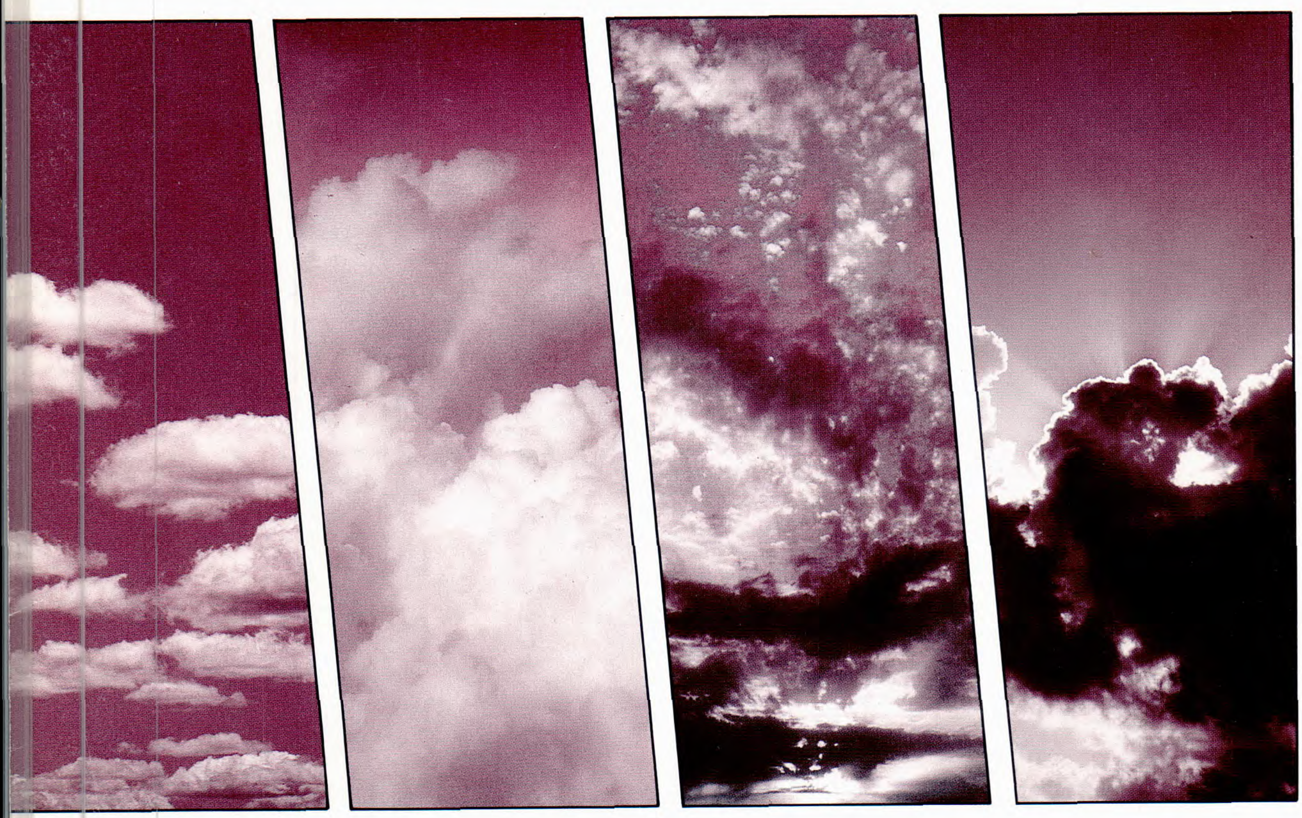
The Met. Office

Technical and Scientific Review



1991/92

METEOROLOGICAL OFFICE

EXECUTIVE AGENCY

TECHNICAL & SCIENTIFIC REVIEW 1991/92

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FOREWORD

In my foreword to this first Annual Review since succeeding Sir John Houghton as Chief Executive on 1 January 1992 I must begin by saying how impressed I have been by the Meteorological Office, and how welcoming and helpful everyone has been. Sir John added his distinctive contributions to those of his illustrious predecessors, from Admiral FitzRoy onwards, in leading the Meteorological Office towards its present high standing, and in encouraging the friendliness and dedication of its staff. I shall work hard to continue this tradition. It is quite a challenge learning about the Meteorological Office's many functions and to visit even a small fraction of its sites. As well as making a start on the visits, I have also had meetings with some of the Government departments, businesses and research organizations whom we serve, and with whom we collaborate.

