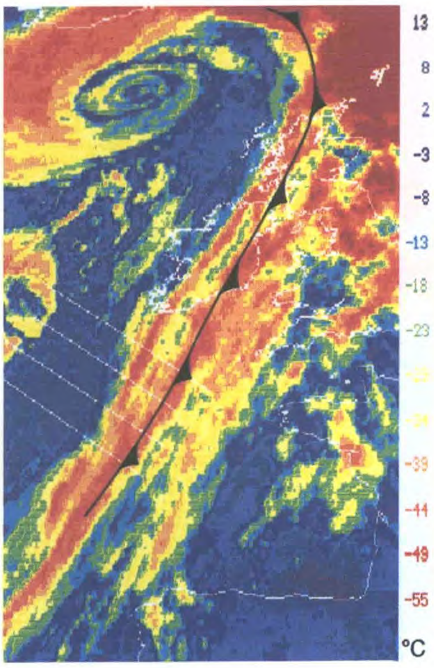
During the period of the experiment six major cases were studied using measurements from the new dropsonde system on board the MRF Hercules aircraft, aircraft from France and the Federal Republic of Germany and ground-based dual Doppler radars, together with other observations from Brittany and south-west England. The dropsonde system proved capable of resolving features on a 25–100 km scale over an area of 400 km × 500 km. The combined observations will provide some of the most comprehensive data on fronts yet obtained — a valuable basis both for theoretical studies and for the development and testing of improved numerical forecast models.

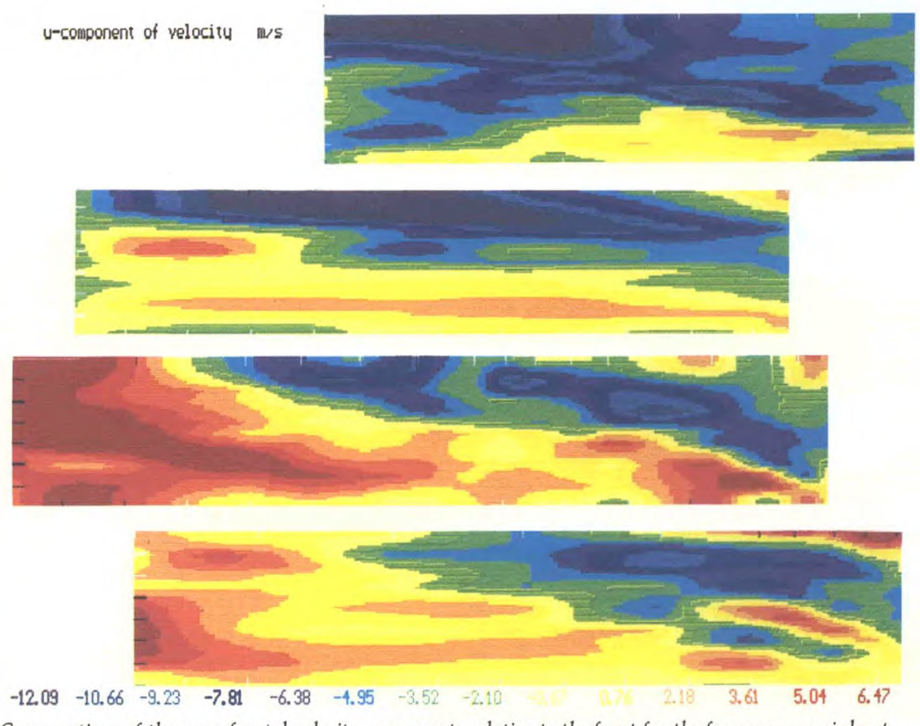
The first case to be analysed in detail occurred on 9 January. It was a classical cold front with minor wave perturbations evident in satellite imagery. Vertical cross-sections from the dropsondes showed marked variations of the circulation across the front associated with the wave. Results from the mesoscale model suggest that the evaporation of precipitation may have had an important influence on the dynamics. The high resolution of the observations also indicates the complexity in the structure of the fronts in mid troposphere on scales of 100 km and less, with steps or folds in the thermal structure and sharp moisture gradients. This and other features near the surface front suggest the occurrence of conditional symmetric instability in places, a process thought to be central to the organization of frontal rainfall into bands.

The mesoscale model successfully captured many aspects of the observed frontal structure. Further model studies are in progress to identify the roles of the larger-scale dynamics and the interactions between diabatic processes and the dynamics.

Equivalent potential temperature cross-sections (height 7 km, length 650 km) along third aircraft run at 1200 GMT on 9 January from (a) dropsonde observations and (b) mesoscale model forecast initiated at 0000 GMT on 9 January. Many features are well captured by the model, including the tongue of cold dry air below the frontal surface, and the slope of the transition.

Meteosat infra-red image valid for 0900 GMT on 9 January, with the positions of four dropsonde aircraft tracks and position of surface front indicated





Cross-sections of the cross-frontal velocity components relative to the front for the four runs carried out on 9 January. Positions of dropsondes are shown at the top of each panel. Sections are aligned such that the front is in the same position in each.

World climate

The climate system

Climate and the potential for global climate change have, of late, come into the public eye and much current interest and awareness has been generated in the impacts of man-made pollutants on the climate system. The ozone hole provides the clearest demonstration so far that man can influence the environment on a global scale. Changes in the concentrations of trace gases, via catalytic photochemical reactions involving, in particular, the chlorofluorocarbons, can lead to important modifications in the chemistry of the atmosphere. Of special concern also are the changes to the earth's radiation balance that may be brought about by increases in the atmospheric concentration of carbon dioxide (CO_2), water vapour, ozone, methane and other radiatively active trace gases (collectively known as 'greenhouse gases').

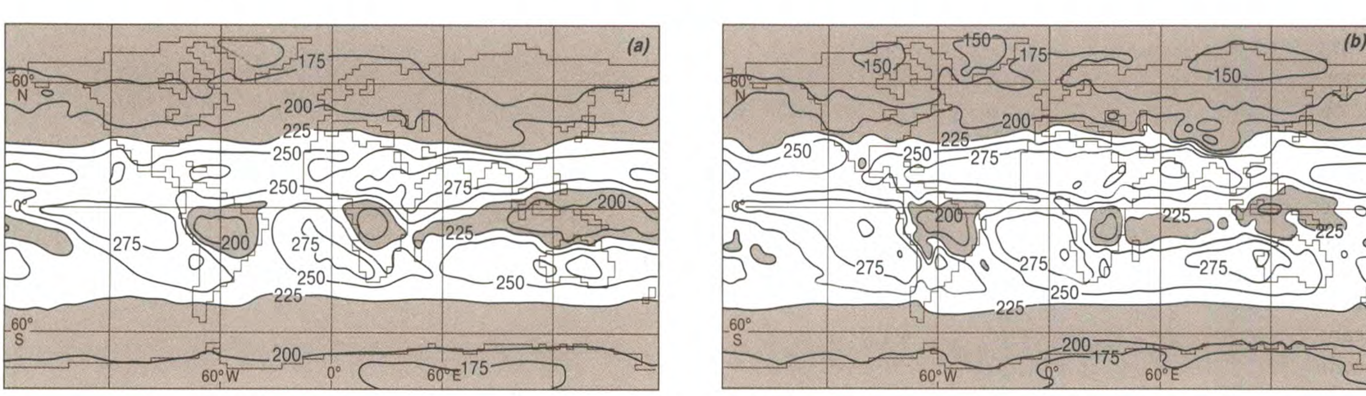
Studies of the global climate are undertaken by the Office; these are leading to a better understanding of the mechanisms underlying climate variations, both natural and man-made. These variations, whether they occur as long-term transitions or as part of the year-to-year variability (such as 'El Niños' — warmings of the tropical east Pacific that occur every few years), can disrupt agriculture and fishing and cause starvation, loss of life and damage to national economies by upsetting the normal weather patterns. A combination of modelling and careful analysis of observational records provides the essential means for the study and prediction of the complex interplay between the various processes that are important for the climate system and for climate change. In the atmosphere, these processes include the interactions and feedbacks between clouds and radiation, the land surface and the atmospheric boundary layer and the exchange of properties between air and sea. The oceans are important also because of their large heat capacity and because of the effects on the atmosphere resulting from the changing extent of sea-ice.

Modelling physical processes

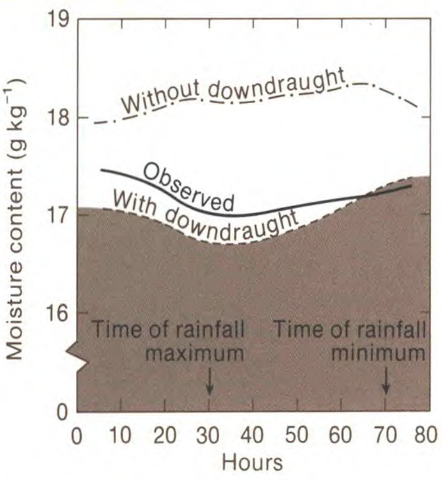
Numerical models of the atmosphere, of the ocean, and also of the complete atmosphere, ocean, sea-ice and land surface system, provide a major facility within the Office for studying the physics of climate and climate change. The representation of layer cloud in the atmosphere model based on the explicit prediction of a cloud water variable has improved the simulations of cloud and radiation to a point where the distributions are now broadly similar to those observed (see figure below). An additional important benefit of including cloud water is the scope it gives for improving the representation in the model of the radiative properties of clouds by taking some aspects of cloud microphysics into account. It has long been recognized that the assumption of uniform cloud radiative properties is unrealistic as well as restrictive in a model used for studies of climate change. To improve confidence in the model's simulations of present and perturbed climates the calculation of physical properties and processes should be based as far as possible on physical principles rather than on empirical formulae. As a first step towards making cloud radiative properties fully interactive in this way a scheme has been developed for calculating the short-wave reflectivity and transmissivity of water clouds as functions of the cloud liquid water and the equivalent radius of the drop size distribution. Tests against a complex radiative transfer model and observations made with the Hercules aircraft of the Meteorological Research Flight (MRF) show that the scheme predicts the bulk cloud radiative properties to good accuracy.

Tests with a physically realistic treatment of cloud microphysics in the model's convection scheme have produced good estimates of the liquid water content of convective clouds. Previous work with the convection scheme had demonstrated the importance of including downdraught processes; an explicit representation of convective downdraughts has therefore been developed. A downdraught is treated as an inverted plume that entrains environmental air as it descends and into which convective precipitation is allowed to evaporate. Results obtained using the scheme in a one-dimensional model compare well with observed data. In particular, improved simulations of the thermodynamic structure of the sub-cloud layer are obtained as a result of the transports of heat and moisture into this layer by downdraughts (see figure top right).

If reliable estimates are eventually to be made of regional climate change, it is important to assess the ability of the model to represent the detailed climate of particular areas. Examination of the near-surface temperature and wind simulated over southern Britain by the climate model revealed an unrealistic decoupling of the bottom two model layers in very stable conditions in winter. A revised formulation of the



Observed (a) and modelled (b) outgoing long-wave radiation at the top of the atmosphere (W m^{-2}) for December, January, February 1979–80. Areas with values below 225 W m^{-2} are shaded.



Evolution of sub-cloud layer moisture content over the tropical east Atlantic through a tropical wave for experiments with and without downdraught representation in the convective scheme. Observed values are also shown.

boundary-layer mixing coefficient, which does not cut off all mixing above a critical stability, allows the surface and near-surface model variables to respond more quickly and realistically when a change of weather regime takes place in the model simulation.

Climate simulations on both the global and regional scales are also sensitive to the treatment of land surface processes. The model has been altered to allow the surface roughness to depend on the depth of lying snow. The simulation of snow melting in spring has been shown to be sensitive to the calculation of the albedo of snow-covered surfaces, emphasizing the need to treat snow processes in a more detailed way.

To date global ocean models used for studies of the climate system have been of comparable horizontal resolution to those of the atmospheric models to which they are coupled. Such models are incapable of resolving the much smaller-scale oceanic eddies. A limited-area model of the North Atlantic Ocean is therefore being used to assess the impact of increased resolution on the model simulation. Preliminary results from a model with a resolution of 1 degree show enhanced Gulf Stream transports and point to possible benefits from the higher resolution. A further important element in the simulation of the ocean climate is the specification of the momentum, heat and freshwater fluxes across the air–sea interface. Studies are under way with the oceanic component of the coupled model, to assess the impact of forcing on the simulation of the global and tropical oceans. Data from: the atmosphere, specified for the observed climatology; the climate model; and the operational numerical weather prediction (NWP) model are being used in the studies. These studies reveal sensitivity both to the fluxes themselves and to the way in which they are mixed down into the surface layers of the ocean and demonstrate that some improvement to the model physics is necessary.

Tropospheric chemistry

Ozone, and other photochemically active gases such as peroxyacetyl nitrate, can affect the biosphere directly, influencing crop yields and plant and animal health. Oxidation in the troposphere, mainly by reaction with the hydroxyl radical, is the major atmospheric removal mechanism for many gases released anthropogenically. A short tropospheric lifetime ensures rapid removal from the atmosphere, lowering tropospheric concentrations and preventing potentially damaging gases from reaching the stratosphere.

Many alternatives to chlorofluorocarbons (whose use is now being increasingly restricted by the Montreal Protocol) are now being proposed by the chemical industry. A knowledge of the present, and a reliable prediction of the future, oxidizing potential of the troposphere are essential if the implications for global climate change of these alternatives are to be properly assessed.

A programme of measurements and computer modelling of tropospheric photochemistry is under way at the Office, using the MRF Hercules aircraft and the Office's computing facilities. In collaboration with scientists in the Federal Republic of Germany, the existing suite of instruments for measuring chlorofluorocarbons, hydrocarbons, ozone, peroxyacetyl nitrate and water vapour is in the final stages of being enhanced so that nitric oxide, and total reactive nitrogen can also be measured. A highly sensitive instrument capable of detecting the low concentrations of water vapour characteristic of stratospheric air has undergone several successful flight trials.

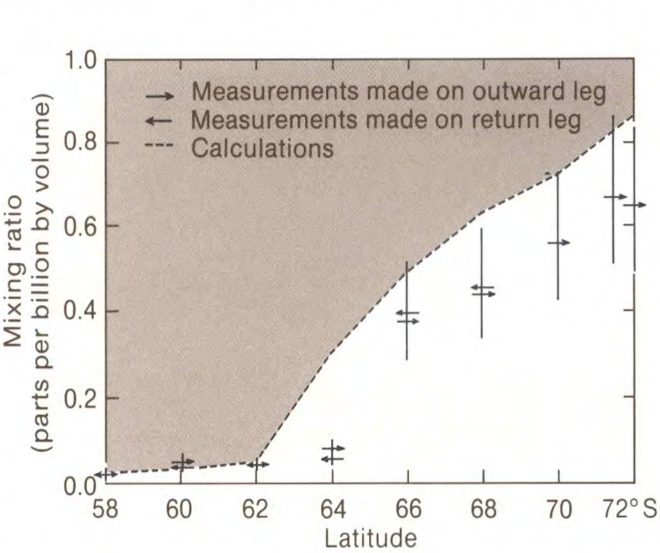
Stratospheric ozone

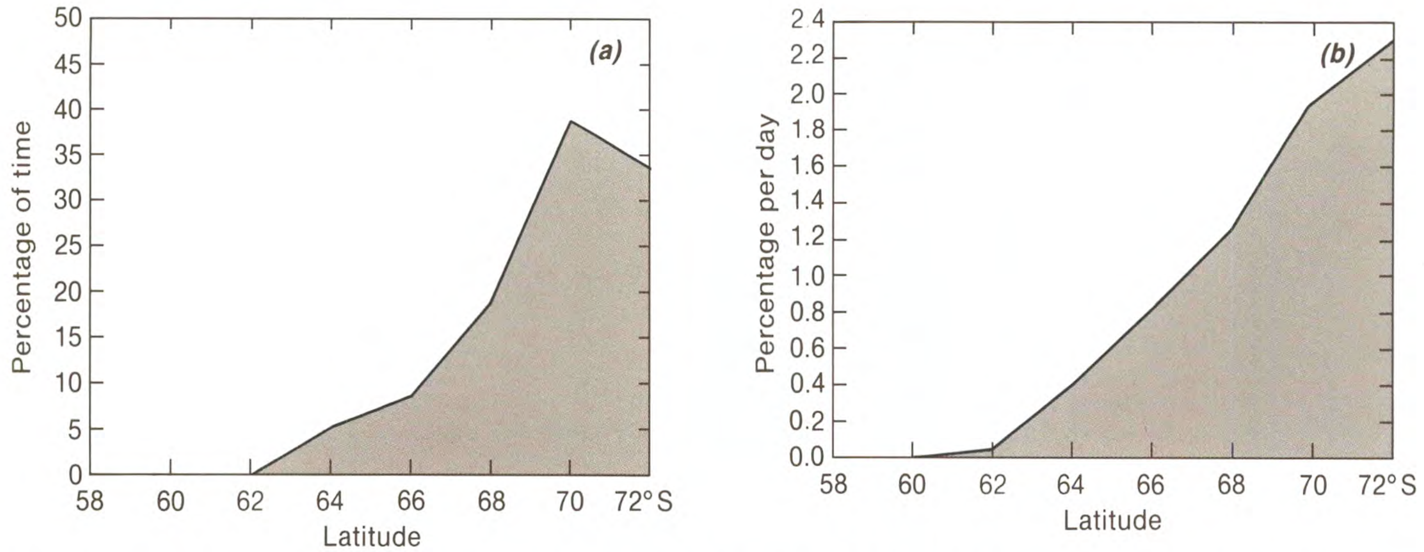
Ozone, concentrated in a layer centred at about 25 km altitude, is an important absorber of solar radiation at wavelengths between 280 and 320 nanometres, By absorbing solar radiation the ozone layer both protects the biosphere from biogenically harmful radiation and heats the upper atmosphere, thus influencing the atmospheric temperature structure and circulation.

The Office is actively involved in monitoring the atmospheric ozone amount from a number of ground-based stations as part of a world-wide programme under the auspices of the World Meteorological Organization (WMO) (see section on observations). Work to correct a number of calibration problems noted in the Bracknell records is in hand to ensure that a high standard of instrument calibration is maintained into the future. Such a commitment is essential if past and future trends in atmospheric ozone are to be quantified reliably.

In the mid-1980s the ozone column over Antarctica suffered major depletions in the Austral springs. This depletion was not predicted by computer models of atmospheric photochemistry of the early 1980s. In 1987 column ozone values above Antarctica fell to the lowest ever observed (around 125 Dobson units in early October). A substantial ozone depletion was also observed in 1988, but it was less severe than in 1987 with column ozone values within the hole being generally comparable to those of 1984. Though not fully understood, such a marked interannual variability is not unexpected; it reflects the complex interaction between the photochemistry and the atmospheric circulation which is known to exhibit large variability on approximately a 2-yearly time-scale.

Comparison between observed (vertical bars are estimated measurement errors) and modelled chlorine monoxide mixing ratios as a function of latitude at 70°W at approximately 18 km on 4 September 1987. Errors in the simple cloud formation scheme in the model are thought to be responsible for the discrepancy at 64°S. (Observations by courtesy of Dr J. Anderson, Harvard University)





Percentage of time air mass trajectories are computed to spend in polar stratospheric clouds (a) and modelled daily percentage of ozone destruction (b) as functions of latitude

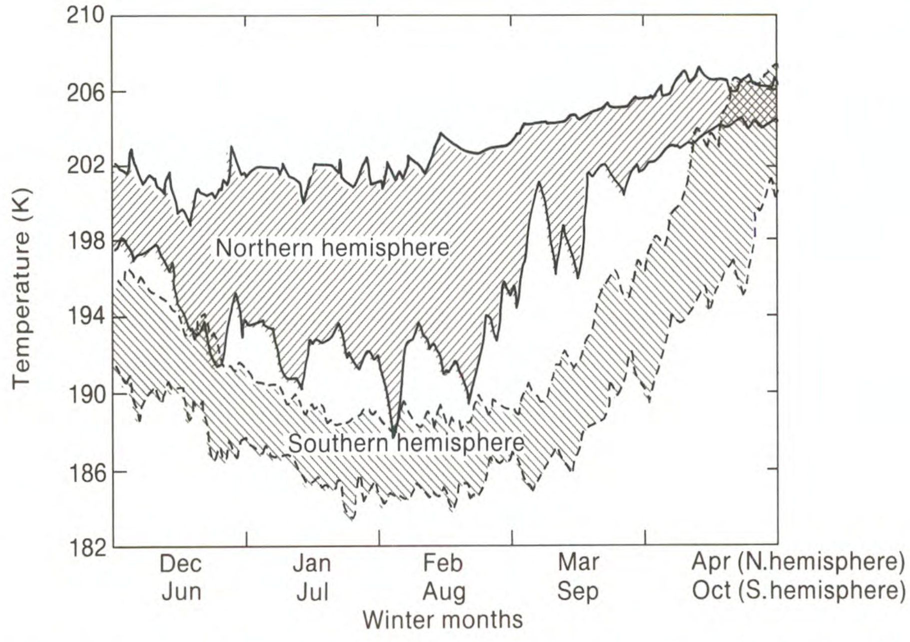
The Office collaborated with scientists from the US National Aeronautics and Space Administration (NASA) and the National Oceanographic and Atmospheric Administration (NOAA) in the Airborne Antarctic Ozone Experiment to study the photochemistry of Antarctica in August and September 1987. A computer model of atmospheric photochemistry developed at the Office was used to analyse chemical measurements made within the Antarctic vortex. Wind and temperature fields from the Office's coarse-mesh forecast model were used to determine details of the atmospheric flow in the low stratosphere around Antarctica.

Stratospheric clouds are frequently observed in the Antarctic low stratosphere during winter. The photochemical model used for the analysis was extended during the year to include a simple cloud formation scheme together with parametrization of chemical reactions on the surfaces of the cloud particles. The model reproduces the observed latitude gradients of a number of photochemically active species. A comparison between the observed and the modelled gradient in chlorine monoxide is shown on page 39. The sharp latitudinal gradients in chemical composition in the model are produced by a sharp increase with latitude in the frequency with which air in the low stratosphere encounters cloud particles; ozone is chemically destroyed by several chains of chemical reactions involving chlorine monoxide, bromine monoxide and the hydroxyl radical. The dominant photochemical destruction mechanism is a reaction chain involving only chlorine compounds, mostly of anthropogenic origin. The modelled rate of ozone destruction increases sharply with latitude approaching 2.5% per day at 72°S. The abrupt onset of ozone destruction implies a well defined region within which ozone can be virtually removed from certain levels of the atmosphere during a 40-day period from late August to early October. This is consistent with observations made in 1987.