The Meteorological Office is first and foremost an outstandingly successful **operational** organization. Our experience is mainly in meteorology, but our customers have wider environmental interests for which we can provide expertise, such as air quality, sea ice, waves, surges of coastal waters and soon, currents and temperature structure of the deep ocean. The Office is distinguished by being:

- a research organization of the highest international standard,
- a worldwide observing and communications organization, working within the World Meteorological Organization (WMO) and EUMETSAT (the organization responsible for managing Europe's meteorological satellite activities), and contributing its own high-quality data (based in part on the work of many voluntary observers),
- unique for its thorough validation of data and its comprehensive archives,
- a world-class operational centre for numerical modelling and computation of atmospheric and oceanic processes,
- an integrated operational organization serving the meteorological and other environmentally related needs of the defence services, aviation, commerce and the general public,
- an organization which practises good management, strong financial control, and high standards of training,
- staffed by highly professional and well-motivated personnel, about three-quarters of whom are trained meteorologists. (Of these a high proportion also have expertise in business, technology and other sciences.)

In the past year the Meteorological Office has continued to make further progress in meeting the demanding targets that are set each year in consultation with government, and in reaching the objectives set when the Office moved to Executive Agency status in 1990. These will be reconsidered, when the Framework Document is reviewed in 1992/93.

The accuracy of UK forecasts has continued to improve beyond the already high figure of 84%, achieved for the early-evening BBC Radio 4 forecast for the next day's weather. The accuracy of this forecast is continually reviewed at top management level, and fresh initiatives have been introduced this year to improve verification of a range of other forecast products and services. The National Severe Weather Warning Service, introduced after 1987, is functioning well. We have recently introduced a 30-day forecasting service for commercial customers known as the Monthly Prospect. This successful service provides a significant improvement on simply using climate records, and has a substantial commercial value. At the same time we are also concentrating on very-short-term local forecasts, particularly where hazardous weather is involved, and their dissemination to a range of customers.

I have learnt about the ever-increasing number of our commercial products and have been pleased to hear about our many satisfied customers, for example the world's airlines, a majority of which use Bracknell's forecasts for their international flights. At the other end of the scale I have been impressed by the hard work of sales staff in regional Weather Centres winning many small contracts for providing local weather information. All these customers make a vital financial contribution to offsetting the Office's core costs.

Invoiced revenue from Commercial Services showed a substantial increase this year, despite adverse effects of the continuing recession. This is an excellent result.

An important development in 1991 was the announcement by HM Government of a reduction in the size of the Armed Forces. This will lead to a reduction in numbers of Meteorological Office personnel as airfields are closed under the Options for Change programme. However, the United Kingdom's defence will continue to rely on the most advanced technology. There will be a continuing need for the very best local and global forecasting, including, for the Royal Navy, ocean forecasting using new models and new sea-surface data from satellites. My visits to RAF stations confirmed that defence applications of meteorology present a great technical challenge which provide a constant spur to improve our forecasting. Improvements in dissemination of weather information to aircrew and other operational staff are essential if the full value of currently available information is to be realized. Such improvements will be achieved wherever possible, by incorporating information, in the Automated Low Flying Enquiry and Notification System (ALFENS), which is being developed under National Air Traffic Services auspices. At a number of non-ALFENS sites derivations of the Meteorological Information System (MIST) will be employed. There is spin-off into commercial applications.

The Research Directorate, comprising three Divisions, has continued to maintain its standards of excellence and to show its commitment to applying its expertise to improve the Office's operations and providing advice to government on environmental change, both on a global and local scale. We congratulate Dr Keith Browning of the Research Directorate on his election as a Foreign Associate Member to the US National Academy of Engineering for his pioneering research on weather radar and its application for nowcasting–which was further developed in 1991 with the expansion of the weather radar network covering Scotland.

In June last year the Research Divisions, in close collaboration with the Central Forecasting Office, implemented a new higher-resolution numerical weather prediction model on the Cray Y-MP8 computer, leading to further improvements in forecast accuracy. The new model is the culmination of 100 man-years of research and extensive operational testing. It will continue to be improved. A version with 15 km resolution is also being developed to provide more-detailed weather patterns over the United Kingdom or over other regional areas anywhere in the world.

Increasingly, much of the research activity in the Office is planned to be part of wider projects involving other European and international research groups.

It is our intention that establishment of the European Climate Support Network, planned for 1992, will reinforce these activities in the field of research, prediction, and monitoring of climate. Other European and international initiatives are described in this review. Particularly noteworthy is our participation in the formation of an Economic Interest Grouping with other European Meteorological Services in order to promote development of commercial services on a European scale, that becomes possible with the advent of the Single Market.

Some new initiatives of an organizational nature are just beginning to make an impact; some of the more important examples are the Financial And Management Information System (FAMIS), improvements in project management, introduction of Total Quality principles for the systematic incremental improvement of performance and organization of many aspects of the Meteorological Office, and the introduction of advanced 'workstations' in the Central Forecasting Office and at outstations to replace paper charts wherever possible. Other important innovations relate to changes in personnel policy and improved internal communications aimed at enhancing staff morale. During the 1990s, the Meteorological Office is concerned with two major projects: expanding the computational power of the Office (and, probably, changing the nature of the computers used) and the introduction of a new generation of satellite for operational meteorology and climatology.

J.C.R. Hunt, Chief Executive, 30th June 1992

INFORMATION

Information is at the heart of the Meteorological Office's activities. The main 'production line' of the Office involves observations, and generating a range of forecasts and weather-related products. Information technology has always been used to assist this process, and is critical to achieving the required quality and timeliness of delivery of forecasts at an acceptable cost.

Operations

The Meteorological Telecommunications Centre (Met. TC) at Bracknell operates round the clock, gathering and disseminating the weather observations and forecasts, these may be exchanged as coded messages or data files between computers or forwarded to telex or facsimile machines. Almost all the messages (roughly 100 000 in, 600 000 out per day) are switched completely automatically. The Met. TC also processes and distributes radar and satellite imagery, and transmits products by radio and satellite broadcasts. This work is carried out by several computer-based systems.

Phase IV A - Tandem TXP. This is the main message switch and it is employed on international circuits, on the NMC task, on supporting military bases overseas and on links with other centres in the Bracknell zone of responsibility. It can receive data on up to 192 channels at signalling rates between 50 baud and 64000 bps (roughly 7 to 8000 characters a second) and it transmits data to computer-based forecaster aids at outstations (OASYS, ODS, MIST and HORACE).

Phase IV B - Tandem VLX - back-up system. This is installed at HQ RAF Strike Command (HQSTC) at High Wycombe; it is used to provide specialized broadcasts for the RAF, to support the display systems AOSYS and HORACE and to provide back-up to Phase IV A in the event of a system failure.

Phase IV E - Tandem CLX - enhancement system. This has duties similar to Phase IV A but at a reduced level, and is employed in providing data to commercial customers.

NETLINK is a group of DEC MicroVaxes which are nodes on the Met. Office Central Data Network (CDN). Transfers to and from the Global Telecommunication System are via Phase IV A. NETLINK acts as a gateway between systems using file transfer protocols and systems using WMO message transfer protocols.

Autosat-1 is a system installed in Met. TC based on DEC PDP11/60s which processes analogue satellite data from the ground station at Lasham in Hampshire and distributes it by facsimile: it is expected to be phased out during 1992.

Autosat-2 is an ELXSI computer system installed at Lasham which processes digital satellite data and sends image products to Bracknell. The data stream is passed via the CDN to COSMOS, NETLINK (for ODS and ECMWF), ARTIFAX and HQSTC for operational use and to other HQ systems for development work.

Large-scale scientific processing is performed on two Cray Y-MP8 machines. A new set of models for numerical weather prediction was transferred from the 10-year old Cyber 205 to one of the Cray machines in June 1991.