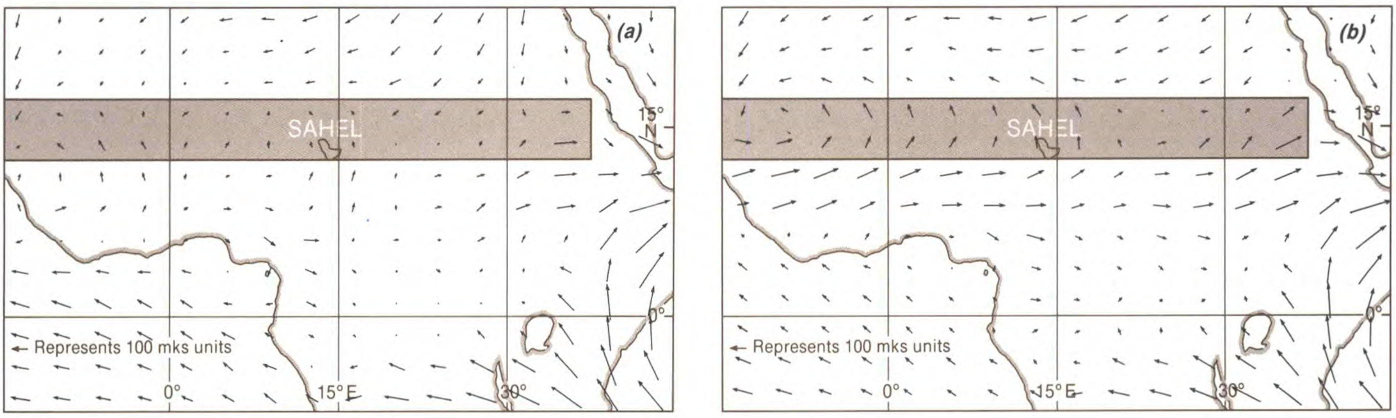
Two key questions remain from the 1987 studies. First, what factors influence the frequency of occurrence of the polar stratospheric clouds essential for the anomalous chemistry to develop? Second, to what extent can air photochemically depleted of ozone in the vortex irreversibly move to low latitudes, possibly even before the vortex breaks down? The first question is relevant to possible explanation of the observed interannual variability in the depth of the ozone 'hole'. The second determines in part the hemispheric and possible global implications of the polar ozone depletions. Both problems have been studied using regional analyses of motion and temperature fields from the coarse-mesh model in conjunction with observations from the 1987 experiment.

From this study, it became clear that, at least in 1987, many areas of polar stratospheric cloud formation occurred on the synoptic scale, forced by tropospheric weather patterns. Low-stratospheric air within the vortex ascends and cools adiabatically above tropospheric anticyclones which extend polewards over Antarctica distorting the upper-level flow. Several such events were diagnosed from coarse-mesh model fields during August and September 1987.

Current understanding of the Antarctic ozone depletions suggests that in the warmer, more disturbed northern hemisphere winter vortex the stratospheric cloud will be less evident and thus the anomalous ozone-destroying chemistry will be less effective than over Antarctica. However,



Year-to-year range of minimum temperature recorded for the lower stratosphere poleward of latitude 20° during the period 1980–88



Modelled low-level moisture flux for a year of light rainfall over the Sahel (1984 (a)) and a year of heavy rainfall over the Sahel (1950 (b))

in a recent NASA/WMO report, wintertime depletions in column ozone of up to 8% were noted over the past two decades at latitudes that include the United Kingdom. These changes are two to three times greater than model-predicted ozone changes over the same period. There are also indications of enhanced concentrations of chlorine species similar to, though less marked than, those over Antarctica.

In January and February 1989, the Office will collaborate with NASA and NOAA scientists in a detailed investigation of the northern hemisphere winter vortex, along the lines of the 1987 Antarctic experiment; two scientists and two forecasters will be detached from the Office to the mission base in Stavanger, Norway during the project. The data gathered will be analysed with the help of analyses and forecasts from the coarse-mesh NWP model and with the use of a coupled microphysical–photochemical model, recently developed in conjunction with US scientists, that includes a detailed treatment of cloud formation and chemical reactions on the surfaces of cloud particles.

Middle atmosphere dynamics

Satellite-borne stratospheric sounding units developed at the Meteorological Office are providing invaluable information on the complex flows to be found in the region of the atmosphere above the tropopause. The data are being used for both operational and research work in the Office, and have been supplied to scientists elsewhere to foster co-operative research. The data record is now long enough (10 years) for studies to be made of the interannual variability in the stratosphere, and of how this variability is connected to year-to-year changes in the circulation of the underlying troposphere. The variability is typically much less in the stratosphere of the southern hemisphere than it is in the northern hemisphere, where the influence of the troposphere appears to be stronger (see figure below left). Such differences between the hemispheres give vital clues about the dynamical and physical processes that govern the circulation. In particular, the figure shows lower temperatures in the southern hemisphere stratosphere; these are likely to favour development of polar stratospheric clouds.

Tests of our understanding of these processes can be made by using numerical models; a model of the stratosphere and mesosphere is being used for investigating the interaction between dynamics and radiation in the middle atmosphere. In preparation for the Office's participation in the international Upper Atmosphere Research Satellite project (the satellite is scheduled for launch in 1991), the model is being extended to represent the effects of transport and photochemistry on the concentrations of trace chemicals and on the ozone distribution. This work involves close collaboration with the University of Oxford and with the Universities' Global Atmospheric Modelling Project.

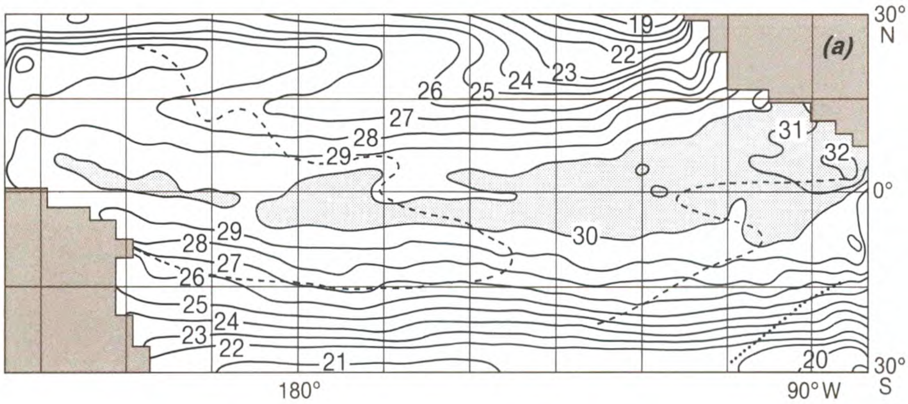
Experiments have been run to model the effects of stratospheric ozone depletions on the temperatures and circulation. Detailed ozone data obtained from sondes from Halley Bay and the South Pole for 1987 were used to define the intensity and variation with time of the decreases, while the spatial structure was based on satellite data collected over the last few years. The results showed a rapid cooling in the depleted region; this is to be expected since ozone is the major absorber of solar radiation at these levels. Comparisons with the long record of lower stratosphere data for Halley Bay obtained by the British Antarctic Survey revealed a close agreement which suggests that the observed cooling which has accompanied the decline in ozone can be explained wholly by the radiative effects of the ozone; this contrasts with earlier published suggestions that the cooling and the ozone depletion were separate manifestations of a change in circulation. Changes in circulation are obtained in the model but they tend to warm not cool the depleted region, so partly compensating for the reduced radiative warming.

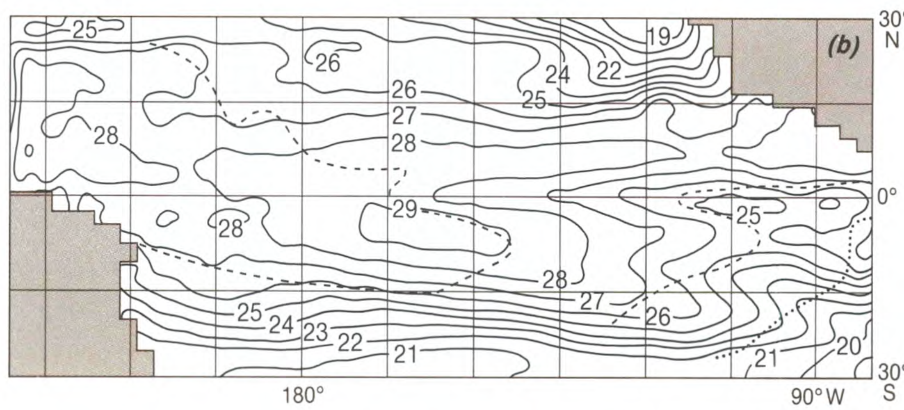
Short-term climate variability

Over the last few years it has been demonstrated that world-wide sea surface temperature anomaly (SSTA) patterns exercise considerable control over seasonal rainfall in various tropical regions, in particular the Sahel region of Africa and the Nordeste region of Brazil. SSTAs usually change only slowly so that anomaly patterns ahead of the rainfall season can be used to predict rainfall. Forecasts using this technique were remarkably succesful in 1986 and 1987. However, the forecast for the Sahel rainfall in 1988 was not successful because large changes in the global pattern of SSTA took place between the spring (when the forecast was made) and the summer rainfall season. Instead of the forecast dry conditions, the Sahel saw a return to average rainfall after a dry period of about 18 years. The 1988 rainfall season provides a rare opportunity to study more closely the large-scale atmospheric circulation patterns which accompany a year with average rainfall in the Sahel, and to compare those patterns with results from experiments using the general circulation model.

The model, forced by observed SSTAs, has successfully simulated both very wet years and very dry years in the Sahel. It demonstrates clearly how the low-level moisture flux into and across the Sahel changes drastically between simulated wet and dry years (see figure above). In 1988 when the model was used with summer SSTAs it did simulate wet conditions in the Sahel, though rather wetter than observed.

Coupling between the ocean and atmosphere can occur on a variety of





Monthly mean SSTs for June obtained from a coupled tropical ocean–global atmosphere model integration started the previous June (a) and results from the integration with the revised physics (b). Temperatures greater than 30 °C are shaded. The climatological 28 °C contour is shown dashed with the 25 °C contour dotted.

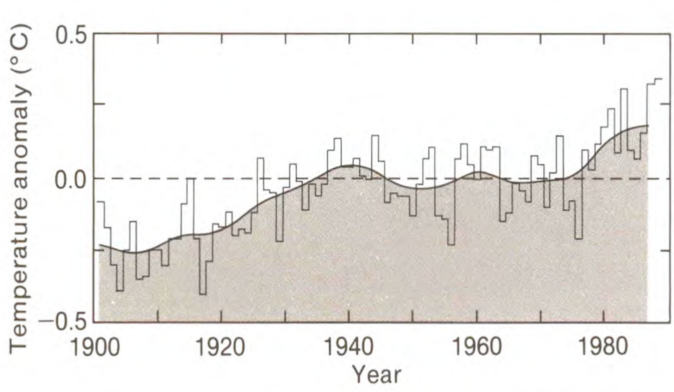
time-scales. It is particularly strong and fast in the tropical regions, where it manifests itself, in particular, as El Niño events. This year has seen the opposite phase of the cycle, with temperatures in the eastern Pacific up to 2 °C lower than normal. There is increasing interest in such cold (La Niña) events; these result in stronger trade winds, distinct atmospheric convergence zones and associated deep convective bands.

Studies of the interactions between the tropical oceans and global atmosphere are being carried out with a tropical Pacific ocean model coupled to the atmospheric general circulation model. A topic of particular concern has been the model's tendency to produce persistent and high SSTAs in regions of light winds. In such regions, the evaporative heat loss from the surface in the model is felt to have been underestimated, because of neglect of the effects of wind gustiness not resolved by the atmosphere model's 300 km scale grid. In the tropics, light wind conditions tend to be associated with areas of active convection and precipitation and so with mesoscale gustiness. An analysis of data from the tropical Atlantic has shown a close correlation between sub-grid-scale wind variability and precipitation. To quantify the impact on the model of including the effect of gustiness on surface evaporation, the wind variability was specified as a function of the model's convective precipitation rate and used in the calculation of the evaporation. This modification, and other improvements to the atmospheric model physics, particularly with regard to radiation and cloud (see above), has much improved the simulation of Pacific sea surface temperature (SST) (see figure above).

Simplified, but still physically realistic, models allow for a wide range of experiments to be carried out at much lower computational cost than is possible with full general circulation models, on both the coupled system and the individual components. Such a coupled model of the tropical regions has been used to investigate the growth of small perturbations that amplify in the model and propagate eastward with, in some cases, lifetimes of several years. Such instabilities appear to be an intrinsic part of the ocean–atmosphere coupling and an understanding of them in such models can be expected to aid interpretation of the more complex general circulation model results. Work with the atmospheric component of this model has concentrated on gaining further understanding of the physics and dynamics of the intra-seasonal variations of the atmosphere, in particular the 30–50 day planetary-scale waves. Experiments run with a wide spectrum of thermal forcing showed sensitivity to the presence of the warm pool of water in the west Pacific, representation of which in the model increases the periods of the modelled waves from 20–30 days to their observed range.

Climate change

Careful analysis of observations is essential for assessments of past climate change. Global sea surface temperature data, analysed at the Meteorological Office, have been combined with land surface air temperature data, compiled at the University of East Anglia Climate Research Unit, to give optimal global coverage since the start of the century; both data sets have been subjected to careful quality-control procedures. Comparisons between sea surface and near-surface air temperatures observed from ships show that, for climate monitoring, the more numerous and more reliable sea surface temperatures may be used as proxy for air temperatures over the ocean. The record shows an overall warming by about 0.5 °C in the last 80 years, the six warmest years being in the 1980s (1988 being the warmest). Whilst it may be premature to link this warming with the increased abundance of greenhouse gases, the recent warming has given added urgency to the question 'Has man already begun to alter the earth's climate?'. Identification of a 'fingerprint' of man-made climate change, based on the modelled seasonal and spatial



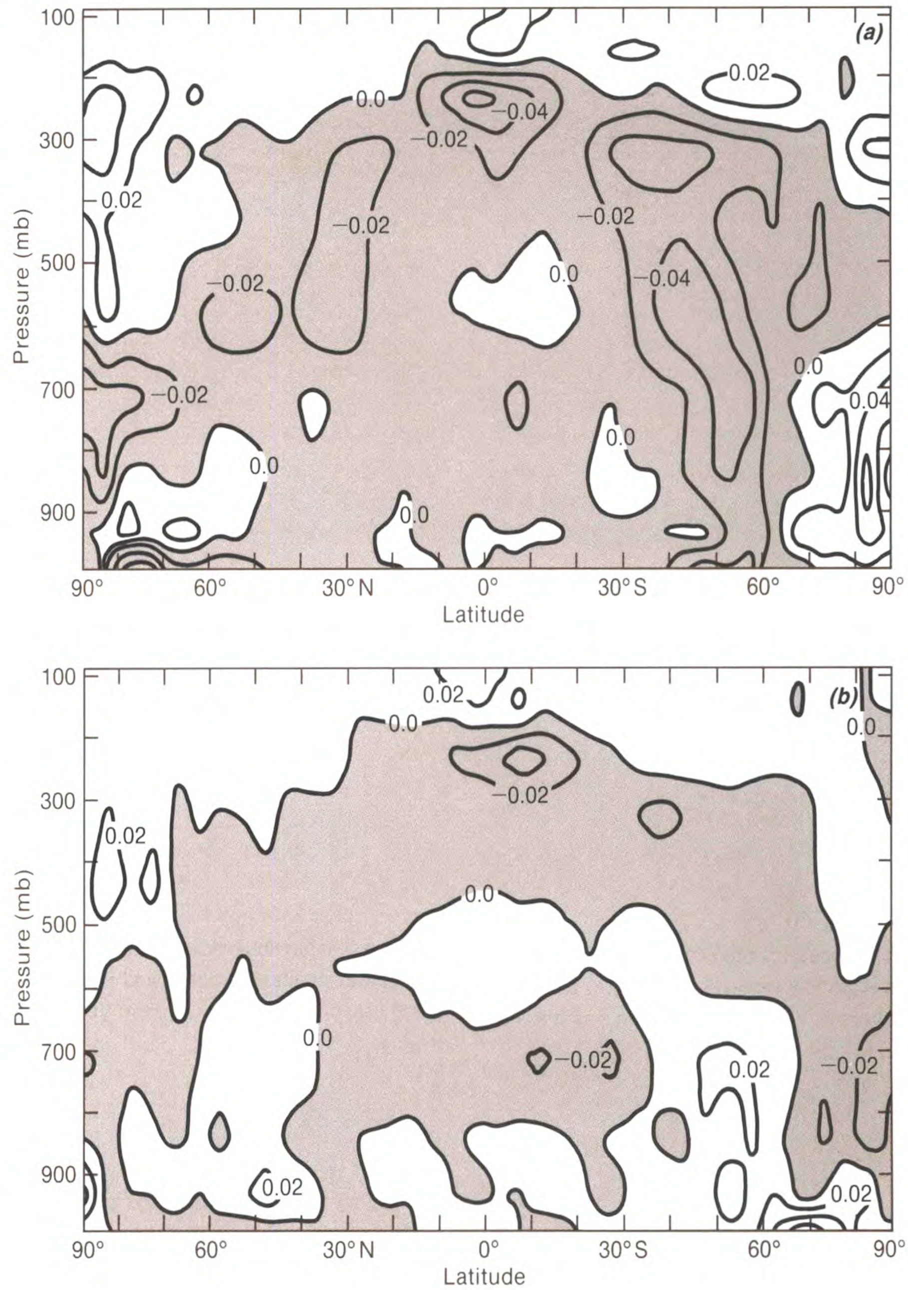
Global near-surface temperature anomalies for 1900–88 compared with the 1950–79 mean. Solid line is the result of applying a 20-year filter.

changes in several variables, may allow the question to be answered more quickly than would be possible from global average temperature data alone.

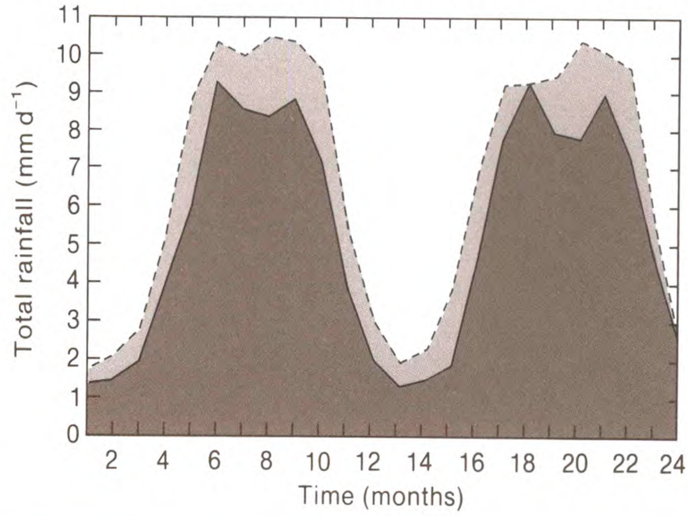
One of the main difficulties in predicting the potential climatic effects of greenhouse gases is to estimate the magnitude of the feedbacks, i.e. the extent to which the climate system may damp or amplify the warming caused directly by the increased trace gas concentrations. For example, a doubling of CO_2 would produce a direct warming of 1.1 °C, which is amplified to 1.7 °C because of the increase in water vapour accompanying the warming. The largest uncertainty concerns the effects of possible changes in the nature and distribution of cloud. Clouds have a profound climatic effect: they both cool the earth–atmosphere system by reflecting solar radiation back to space, and warm the system by reducing the effective radiating temperature of the planet. The latter effect is most pronounced for high cloud. Numerical studies in which cloud cover is dependent on relative humidity (the degree to which the atmosphere is saturated with water vapour) suggest that doubling CO_2 concentrations would reduce the amount of low- and medium-level cloud, particularly in middle latitudes, leading to enhanced absorption of solar radiation and almost doubling the predicted warming.

These experiments have been repeated using a cloud scheme that explicitly represents cloud water, both liquid and frozen. Preliminary results from an experiment in which the cloud radiative properties (for example, reflectivity) depend on cloud water and ice content indicate that this change reduces the sensitivity to doubling CO_2. These results have important consequences for both the distribution of climate change following increases in trace gases, and the rate at which the climate system responds. Current research is therefore aimed at reducing the uncertainties in estimates of cloud– climate feedbacks due to these and other processes.

Climate has previously been shown to be sensitive to modifications of the land surface. Probably the largest such modification currently in progress is deforestation in the Amazon basin. The climate model can now represent several aspects of the land surface changes associated with deforestation including the reduced roughness of the surface, increased reflectivity for solar radiation and changes in the hydrological characteristics. An experiment with this version of the model indicates that significant changes result in the local climate as a consequence of deforestation. Evaporation is decreased and there is a warming of about 2 °C in surface temperatures. Most importantly, rainfall is reduced over a deforested Amazon basin throughout the year with annual reductions of over 15% in the area mean.



Modelled zonally averaged changes in low-and medium-level cloud amount (percentage) due to doubling CO_2 for December, January, February using a relative humidity based cloud scheme (a) and results obtained using a cloud scheme that explicitly represents cloud water, both liquid and frozen (b)



Monthly rainfall over the Amazon basin for the first two years of control (dashed line) and deforestation (solid line) experiments

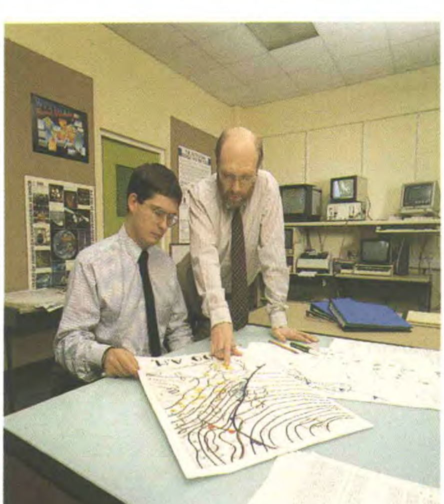
Training and careers

As a scientific discipline meteorology is a specialism, though it is rooted firmly in mathematics and classical physics. It is also a subject undergoing rapid development. This gives rise to the need both for teaching the elements of meteorology to new recruits and for updating the knowledge and practical skills of staff at regular intervals. Training is therefore a major consideration in the Office's career management strategy.

With staff working in a diversity of roles — forecasting, research, computing, marketing, administration, etc. — the Office's training is equally diverse and is carried out in a wide variety of ways, including in-house courses, on-the-job training, local technical colleges, specialist colleges and universities.

The major part of formal training is conducted at the Meteorological Office College at Shinfield Park, Reading (it is here that most staff undergo their initial training). Set in 50 acres of parkland, the College has teaching and residential facilities for approximately 110 students. Some training is also provided for members of other organizations, such as air traffic control observers and, when space on courses is available, the staff of other National Meteorological Services. Students from 77 different countries have received training at the College during the last 10 years.

The Office's School of Technical Training has facilities at both Shinfield Park and Beaufort Park, the latter being the site for operational instrumentation development located on the outskirts of Bracknell; technical instruction is given to Office and to overseas students. A new 8-month technical training course for meteorological engineers, designed for overseas students, was introduced during the year. The take-up of places on the first course was very encouraging; the syllabus of the course has been constructed to allow the relevant material to be covered in a shorter time than courses previously available in the subject.



All courses* have a strong emphasis on student participation — in a typical day approximately half a student's time is spent on practical consolidation of lecture material. Courses vary in length from a few days for specialist seminars to several months for other courses. There is a well structured continuation training programme. The aim is to provide courses, usually of a few weeks' duration, every 5 years or so for the majority of staff.

The training programme is subject to frequent monitoring, review and updating. Most courses at the College have undergone changes in recent years in response to the introduction of new equipment within the Office and new teaching facilities at the College. The College has acquired several new items during the past year, including an Outstation Display System work station, a microcomputer system that provides rapid animation of radar and satellite imagery, and a video editor. Installation of new technology, particularly microcomputers and word-processors, in the outfield has created the need for new and well targeted instruction programmes. This is being met by a combination of courses and workshops, some College based and others at local sites.

One of the most ambitious new ventures undertaken in recent years was the organization of commercial training for several hundred staff. A 2-year programme of training, launched in 1987 in conjunction with John Wilmshurst Marketing Consultants Ltd, has been in full swing throughout the year.