The second Cray is dedicated to the climate research work for the DoE. A general-purpose computing service is provided by an Hitachi Data Systems EX100 machine, which also acts as a front end to the Cray machines. The work undertaken by this machine has increased by around 40% during the year, reflecting the increase in work generated by the two Crays and as a direct consequence of bringing into operation the new, higher-resolution models.

Notable projects

ARTIFAX (Automatic Routine Transmission of Information by Facsimile) is a new system which can receive text or graphical products via a LAN and disseminate them over the public telephone network as faxes to customers equipped with standard Group 3 machines. This method is very popular with recipients who already have such a machine for business use. It can also send faxes to a bureau into which customers may dial for selection of specific products.

There are growing requirements for the management and storage of data. With the increase in available scientific computing power, much larger volumes of data are being generated in support of operations and research. Several terabytes (million million bytes) of data which need to be retained are now being generated each year. In order to cope with these demands in an effective way, high capacity storage media are required, together with appropriate systems for their control and management. The necessary hardware and software will be procured during the next year.

The technology of observation

At present observations and products are collected and disseminated around the United Kingdom by a variety of techniques ranging from teleprinter and facsimile broadcasts to computer networks. The aim is to replace this diversity with an integrated digital network running an international-standard message service. Good progress has been made in testing the hardware and software components of such a network and implementation is planned over the period 1993-95. A large effort is also going into the modernization of the systems in the Met. TC, notably the main message switch, to give greater capacity and keep up with the demand for new facilities to support the growth in activity.

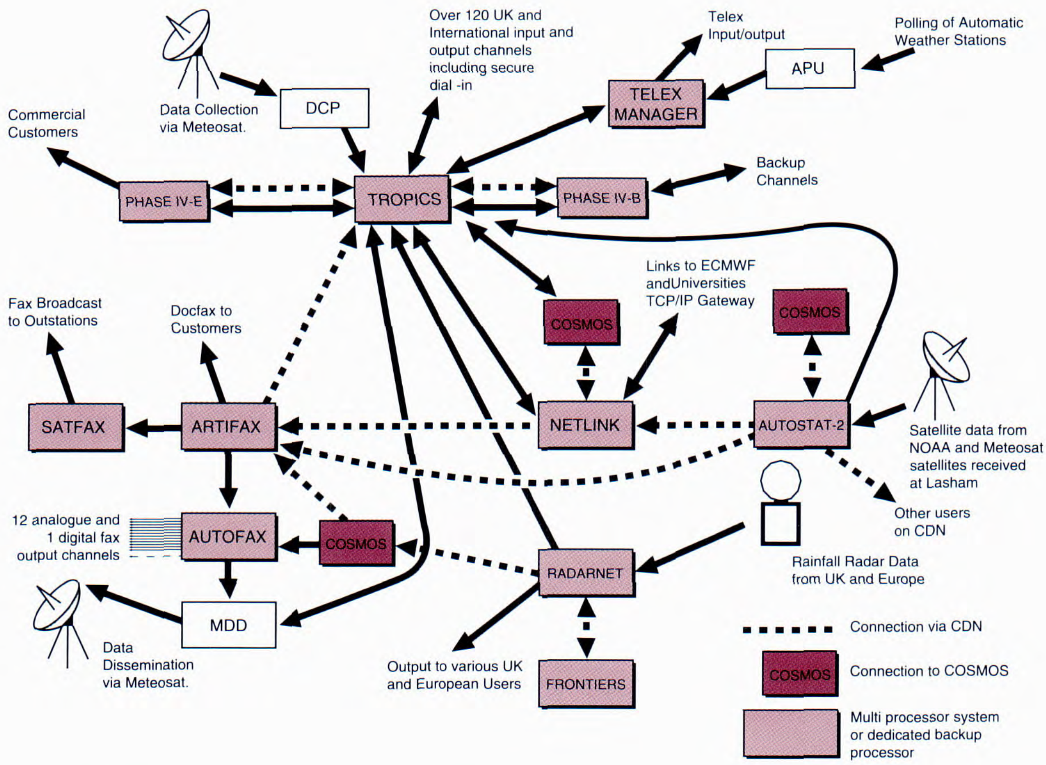

Figure 1. Showing the interconnections between the main Met. Office computer systems. For clarity, the main system, COSMOS, is shown three times.