In response to recommendations in the offical report *The storm of 15/16 October 1987*, produced in January for the Secretary of State for Defence by Sir Peter Swinnerton-Dyer and Professor Robert P. Pearce, a thorough review of the training, career management and status of senior forecasters has been undertaken under the chairmanship of the Director-General. The training programme for forecasters in the Meteorological Office was found to be as good as, or better than, those of National Meteorological Services in other countries, but there was a need for an extension of the initial training of graduate recruits to provide instruction on recent theoretical developments and for improved continuation training for forecasters.

College courses represent only one facet of the Office's training policy. Learning on the job is also very important; forecasters spend as much time on supervised on-the-job training as on College-based courses. A strong tradition of further education also exists and staff are encouraged to advance themselves through acquiring additional academic qualifications. Funding is provided for courses covering a wide variety of subjects, from mathematics to graphic design, and academic qualifications, from GCSE to PhD. Many staff also follow Open University courses.

In addition to in-house courses and external training, a comprehensive programme of scientific meetings and seminars allows staff to keep abreast of new developments and ideas.

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

Careers

The majority of staff are recruited into the Meteorological Office with scientific qualifications, usually in mathematics or physics, but positions also exist for people with other specialist skills such as technical staff, administrators, graphics officers, typists, secretaries, stores personnel, etc. Opportunities exist for staff to expand their expertise by working in different areas of the Office or for specializing in one particular aspect of the work. One of the most important management tasks is to bring together people with appropriate skills and experience into teams capable of tackling, in the most effective way, the various projects in the Office's programme. The following examples serve as an illustration of this.

Some of the staff at Aberdeen Weather Centre. Left to right: Hugh Cumming, Jim Sharp, Alistair Thomson, Iain MacDonald, Gordon McKinstry and Kath Duncalf.

Aberdeen Weather Centre

The Weather Centre at Aberdeen, one of 14 distributed throughout the United Kingdom, provides local weather information to a variety of customers. Most of the staff work shifts to meet the demands of round-the-clock operations. The Centre became operational in September 1988 and took over the forecasting duties which from 1941 had been carried out at Aberdeen's Dyce Airport. The group shown in the photograph are members of the Weather Centre's staff and their skills illustrate the range of experience and expertise that the work demands.

Hugh Cumming is the Senior Meteorological Officer. Hugh returned to the Meteorological Office after spending 4 years with the RAF Meteorological Recce Flight. His career has been typical of many forecasters, with postings to a number of stations in the United Kingdom and overseas. He was one of the first forecasters to work offshore giving meteorological advice to the oil industry in the mid-1970s. Later he spent 3 years at Headquarters at Bracknell before taking charge at Aberdeen in 1985. Jim Sharp's Office career began in 1973 and has been a mixture of time spent at outstations, as both assistant and forecaster, and at Headquarters. Skills in computing, gained at Headquarters, have proved very useful in a modern automated forecasting office. Like Hugh, he has also done offshore work. Alistair Thomson joined the Office in 1978 and until 1985 worked predominantly at Prestwick Airport. He moved to Aberdeen Airport after the reorganization of meteorological services in south-west Scotland, subsequently becoming one of the staff to move to the new Weather Centre. Iain MacDonald is another whose career has taken him to many UK stations, and also to Bahrain. His career took a new turn this year, with his appointment as Commercial Manager at Aberdeen; previously he had done a variety of jobs, including observing, administration and computing. Gordon McKinstry is a newcomer to forecasting. While an assistant, he studied for an HNC under the Office's external training programme. He completed the Initial Forecasting Course in 1987 and is now undergoing a period of on-the-job training. Kath Duncalf is a typist. She has been in the Office for 3 years and works part-time.

The climate change group. Left to right: Joe Lavery, Paul Whitfield, John Mitchell, James Murphy, Cath Senior, David Roberts and Dave Jerrett.

Climate change

The development of numerical models of the earth's climate system began in the Office some 25 years ago and the group is now recognized internationally as being among the leaders in the field. The topic receiving special attention at the present time is the effect on the global climate of increased concentrations of carbon dioxide (see section on world climate); other recent investigations have included simulations (and comparison with the present) of the climate 9000 years ago when the earth's orbit was rather different from now, and the likely climatic effects of nuclear war. The work demands a thorough understanding of physics, a good appreciation of meteorology, insight into allied interdisciplinary factors (climatology, oceanography, hydrology, glaciology, etc.), mathematical skills and specialist computer programming ability. The group is a major user of the Office's supercomputer.

The leader of the group, John Mitchell, joined the Office in 1973. Rather surprisingly perhaps, his PhD degree was in atomic physics. He has spent his entire career working in climate modelling, apart from a 15-month spell doing practical forecasting in the Central Forecasting Office in 1977, and again for 4 months during the Falklands War. His expertise in climate modelling was recognized by his Individual Merit promotion to Grade 6 this year. David Roberts is the group's expert on numerical modelling of the oceans and of sea ice. He joined the Office in 1984 (completing a PhD in applied mathematics about a year later) because he particularly wanted to do research on climate. Cath Senior, a mathematics graduate who came into the Office in 1986, is rapidly becoming an authority on the role of clouds in climate change. Paul Whitfield is a programming expert whose past career includes 6 years in the Merchant Navy, liaison with the Voluntary Observing Fleet in the Port Meteorological Offices in Cardiff, Hull and Newcastle and computer programming in cloud physics. Dave Jerrett, James Murphy and Joe Lavery have all joined the group relatively recently after several years' experience in other parts of the Office. Dave spent 6 years at outstations in Scotland before taking 4 years off to read for a degree in applied mathematics; he has subsequently worked at Headquarters. James, a physics graduate, has spent 7 years doing research into the use of dynamical models for long-range forecasting. Joe was an assistant at outstations in Aldergrove and Belfast from 1974 before moving to Bracknell to take up computer programming.

Weather in Vision

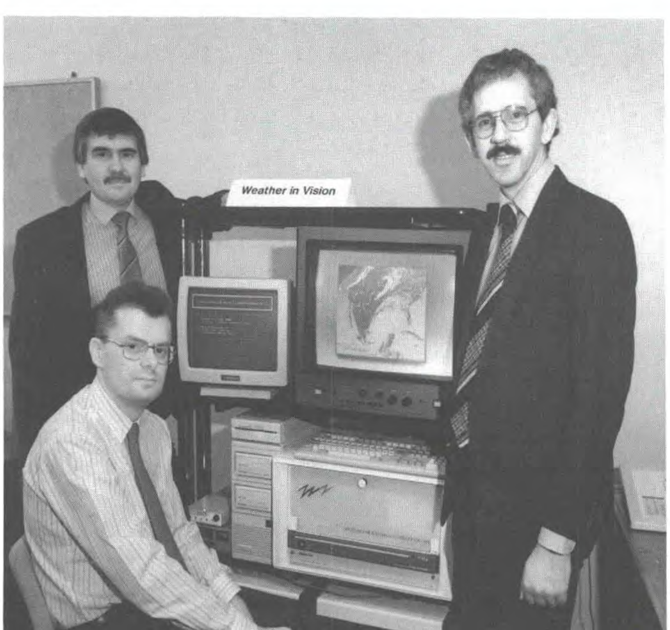
The Weather in Vision technical development team has come together one by one over the last 2 years as the project has evolved from its inception to the launch of services to television companies. The object of the project is to sell weather forecasting services, together with specially developed modern computer graphics facilities, to television companies (see section on services). A variety of expertise is required from program development through to the design of sophisticated television productions, as well as project management and product marketing. None of the team claims to excel in all these fields, but the work calls for at least an appreciation of them all. When necessary the team brings in experts from outside and close co-operation is enjoyed with Spaceward Microsystems Ltd, who provide hardware and software for the high-quality television graphics.

The technical project manager is Martin Jones. Martin joined the Office in 1967 with a degree in mathematics. He developed his computing skills when working with the operational numerical weather prediction system. Computing projects he has led include OASYS (a minicomputer system for outstations) and the development of television weather graphics in conjunction with the BBC. After a period in meteorological telecommunications he returned to the television scene to take up his present job. Rex Roskilly is the team's communications expert and systems analyst. Since his recruitment in 1962 he has had a varied career, observing, developing instruments, forecasting, computing and as a consultant in systems analysis at the European Centre for Medium-range Weather Forecasts. Martin Gange also has a degree in mathematics and is responsible for automating the daily generation of material for particular television productions. His first job, in 1981, was in the field of numerical weather prediction model development when he learnt to program the Cyber 205 supercomputer. He now makes extensive use of the IBM mainframe computer system.

Satellite instrumentation

The quartet are part of the Office's satellite group and are pictured with the latest item of space hardware — the focal plane assembly (FPA) of an instrument called the ATSR (Along Track Scanning Radiometer). The ATSR is designed to make very precise measurements of sea surface temperature and it forms part of a package of instruments that will fly on a European satellite (ERS-1) due for launch in September 1990. The FPA has been designed, built and tested within the Office and it is currently being integrated with the rest of the ATSR at the Rutherford Appleton Laboratory before delivery to the European Space Agency.

David Tinkler is the manager of the ATSR project. His qualifications, a BSc in physics and an MSc in atmospheric physics and dynamics, proved useful in



The Weather in Vision team (above). Left to right: Rex Roskilly, Martin Gange (seated) and Martin Jones. The satellite instrumentation group (right). Left to right: Tony Jukes, David Tinkler, Steve Stringer and Alison Smith.

the task of designing, building and testing both the FPA and the black-body targets for the ATSR. However, he had to acquire the additional specialized engineering knowledge required for satellite instrument design on the job as the ATSR project developed. Steve Stringer joined the Office in 1978. After 2 years in boundary-layer research, the Office sponsored him for a physics degree course. He has since worked on a number of satellite projects, including the Stratospheric Sounding Unit and a new humidity sounder, as well as the ATSR. Alison Smith is a physics graduate. After joining the Office in 1986 she worked briefly on the integration of rainfall data from radars with data from more conventional gauge instruments before moving to the ATSR team. Tony Jukes provides the necessary technical expertise for the group. In his early career he worked as an assistant in the Central Forecasting Office and at Upavon, but having developed an interest in equipment in these jobs he successfully underwent technician training in 1977. Subsequently he has worked alongside research scientists and has been involved in major international experiments in the Federal Republic of Germany and in the USA.

Lectures and colloquia

Many staff are at outstations around the country and overseas. Arrangements are needed to ensure that they are kept in touch with what is going on in the Office as a whole, including both scientific and organizational matters. Heads of the major outstations attend the 2-day Conference of Chief and Principal Meteorological Officers held each year to discuss the Office's current policy and its plans for the future. A series of Outstations Colloquia is also run each year at the College to provide up-to-date information on new developments that have special relevance to forecasters. Each colloquium contains a mix of lectures and discussions which extend over a period of 1½ days. About 160 forecasters participated in the 1988 colloquia series.

Nearly half the Office's staff are based at Bracknell where various lecture series are convened throughout the autumn, winter and spring. One series, the Advanced Lectures, forms part of the initial training for recently recruited graduates. Other staff who are interested can also attend. Each year approximately 40 lectures are presented on four areas of active research. A rolling 3-year programme ensures that a comprehensive range of material is covered. In 1988 the subjects presented were: the physics and dynamics of the climate system, the climate of the world, the atmospheric boundary layer, and a forward look to numerical weather prediction in the 1990s.

Headquarters Colloquia, usually held each week between September and April, cover specific topics of current interest. Examples from the year's series include: the new supercomputer, fluctuations in the earth's rate of rotation due to meteorological and other causes, new methods of treating satellite data in numerical weather prediction models, and public relations and communications in marketing.

The Summer School

Summer Schools, normally biennial events, were inaugurated in 1985. Their purpose is to bring together forecasters and research workers from within and outside the Meteorological Office to learn of current research and to consolidate that learning through practical case-study investigations. The storm of 16 October 1987 was such an exceptional event that it merited a special additional Summer School in 1988. Like its two predecessors, it was run in close collaboration with the Department of Meteorology, University of Reading.