OBSERVING SYSTEMS

Overview

All meteorological services and products depend to varying degrees upon observational data. For some applications, data are required globally at fairly coarse spatial and temporal resolutions. For other purposes, detailed data are required at high resolution over and around the British Isles. Well tried and tested *in situ* observations are provided by all countries to standards and in formats agreed within WMO. For its part the Met. Office puts data from the United Kingdom and certain overseas territories from aircraft, ships, buoys, platforms and islands into the Global Observing System. For use within the United Kingdom the relatively coarse data network that serves international obligations is supplemented by other data sources ranging from the simple rain-gauge to a comprehensive nationwide radar network.

The Met. Office is increasing its efforts to improve the accuracy and reliability of space-based systems which are especially important for the measurement of the weather over the oceans, ice-caps and deserts. We contribute directly to satellite-borne systems in two ways. Firstly, there is the provision of passive sounding equipment to the United States satellites operated by NOAA. Secondly, there is the contribution to European Satellite systems developed by the European Space Agency and operated by a consortium of sixteen countries (EUMETSAT).

The following sections describe, briefly, the complex and multifaceted work directed at providing the basic observational databases needed by the Met. Office.

Surface observing networks

A network of approximately 300 synoptic stations is maintained over and around the United Kingdom. The composition of the network is kept under review in the light of the changing requirement for observations and changes in the availability of observing sites due largely to changes in Defence and Civil Aviation operations.

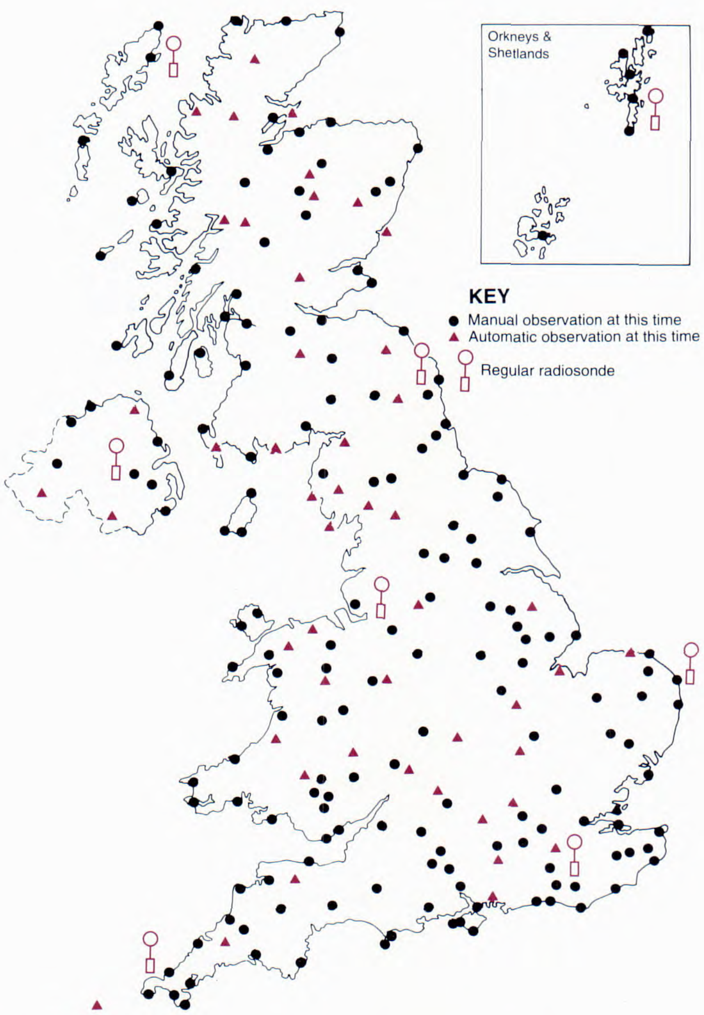

Figure 2. This shows the maximum hourly cover of observations in spring 1992. The eight regular radiosonde stations are also shown.