The 1988 Summer School was particularly successful in attracting forecasters and was over-subscribed. Approximately 70 participants spent 3 days exploring the observational data, the analyses and various numerical forecasts, some of which were run as part of the 'post-mortem' investigations and were not available to forecasters at the time of the storm. Attendance by meteorologists from France, the Federal Republic of Germany, the Republic of Ireland, Jersey and The Netherlands was especially welcome, and very helpful in providing different perspectives of the event.

The size of weather systems and the distances they move during their lifetimes are larger than nations so that meteorologists in various countries are necessarily interdependent; meteorology was one of the earliest disciplines to require organized international collaboration on a basis of mutual interest.

Thus support for the World Meteorological Organization (WMO) not only demonstrates the United Kingdom's continuing commitment to the United Nations (UN) through an Agency where the UN system is working well, but it is also necessary if meteorology is to work from day to day. For example, global centres such as Bracknell depend on observations from all countries, while many of the less developed countries depend on the products from gobal centres' supercomputers. WMO provides the forum in which this constructive living-together can be planned. Thirty-nine members of the Office serve on various bodies of the Organization; in particular, Dr J.T. Houghton is Third Vice-President of WMO and Mr R.J. Shearman is Vice-President of its Commission for Marine Meteorology.

In common with all other UN bodies, the Secretariat of WMO was short of funds in 1988 because some Members were unable to pay some or all of their contributions. Nevertheless, WMO's many essential basic functions continue. Recently they have included the provision of:

- the philosophy and technological framework needed to meet changing needs for regular and timely exchange of observational data;
- explicit recognition of the need for a two-way flow of information between the more developed and less developed National Meteorological Services; and
- scientific and technical leadership in the World Climate Programme.

As Third Vice-President, Dr J.T. Houghton acted as host to a session of the Organization's Bureau: the President (Mr Zou Jingmeng of China), the First and Second Vice-Presidents (Dr Zillman

Plessey wind-finding radar on the roof of the Meteorological Office, Tamanrasset, Algeria — an important centre in the struggle against the desert locust

of Australia and Comodoro Alaimo of Agentina), himself, and the Secretary-General (Dr Obasi of Nigeria). The Presidents of WMO's Regional Associations for Africa (Mr Degefu of Ethiopia) and for North and Central America (Mr Berridge of the British Caribbean Territories) and representatives of the World Meteorological Centres at Washington and Moscow (Dr Hallgren and Dr Hodkin) also attended.

In June Dr Houghton was accompanied by two members of the Office and by staff from the UK Permanent Mission in Geneva when he attended the annual session of WMO's Executive Council. The Council made recommendations on: fighting the plague of locusts in northern Africa, climate change, airborne transport of hazardous materials, Antarctic meteorology and 'special' (i.e. commercial) meteorological services.

The Council decided that Dr J. Nash of the Office, together with Mr F. Schmidlin of the National Aeronautics and Space Administration, should jointly receive the Professor Dr Vilho Väisälä Award for their paper 'WMO International Radiosonde Comparison'.

The basic functions and international collaboration needed for operational meteorology were reviewed and updated at a session of WMO's Commission for Basic Systems in Geneva; the UK delegation was led by Dr D.N. Axford, who also acted as Chairman at meetings evaluating operational systems for the North Atlantic. Later, at a meeting of the North Atlantic Ocean Stations (NAOS) Board, also in Geneva, the Marine Superintendent reported that after the NAOS Agreement lapses in November 1989 the United Kingdom expected to be able to finance and operate an independent weather ship — probably until at least 1991.

The Marine Superintendent represented WMO at the International Maritime Organization's Committee on the Safety of Navigation and took part in discussions on the introduction of the Global Maritime Distress and Safety System.

As part of WMO's Voluntary Cooperation Programme, the United Kingdom provided Fellowships, equipment and services to the National Meteorological Services (NMSs) of 32 countries and helped in a project to evaluate the use of satellite techniques to improve meteorological telecommunications in and with Africa. 'Services' involved Office experts visiting Korea, Switzerland and several African countries.

The Office worked with WMO and the Overseas Development Administration towards the establishment of an African Centre of Meteorological Applications for Development (ACMAD). At meetings in Niamey, Niger, and in Geneva, the Office made clear its interest in buttressing ACMAD technically. Mustering enough funding from major national donors, however, continues to be a challenge; such support is essential if ACMAD is to be the focus for meteorology's potentially valuable contribution to the social and economic development of Africa. Drought Monitoring Centres in Nairobi and Harare, and the continent's NMSs will work together with ACMAD as complementary parts of a single strategic system; other UN Agencies' interest in support for ACMAD and World Bank interest in meteorology generally in Africa are encouraging. So too is the continuing evaluation of the use of satellites to improve meteorological telecommunications within, to, and from the continent.

In Europe, the Office provided the UK representatives on various bodies that help maintain the required flow of imported data, products and knowledge. For example, the Office is represented on various committees of the European Centre for Medium-range Weather Forecasts which is engaged in research in forecasting for 4 to 10 days ahead to provide the best forecasts possible for that period. In EUMETSAT (the organization set up to run meteorological satellites for Europe), where Dr K.A. Browning represented the United Kingdom on the Council and on its Policy Advisory Committee, there was considerable debate on Europe's contribution to the world system of weather satellites beyond the mid-1990s.

The Office provides active participants in a wide range of other international meetings, including several concerned with climate and climate change, in places as far apart as Moscow and Florida. In Toronto in June, the Director-General, together with the Chief Scientist of the Department of the Environment and representatives of other government departments, attended a conference on '*The changing atmosphere*', which was the first serious international meeting to discuss policy on the greenhouse effect and possible consequential global warming. The Director-General also led the UK delegation to the Intergovernmental Panel on Climate Change in November.

The new Headquarters for the Office Nationale de la Météorologie, Algiers, due to be completed in 1989 and equipped with modern telecommunications and data-processing facilities

As a result of a visit to Saudi Arabia, a package of UK equipment and services is being considered under the government-to-government Al Yamamah 'offset' programme. Visits to China by several Office staff were part of a growing collaboration with the Chinese State Meteorological Administration.

In April Dr S.J. Caughey attended a meeting in Kiev, USSR of the WMO Executive Council's Working Group on the Accidental Release of Hazardous Materials; recommendations from the meeting concerned the development and validation of models for predicting the transport, dispersion and deposition of radioactive material released to the atmosphere and the need to prepare guidance material relating to nuclear accidents and the establishment of international response mechanisms.

Other senior staff serve on a large number of international bodies including Dr P.R. Jonas on the International Commission on Cloud Physics and Dr R. Hide on the Advisory Board on Scientific Policy of the International Union of Geodesy and Geophysics.

Liaison visits to developing countries are an important way of ensuring that money for the Voluntary Cooperation Programme is spent effectively. Shown right is a visit being made to the climatological data-processing section of the Ghana Meteorological Service.

Interaction with the national infrastructure

The Meteorological Office has close relationships with a number of other scientific organizations and government departments in the United Kingdom. It contributes its expertise to the scientific life of the nation through the membership of individual staff members, in either a representational or personal capacity, of a variety of scientific bodies. Contacts also arise through the provision of the Office's professional services and the normal liaison processes that facilitate the work of the Office.

The Office interacts with the wider scientific community 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. Dr Hide was recently elected a member of its Council and several other 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, Aquatic and Atmospheric Physical Sciences Grants Committee, Committee for the Strategy of Remote Sensing and its Steering Committee on the Hydrological Aspects of Weather Radar. The Director of Research is Chairman of the Meteorological Office/Research Councils Committee on Climate and serves on the United Kingdom Coordination Committee for the World Ocean Circulation Experiment. The Deputy Director for Communications and Computing is a member of the National Policy Committee for Advanced Research Computing.

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 Office is closely involved in the promotion of meteorology through the Royal Meteorological Society: the President, one Vice-President, two Secretaries and the Editor of the Quarterly Journal are all Office staff.

A recent example of a collaborative venture between the Meteorological Office and the universities is the establishment of a Joint Centre for Mesoscale Meteorology with the University of Reading. Its objectives are to increase the basic scientific understanding of mesoscale weather systems and to improve the skill in forecasting them. There is a steering group of senior University and Office staff, and contributions from three groups are co-ordinated: a mesoscale dynamics group within the University, a Meteorological Office group dealing with observations and diagnostics, also located at the University, and a Meteorological Office group dealing with forecast models, located at Bracknell. The Chancellor of the University (Lord Sherwell), in the company of the Vice-Chancellor, the Head of the Department of Meteorology, and the Director-General of the Meteorological Office formally opened the Joint Centre on 5 December.

In connection with its forecasting and advisory services the Office 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 and the corresponding departments in the Scottish and Welsh Offices and Northern Ireland Ministries, the Foreign and Commonwealth Office, the Health and Safety Executive, the Central Office of Information, British Nuclear Fuels, the Civil Aviation Authority, the British Standards Institute, the Crown Prosecution Service, the Water Authorities and River Purification and Hydroelectric Boards, and the Exploration and Production Forum of the Offshore Industry.

Staff also serve on government interdepartmental committees and other bodies. These include the Interdepartmental Committee on Post-Chernobyl Activities, which has continued its work of implementing the National Response Plan for European nuclear accidents. The Meteorological Office has a prominent role in this Plan. Phase I, which includes the RIMNET (Radiation Incident Monitoring NETwork) and a Mark 1 version of a numerical prediction model capable of simulating the transport and deposition of radioactive material, was implemented during 1988.

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, the Interdepartmental Committee on the Surface and Ground Water Archive and the interdepartmental 'Whitehall Group', which is concerned with the remuneration of staff in the Co-ordinated Organizations of which the European Centre for Medium-range Weather Forecasts is one.

Personnel

The changes heralded in the 1987 report have, in most cases, had time to take effect, and it is becoming possible to assess their impact. The restructuring and the accompanying (but independent) regrading of a number of posts has resulted in considerable improvements in pay for a number of staff in the Telecommunications Technical Officer grades. This has maintained the number of junior Assistant Scientific Officer staff wishing to train for and transfer to those grades.

The additional financial assistance given to staff transferred to high cost areas of the country has helped to alleviate some of the difficulties associated with such moves. However, the Office still encounters a number of problems in finding staff (and their families) who will happily accept such a move, especially on those occasions when a loss in shift working is involved. Concern over possible financial penalties of this kind remains the main cause of eligible staff declining invitations to Promotion Boards.

Recruitment, especially in the south-east of England, has become increasingly competitive, so the Office continues to make strenuous efforts to attract newcomers of the right calibre. There has always been a core of enthusiasts who apply to join the Meteorological Office because of a deep interest in meteorology, and this continues to apply at all levels from school-leaver to postgraduate. The quality of applicants has continued to be of a very high level. However, there are warning signs that, because of competition from industry, reliance on enthusiasm may no longer be enough and a more active recruitment policy needs to be pursued. Recruitment and retention difficulties are, however, by no means confined to the Meteorological Office, and the approaching 'demographic trough' means that the situation is likely to become even more competitive.

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)	25
Principal Scientific Officer (Grade 7)	119
Senior Scientific Officer	291
Higher Scientific Officer	420
Scientific Officer	415
Assistant Scientific Officer	531.5
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	18
Administrative Officer	56
Administrative Assistant	53.5
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	3
Higher Professional and Technology Officer	20
Professional and Technology Officer	7
Telecommunications staff	
Senior Telecommunications Technical Officer	7
Higher Telecommunications Technical Officer	34
Telecommunications Technical Officer	51
Assistant Telecommunications Technical Officer	35
Signals grades	23
Teleprinter grades	27
Typing and miscellaneous non-industrial grades	78
Security officers	11
Industrial employees	37.5
Locally entered staff overseas	52

Numbers include part-time staff counted as 'half'

Staff honours and awards

The L.G. Groves Memorial Prize for Meteorology was awarded to Dr A.P. Cluley and Mr T.S. Hills.