About 60 sites are fully automated, and a further 150 are manned by Auxiliary Observers (coastguards, oil-rig personnel, etc.) whose efforts in producing current weather information are greatly appreciated. A five-year programme of partial automation at the 80 officially manned stations is proceeding to schedule and will maintain or improve the network performance. Automatic encoding and transmission of observations has already been implemented for most Auxiliary Observers by the use of small portable personal computers and modems.

A network of 500 climatological stations and 4000 rainfall measuring sites is maintained together with 36 sites at which measurements of solar radiation are made regularly. At the majority of the climatological and rainfall sites, together with 22 of the radiation sites, observations are made by private individuals or staff of other organizations. The efforts of all these very keen voluntary observers are fundamental to the maintenance of the climatological archive.

Shipborne observing

Not only do merchant ships provide valuable weather data for meteorological use but these voluntary marine observers also help to further the cause of science with reports of marine and meteorological phenomena from the oceans. About 500 UK ships, of which the new British Antarctic Survey vessel *James Clark Ross* is one of the latest recruits, form part of the 7000-strong WMO Voluntary Observing Fleet. The Office is grateful to shipmasters and their companies for the supply of these data. Port Meteorological Officers visit ships of all nationalities liaising with the crews to maintain good observing standards. These visits may also resolve causes of observational error detected through data monitoring carried out during operational analysis in the numerical weather prediction programme suite or during subsequent archiving into historical data banks.

UK observing ships were asked to respond to a questionnaire circulated by WMO to monitor the effectiveness of the weather and sea bulletins produced and transmitted by the World's National Meteorological Services. A good response was received and is being collated by the Marine Department of the Hellenic Meteorological Service.

The Office has 23 systems on board British VOF Ships to enable messages to be transmitted via meteorological satellite with substantial transmission cost savings. The Marine Superintendent has been closely involved in discussions on the Global Maritime Distress and Safety System by which all ships over 300 tons will gain the facility to transmit weather messages via INMARSAT. This is expected to lead to more ship observations becoming available and at a lower cost than current ship-to-shore communications.

The UK-run Ocean Weather Ship *Cumulus* and about twelve North Atlantic container ships make upper-air soundings by radiosonde balloons, with one of the container ship operations funded by the United Kingdom. *Cumulus* remains as a purpose-operated weather ship, gathering valuable data on former Station 'Lima', (57° N, 20° W), to the west of Scotland. *Cumulus* contributes to MOD (Navy) operations by collecting sea-water temperatures and salinities at various depths, by use of expendable bathythermographs. Soundings are taken every six hours when on passage, and twice daily when on Station 'Lima'. In common with all data collected on the weather ship, this information is transmitted by satellite for immediate analysis ashore. The weather ship is also employed as a floating classroom for those seeking training in meteorological and oceanographic studies.

Upper-Air observing networks

Four of the eight balloon-sounding (radiosonde) sites comprising the main operational network are now equipped with NAVAID windfinding using the LORAN system. This development has simplified balloon launching, allowing single-manned operation and a reduction in staff. The remaining four sites continue to use radar windfinding, those at Camborne and Lerwick being tasked to provide data up to 5 hPa (36 km). The station at Shanwell (Taymouth) was closed and the operation moved to Boulmer, Northumberland. This allowed collocation with a key surface observing site, and more cost- effective working. The purchase of land for a new combined radiosonde station and key surface observing site at Herstmonceux was completed and planning permission obtained. When this is completed all but two radiosonde stations will be collocated with key surface observing sites.

Balloon-borne soundings are also made as and when required at a number of airfields and at MOD experimental ranges.

Regular twice-weekly balloon-borne ozone sounding flights have been made from Lerwick during the winter. This work, funded by DoE, is a part of the European Arctic Stratospheric Ozone Experiment. The ozone vortex or hole in northern latitudes was detected and monitored.