The Professor Dr Vilho Väisälä Award was awarded to Dr J. Nash.

The Gold Medal of the Royal Astronomical Society was awarded to Dr R. Hide.

The Buchan Prize of the Royal Meteorological Society was awarded to Dr G.J. Shutts.

On a fully cost-accounted basis, the total cost of the Office in 1987/88 was £84.1 million compared with £80.8 million in 1986/87. The net cost after earnings from services was £58.3 million compared with £57.2 million in 1986/87. Charges for repayment services were increased in 1987/88 to cover Meteorological Office pay and price increases.

The Office's voted expenditure is borne on the Defence Budget to which receipts from repayment services are credited. Summary figures are shown in the *Annual Statement on the Defence Estimates.* However, for costing purposes, a fully cost-accounted Memorandum Operating and Trading Account (MTA) is also maintained. The tables show: the allocation of costs to functions derived from the MTA (top), the net cost after deduction of receipts (middle), and a summary of the MTA costs by input resource categories (bottom). 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.

Statement of operating expenses for the Meteorological Office for the year ended 31 March 1988

	1987/88	1986/87
	£000	£000
Customer activity costs	21 746	21 137
General Meteorological Office core activity costs:		
Research	9 298	8 113
Administration and personnel	5 103	4 331
Central Forecasting Office	4 167	3 541
Computing	1 614	1 196
Maintenance	2 503	2 351
Observations	20 864	22 150
Technical support	2 973	2 837
Telecommunications	5 620	5 392
Training	3 197	3 005
Others	3 056	2 818
Total Meteorological Office management costs	80 141	76 871
Share of MOD HQ costs and interest on capital	3 996	3 958
Total Meteorological Office costs	84 137	80 829

Statement of the cost of meteorological services for the year ended 31 March 1988

	1987/88		1986/87	
	£000	£000	£000	£000
Total meteorological services (cost accounted)		84 137		80 829
Receipts		25 802		23 608
Net expenditure:				
Defence and other Exchequer departments	34 012		32 993	
General public services and international	24 323		24 228	
		58 335		57 221

Statement of costs analysed by input resource categories

	1987/88	
	£000	(%)
Staff costs	46 210	(54.9)
Office support, telecommunications and accommodation	8 575	(10.2)
Grants and subscriptions to international bodies	11 953	(14.2)
Materials and miscellaneous	11 633	(13.8)
Depreciation and interest on capital	5 766	(6.9)
Total input costs	84 137	(100.0)

Appendices

APPENDIX I
BOOKS OR PAPERS BY MEMBERS OF THE STAFF

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WOODROFFE, A.; Summary of weather pattern developments of the storm of 15/16 October 1987. *Meteorol Mag*, **117**, 1988, 99–117.

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

ALLAM, R.J.
The analysis of sea fog using Meteosat imagery. *7th Meteosat Users Conference, Madrid*. 30 September.

ANDREWS, D.G.
Lecture course on the dynamics of the middle atmosphere. *Workshop on Large Scale Dynamics of the Atmosphere, Chinese Academy of Sciences, Beijng*. 11–20 August.
Middle atmosphere research. *National Meteorological Centre, Beijing*. 11 August.

BELL, R.S.
Role of satellite data in model initialisation. *Meteorological Office/Remote Sensing Society Meeting, Shinfield Park, Reading*. 5 May.

BENNETTS, D.A.
The use of tactical decision aids in the UK. *Scott Air force Base, USA*. 2 March.
Meteorological support for nuclear and chemical emergencies. *Conference on Disasters and Emergencies, London*. 12 April.

BROWN, P.R.A.
Airborne studies of the ice phase in maritime clouds around the British Isles. *10th International Cloud Physics Conference, Bad Homburg, Federal Republic of Germany*. 15–20 August.

BROWNING, K.A.
The data base and physical basis of mesoscale forecasting. *WMO Executive Council, Geneva*. 14 June.
Organization of clouds and precipitation in extratropical cyclones. *Palmen Memorial Symposium on Extratropical Cyclones and Frontal Zones, Helsinki*. 31 August.
Limitations in the use of imagery. *Royal Meteorological Society Specialist Group on Weather Forecasting, Reading*. 8 November.

BROWNSCOMBE, J.
Uses of rainfall and temperature data in strategic planning of farm activities. *Radio Oxford 'Farming Programme'*. March.

CARTER, M.J.
Lateral boundary conditions for the UK limited-area model. *8th AMS Conference on Numerical Weather Prediction, Baltimore, Maryland*. 24 February.

CATTLE, H.
Ocean modelling and ocean–atmosphere coupling. *Course on Climatic Change and Impacts: A General Introduction, European School of Climatology and Natural Hazards, Florence, Italy*. 12–16 September.
Specification and variability of the surface forcing of the ocean. *NATO Advanced Workshop on Climate–Ocean Interaction, Oxford*. 26–30 September.

CHADWICK, H.M.
Fluxes and transfer coefficients obtained by an instrumental aircraft during HEMAX. *HEMAX Workshop, De Bilt, The Netherlands*. 25–28 April.

CLOUGH, S.A.
Mesoscale structure of fronts as shown by dropsonde and aircraft observations. *Mesoscale Frontal Dynamics Project, Royal Meteorological Society, London*. 20 April.

COCHRANE, J.
Some meteorological aspects of pest control. *Royal Entomological Society, London*. 6 April.

COLLIER, C.G.
Measurement of precipitation using radar data. *School of Geography, University of Oxford*. 25 January.
Use of weather radar and satellite data. *University of Stirling*. 4 February.

CONWAY, B.J.
Combined weather radar and satellite imagery for nowcasting and numerical forecasting. *Royal Meteorological Society, Imperial College, London*. 19 October.

CULLEN, M.J.P.
A Lagrangian model of the structure of cyclones and frontal zones. *Palmen Memorial Symposium on Extratropical Cyclones and Frontal Zones, Helsinki*. 29 August–2 September.
Modelling discontinuous atmospheric flows. *International Conference on Numerical Methods in Fluid Dynamics, Oxford*. 21–24 March.

DICKINSON, A.
The role of the supercomputers in weather forecasting. *BHRA Seminar and Workshop on Powerful Computing Systems for Fluid Flow Applications, London*. 7–8 June.
Systematic errors in 30 day integrations of the UKMO numerical weather prediction and climate models. *CAS/JCS WGNE Workshop on Systematic Errors in Models of the Atmosphere, Toronto*. 19–23 September.

DIXON, J.
Current techniques for assessing (indirectly) the localised incidence of fog on roads. *4th International Conference on Weather and Road Safety, Florence, Italy*. 9 November.

DONOPHY, E.M.C.
Gales on 9 February. *Interview BBC TV*. 9 February.

DUTTON, M.J.O.
Specialized NWP products for aviation. *WMO Technical Conference on Regional Weather Prediction, Reading*. 18–22 April.

ELLIS, R.J.
Visualisation of data from meteorological numerical models. *British Computer Society Displays Group Meeting on Graphics Techniques for Simulation, London*. 18 May.
Superposition of satellite imagery and NWP fields for display to forecasters. *ECMWF Workshop on Graphics in Meteorology, Reading*. 1 December.

EYRE, J.R.
A new inversion method for TOVS data: non-linear optimal estimation applied to cloudy radiances. *4th International TOVS Study Conference, Igls, Austria*. 17 March.
Inversion of cloudy radiances by nonlinear optimal estimation. *Department of Atmospheric, Oceanic and Planetary Physics, Oxford*. 28 April.

FLOOD, C.R.
The Met. Office Open Road Service for Highway Authorities in the UK. *4th International Conference on Weather and Road Safety, Florence, Italy*. 8–10 November.

FOREMAN, S.J.
The ocean as a component of the climate system. *NATO Advanced Research Workshop on Climate–Ocean Interaction, Oxford.* 26–30 September.
Experiences with a coupled global model. *The Dynamics of the Coupled Atmosphere and Ocean, Royal Society, London.* 13–14 December.

FRANCIS, P.E.
Windfield reconstruction. *A Series of Five Lectures in a Course on Ocean Waves and Tides, International Centre for Theoretical Physics, Trieste, Italy.* 26 September–7 October.

GADD, A.J.
Survey of main forecasting techniques for all time scales. *WMO/CBS Technical Conference on Operational Weather Forecasting, Geneva.* 29 January.
A comparison of the Bracknell and ECMWF forecast models. *8th AMS Conference on Numerical Weather Prediction, Baltimore, Maryland.* 24 February.
Regional numerical weather prediction at Bracknell. *WMO Technical Conference on Regional Weather Prediction, Reading.* 20 April.
Operational numerical prediction of rapid cyclogenesis over the North Atlantic. *Palmen Memorial Symposium on Extratropical Cyclones and Frontal Zones, Helsinki.* 1 September.
Limitations of numerical weather prediction. *Royal Meteorological Society Specialist Group on Weather Forecasting, Reading.* 8 November.
Relative accuracy of numerical guidance for forecasting in the northern and southern hemispheres. *Royal Meteorological Society, London.* 16 March.

GOLDING, B.W.
The use of numerical models in weather forecasting — achievements and prospects. *Seminar on Weather Sensitivity and Services in Scotland, University of Stirling.* 4 February.

GORDON, C.
General circulation model simulations of El-Niño. *Jacob Bjerknes Symposium on Air–Sea Interaction, Los Angeles.* 1–5 February.

HALL, C.D.
Systematic errors in short-range forecasts of wind in the tropics. *CAS/JCS WGNE Workshop on Systematic Errors in Models of the Atmosphere, Toronto.* 23 September.
Verification of forecasts from the UK limited-area model. *10th Meeting of European Working Group on Limited-Area Models, Helsinki.* 13 October.
Forecasts of explosive cyclogenesis from the UK fine mesh model. *Royal Meteorological Society, London.* 14 December.

HIDE, R.
Atmospheric excitation of changes in the Earth's rotation. *Imperial College, London.* 5 May.
Rotating fluids in geophysics and planetary physics. *Lindsay Memorial Lecture, Goddard Space Flight Center, Greenbelt, Maryland.* 10 June.
Thermal convection in rotating containers of various topological characteristics. *European Geophysical Society, Bologna, Italy.* 25 March.

HOLT, M.W.
Moist frontogenesis in the geometric model. *Conference on Mesoscale and Subsynoptic Weather Disturbances Affecting Europe, Paris.* 4–6 May.

HOUGHTON, J.T.
The global commons — space. *Royal Society for Arts, London.* 27 April.
Satellite radiance observations. *International Radiation Symposium IRS 88, Lille, France.* 18–24 August.
Infra-red atmospheric physics. *CIRP 4 Symposium, Zurich.* 22–26 August.
Contribution of satellites to meteorology. *Quo Vadimus, Royal Society, London.* 3 October.

HUME, C.J.
Weather and crop diseases. *Agricultural Training Board, Bristol.* 8 February.

HUNT, R.D.
Weather for tourism. *Interview Radio 4 'PM'.* 22 June.

JAMES, P.K.
Surface based atmospheric profiling. *New Observing Systems and Networks for Short Period Forecasting, Royal Meteorological Society, Imperial College, London.* 19 October.

JOHNSON, D.W.
Thermal convection in rotating containers of various topological characterisitcs. *European Geophysical Society, Bologna, Italy.* 25 March.

JONAS, P.R.
Effects of large drops on warm rain formation. *2nd International Workshop on Cloud Modelling, Toulouse, France.* 8–12 August.
Effects of radiation on clouds. *International Radiation Symposium IRS 88, Lille, France.* 18–24 August.

JONES, R.L.
Photochemical trajectory studies of the 1987 Antarctic Spring Vortex. *Polar Ozone Workshop, Snowmass, Colorado.* 9–13 May.
The Antarctic ozone hole — natural or man-made? *Meteorological Office Scottish Lecture, Edinburgh.* 26 May.
The spring 1987 ozone decrease in Antarctica: results from photochemical modelling along trajectories. *Quadrennial Ozone Symposium, Göttingen, Federal Republic of Germany.* 8–13 August.

KAMINSKI, P.J.
How to write a JES3 Dynamic Support Program. *SEAS Spring Meeting, Davos, Switzerland.* 16 April.

LEE, A.C.L.
Precise long-range lightning mapping, with the UK arrival time difference VLF technique. *1988 International Aerospace and Ground Conference on Lightning and Static Electricity, Oklahoma City.* 19–22 April.

LITTLE, C.T.
Why the Meteorological Office use GKS. *SERC/CFTAG Workshop on Graphics Standards, Manchester.* 18–19 October.

LORENC, A.C.
Analysis for an NWP model: representativeness of observational and forecast errors. *WMO Technical Conference on Regional Weather Prediction, Reading.* 18–22 April.
Two lectures: (1) Forecasts on the storm force winds over southern England, 15–16 October 1987, (2) A practical approximation to optimal 4-dimensional objective analysis. *8th AMS Conference on Numerical Weather Prediction, Baltimore, Maryland.* 22–26 February.

McKENNA, D.S.
Diagnostic studies of the 1987 Antarctic spring vortex. *Polar Ozone Workshop, Snowmass, Colorado.* 9–13 May.

MACPHERSON, B.
Developments in data assimilation at the UK Meteorological Office. *8th AMS Conference on Numerical Weather Prediction, Baltimore, Maryland.* 22–26 February.

MASON, P.J.
Diurnal variations in flow and turbulence over hills and valleys. *International Conference on Tropical Micro-Meteorology and Air Pollution, Indian Institute of Technology, New Delhi, India.* 17 February.
Observations and models of flow over complex terrain. *Workshop on Modelling of the Atmospheric Flow Field, ICTP, Trieste, Italy.* 16 May.
The parametrization of orographic drag in numerical weather prediction models. *NCAR Boulder, Colorado.* 31 October.
Large-eddy simulation of the convective atmospheric boundary layer. *Workshop on Large Eddy Models, Breckenridge, Colorado.* 3 November.

MINHINICK, J.H.
Climatological aspects of the new Agricultural Land Classification Scheme. *ADAS Soils Course, Harper Adams Agricultural College.* 14 April.

MITCHELL, J.F.B.
The use of general circulation models as a source of data for impact studies. *SCOPE-ENUWAR, Moscow.* 21–25 March.
Climate sensitivity: model dependence of results. *NATO Symposium on Climate and the Geosciences, Louvain la Neuve, Belgium.* 22–27 May.
The UK low resolution climate model. *US Department of Energy Model Intercomparison Workshop, AER Inc, Cambridge, Massachusetts.* 7–8 July.
Modelling climate; past present and future. *Center for Climatic Research, University of Wisconsin, Madison, Wisconsin.* 11 July.
Two lectures: (1) Simulating climate, (2) Simulating climate change. *Course on Climatic Change and Impacts: A General Introduction, European School of Climatology and Natural Hazards, Florence, Italy.* 12–16 September.
Atmospheric modelling. *NATO Advanced Research Workshop on Climate–Ocean Interaction, Oxford.* 26–30 September.
Climate modelling. *Dansk Ingeniorforenig (Danish Association of Engineers), Copenhagen.* 28 October.

MONK, G.A.
Satellite imagery preceding intense cyclogenesis. *7th Meteosat Users Conference, Madrid.* 30 September.

MORRIS, R.M.
Using a global model to predict the movement of tropical cyclones. *WMO/CBS Technical Conference on Operational Weather Forecasting, Geneva.* 29–31 January.
Evaluation of the forecasting of each tropical cyclone in the SW Pacific during 1987/88, by the Meteorological Office 15 level NWP operational model. *International Conference on Tropical Meteorology, Brisbane.* 4–8 July.
The synoptic–dynamical evolution of the storm of 15/16 October 1987. *Palmen Memorial Symposium on Extratropical Cyclones and Frontal Zones, Helsinki.* 29 August–2 September.

NASH, J.
Three lectures: (1) Comparison of radiances synthesized from radiosonde observations with collocated radiance measurements from the TIROS-N series of NOAA satellites, (2) Data obtained from radiosondes on descent, (3) Practical experience of the operation of quality evaluation programmes for automated surface observations both on land and over the sea. *WMO Technical Conference on Instruments and Methods of Observations (TECO-1988), Leipzig, German Democratic Republic.* 16–20 May.

O'NEILL, A.
The maintenance of the stratospheric Aleutian high before the major warming of January 1987. *European Geophysical Society, Bologna, Italy.* 21–25 March.
Progress with the middle atmosphere of the southern hemisphere project. *Symposium No. 6 of COSPAR Meeting, Espoo, Finland.* 21 July.

PAINTING, D.J.
Auto-observing systems in the Meteorological Office. *Institution of Electrical Engineers, South Midlands Centre, Electronics and Control Section, Birmingham.* 15 June.

PARKER, D.E.
Climatic variability. *Society for Underwater Technology Group on Environmental Forces, London.* 3 March.
Marine temperature trends. *NOAA Climate Trends Workshop, National Academy of Sciences, Washington, DC.* 7–9 September.
The effects of increasing carbon dioxide and other 'greenhouse' gases on climate. *Recorded interview Belgian TV.* 8 June.

POLLARD, K.
Bracknell aviation meteorological services. *ATA Meteorological Committee, Colorado.* 24 August.

POPE, V.D.
Non-conservative changes in the observed and simulated stratospheric circulation. *European Geophysical Society, Bologna, Italy.* 21–25 March.

PRIOR, M.J.
Is every storm a catastrophe? — the UK wind data archive and its applications in structural design. *Insurance Institute of London.* 20 January.

PURSER, R.J.
Two lectures: (1) Three dimensional recursive filter objective analysis of meteorological fields, (2) An efficient semi-implicit semi-Lagrangian finite-difference scheme on a nonstaggered grid. *8th AMS Conference on Numerical Weather Prediction, Baltimore, Maryland.* 22–26 February.

RAWLINS, F.
Current cirrus research and related studies by the UK. *International Cirrus Experiment Workshop, Kronenburg, Federal Republic of Germany.* 8–10 February.
The expected status of the MRF C-130 aircraft for 1989. *Working Group on the International Satellite Cloud Climatology Project and the International Cirrus Project, Koln University, Federal Republic of Germany.* 28–29 June.

READ, P.L.
Chaotic regimes in thermally-driven, rotating, baroclinic flows in the laboratory. *Euromech Colloquium 236, Cambridge.* 12 September.

ROBERTS, D.L.
High latitude processes in a coupled ocean–atmosphere general circulation model. *2nd AMS Conference on Polar Meteorology and Oceanography, Madison, Wisconsin.* 29–31 March.

ROWNTREE, P.R.
Vegetation, evaporation and climate change. *University of Reading.* 11 January.
Climate models: prediction and uncertainties. *Watt Committee Symposium on the Greenhouse Effect and the Energy Industries, London.* 14 April.
The interaction of vegetation with climate. *2nd Results Meeting of the International Satellite Land Surface Climatology Project, Niamey, Niger.* 25 April.
The greenhouse effect. *Interview Radio 2.* 16 August.
Atmospheric parametrization schemes for evaporation over land — basic concepts and climate modelling aspects. *Workshop and Fall School on Measurement and Parametrization of Land-surface Evaporation Fluxes, Banyuls, France.* 10 October.
Requirements of global climate models for runoff data. *Workshop on the Global Runoff Data Set and Grid Estimation, Koblenz, Federal Republic of Germany.* 10 November.

RUDMAN, S.
A comparison of radiometric and immersion temperature measurements in cloud. *10th International Cloud Physics Conference, Bad Homburg, Federal Republic of Germany.* 15–20 August.

SAUNDERS, R.W.
The use of AVHRR data in operational weather forecasting. *KNMI, De Bilt, The Netherlands.* 22 February.

SCOTT, S.J.
Weather products for the BBC. *Weather Observation at Home and in School, Royal Meteorological Society, Bracknell.* 8 October.

SENIOR, C.
The antarctic winter; simulations with climatological and reduced sea ice extents. *European Geophysical Society, Bologna, Italy.* 21–25 March.

SHEARMAN, R.J.
Application of sea state data in wave forecasting and climatology. *Royal Meteorological Society (Specialist Group on Observing Systems) and S.U.T Discussion Meeting on Direct and Indirect Sensing of the State of the Sea, Birmingham.* 7 January.

SMITH, F.B.
The consequences to the UK environment of the Chernobyl accident. *IIT, New Delhi, India.* 17 February.
Short range diffusion in convective light-wind conditions. *NATO/CCMS 17th ITM on Air Pollution Modelling and its Applications, Cambridge.* 22 September.

SMITH, R.N.B.
Systematic errors in an AGCM and their sensitivity to the parametrization of clouds and their radiative properties. *CAS/JCS WGNE Workshop on Systematic Errors in Models of the Atmosphere, Toronto.* 19–23 September.

SPACKMAN, E.
IRRIGUIDE — an approach to irrigation scheduling. *Royal Meteorological Society, London.* 27 January.

STARR, J.R.
Meteorological factors in plant and animal health. *Physics Society, University College of Wales, Aberystwyth.* 19 January.

STRATTON, R.A.
Assimilation using SEASAT altimeter data for 15–20th September 1987. *6th WAM Meeting, Paris.* 21–24 March.
Remotely sensed data for wave forecasting. *Meteorological Office/Remote Sensing Society Meeting, Shinfield Park, Reading.* 5 May.

STUBBS, M.W.
Weather forecasting using satellites. *Department of Electrical Engineering and Electronics, University of Liverpool.* 25 February.

THOMPSON, J.D.
An updatable system for Model Output Statistics. *WMO Technical Conference on Regional Weather Prediction, Reading.* 20 April.

THOMPSON, N.
The Meteorological Office road surface temperature prediction model. *4th International Conference on Weather and Road Safety, Florence, Italy.* 10 November.

THOMSON, D.J.
Two-particle random walk models of concentration fluctuations. *Modelling Concentration Fluctuations in the Atmosphere, European Association for the Science of Air Pollution (EURASAP), Brunel University.* 26 April.
Turbulent diffusion. *2nd European Turbulence Conference, Berlin.* 2 September.

WARD, M.N.
Background to monsoon circulation in relation to floods in Bangladesh. *Recorded interview BBC Overseas Service.* 5 September.

WARRILOW, D.A.
The impact of land-surface processes on the moisture budget of a climate model. *European Geophysical Society, Bologna, Italy.* 21–25 March.

WESTON, M.J.
The UK Radioactive Incident Monitoring Network (RIMNET). *NATO-CDC Working Group on Radioactive Fallout, Home Office.* 20 October.

WHITE, A.A.
Two lectures: (1) Laboratory flow systems and the verification of numerical models, (2) The potential vorticity signatures of large scale geophysical flows. *University of Bonn, Federal Republic of Germany.* 4–5 February.

WHITE, P.W.
The UK Meteorological Office global forecasting model — seasonal and interannual variations of systematic errors and dependence on model formulation. *CAS/JSC WGNE Workshop on Systematic Errors in Models of the Atmosphere, Toronto.* 19–23 September.

WHYSALL, K.D.B.
Influence of bottom drag on the Antarctic circumpolar current. *UK Oceanography '88, Norwich.* 11–16 September.

WILSON, C.A.
Recent developments and immediate plans in the operational suite at the UK Meteorological Office. *10th Meeting of European Working Group on Limited-Area Models, Helsinki.* 11–14 October.

WOODROFFE, A.
Short period forecasts of precipitation for flood warning. *Conference of River and Coastal Engineers, Loughborough University of Technology.* 6–7 July.

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.

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