Observations from aircraft

As part of an international consortium, through WMO the Met. Office has been heavily involved in the automatic acquisition of data from the navigation system on board civil aircraft. This ASDAR system transmits data via satellite relay. Observations are transmitted every seven minutes whilst at cruising level and at predetermined levels on the climb/descent phases. The result is much good quality data over data-sparse areas. The United Kingdom has funded three systems so far, out of six in service.

The MRF C-130 has been fitted with a Global Positioning System capable of measuring the aircraft's position to 100 m for 95% of the time. As a result winds can now be routinely measured to an accuracy of 0.5 m s^{-1}. The aerosol measuring capability of the aircraft has also been improved by the addition of a Passive Cavity Aerosol Spectrometer Probe (PCASP) for detecting and counting particles between 0.2 μm and 3.0 μm diameter and a thermal gradient diffusion chamber for measuring cloud condensation nuclei spectra.

Automatic observing systems

A key element in increasing the efficiency and effectiveness of observing is the introduction of automatic and semi-automatic observing systems into the UK land and marine networks. The implementation plan is phased over several years, and major achievements have been made in three areas:

- The second phase procurement of Semi Automatic Observing Systems (SAMOS) was completed and 17 operational systems were installed. In parallel with the development of systems to meet Office requirements for SAMOS, collaboration continued with Redifon Limited who are developing a commercial version.

- The programme to enhance the Synoptic Automatic Weather Stations (SAWS) to provide additional climatological data has continued. Five enhanced stations became operational during the year and works services were completed for a further 24 out of the total of some 40 stations.

- The offshore buoy network was completed. This comprises five stations moored to the west of the British Isles at the edge of the continental shelf at depths up to 2000 m. Together with increased deployments of drifting buoys in the North Atlantic this completes the observing enhancements planned following the October 1987 storm.

The programme to introduce laser cloud-base recorders (LCBR) and visibility sensors into operational service has continued. After an extended trial period, six of the first batch of twelve LCBRs were installed during the year and thirty visiometers were delivered late in the year.

Other work involving the assessment of sensors included evaluation of present weather devices, the commencement of a trial of commercial wind sensors and the use of commercially available automatic weather stations to provide low cost climate recorders.

Solar radiation sites maintained by the Met. Office were equipped with replacement data-logging computers, giving a great improvement in data collection efficiency.

Equipment user trials

Trials are performed on observing systems to ensure that they meet the operational requirement originally set for them by the user of the data. Notably, further work was carried out upon the Vaisala PC-CORA ground stations now used at most of the balloon sounding sites. An international radiosonde intercomparison between UK, US and Swiss instruments took place at Crawley with approximately 70 multi-sonde flights being made in 2.5 weeks. On this occasion the UK Mark III sonde was flown for the last time. This was one of a series of trials aimed at harmonizing the measurements from the various radiosonde systems around the world. Other trials were of:

- The unique long-range thunderstorm detection system, which depends upon difference in arrival time of the radiation from lightning flashes, to compare its operational performance with the user requirement. The object was to aid decisions on future strategy.

- The SAMOS system when operated by air traffic control staff at Stansted Airport. A report was produced for the Civil Aviation Authority in order to aid future decision-making on observation provision at all civil airports.

- Laser cloud-base recorders now being installed. This is partly to understand the output from this new technology and, partly, to determine the extent to which the visual, subjective reporting of cloud in synoptic messages might be automated.

Weather radar

Three weather radars in Scotland were formally opened by the Scottish Minister for Home Affairs and the Environment on 13 December. The weather radar network now covers the whole of the mainland United Kingdom and, with the addition of data from radars in Ireland (Dublin was due to be incorporated in the network early in April 1992) qualitative weather radar data are now available for the whole of the British Isles and are passed to the FRONTIERS system. A type 45C Siemens Plessey weather radar with Doppler processing was installed at Cobbacombe and evaluation of Doppler processed data will begin next year.

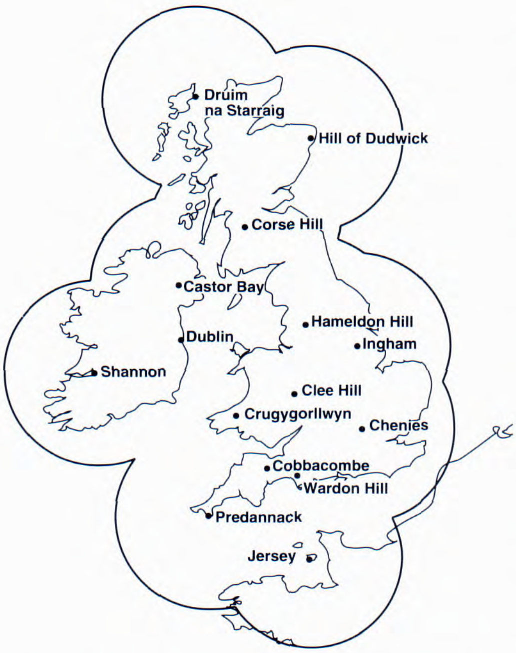

Figure 3. The UK weather radar network as augmented by the new Scottish radars and including units in Ireland.

Quality assurance and data archiving

Many auxiliary observers have now been equipped with laptop PCs into which they may enter the observed weather. The PC performs checks, and then codes the data before automatically dialling a collection point and transmitting a message into Bracknell. The quality of data produced by the observing networks is monitored continually and, where necessary, remedial action by technical staff initiated. Erroneous data are identified, amended if possible or rejected. Every effort is made to eliminate sources of error in observing by monitoring equipment performance, visiting sites, discussing problems with observers and arranging training if required. All Met. Office manned sites, one third of all other manned sites and one half of the automatic stations are inspected each year.

Programs have been developed for assessing system performance and fault identification when monitoring output from the ASDAR systems on behalf of WMO. The feedback results in modifications to the software or operating procedures as appropriate.

The Met. Office has continued to meet its commitment as a Responsible Member under the WMO marine climatological summaries scheme by archiving meteorological data from all merchant ships of the VOF trading across the North Atlantic. By exchange with other Responsible Members, a global archive is also maintained wherein the total amount of marine data has reached 71 million observations, dating back to 1854.

The climatological, rainfall and radiation data from the UK networks are all archived in a timely manner following quality control. Developments in quality-control procedures included the use of radar data to resolve apparent inconsistencies between gauges. This is particularly valuable when there are isolated showers and large local variations in rainfall totals making comparison between neighbouring gauges difficult. Work is progressing on the derivation of climatological averages and other statistics for the internationally agreed 30-year period, 1961 to 1990. Within this project, annual average rainfall totals have been derived and draft maps produced.

Observational support services

A wide range of services are provided to support observing and other operational functions. These include installations of operational equipment, assistance with outstation relocations, procurement of equipment, quality assurance, drawing office and technical writing, mechanical and electronic engineering support. The Maintenance Organization supports the wide and increasing number and range of observing systems and sensors. Good progress was made in establishing an equipment and fault-reporting database with on-line links to the Regional Maintenance Centres. This system is being integrated into the observations quality-control system, the objective being to ensure that user needs for data are being met in a cost-effective manner. To this end equipment performance and maintenance strategies must be monitored continually.

Observations from satellites

Geostationary satellites provide visible images of the Earth and its clouds, measure cloud-top or surface temperature and detect regions of high or low water-vapour concentration. Conventionally the measurements are interpreted as images of cloud and water vapour, and as sea surface temperature maps. These images are available hourly, or more frequently, so that movement and development of weather systems can be monitored and winds can be derived by tracking clouds. In the tropics such wind data are an essential input to forecast models. The European geostationary satellite known as Meteosat (over the equator at 0° E/W), provides local weather information for short-range forecasts.

Polar orbiting satellites provide global coverage but on a less frequent basis. They have the important role of providing information on vertical profiles of temperature and humidity for input into numerical forecast models. They also carry imagers which measure cloud-top or land/sea-surface temperatures. The resulting images have high resolution, and although available less frequently, they make up for the absence of good images from the geostationary satellites at high latitudes. The polar and geostationary orbiting spacecraft are complementary parts of the overall operational meteorological observing system.

The number of conventional soundings from manned stations on land and sea is continuing to decrease globally, so that the importance and necessity of satellites as a cost-effective source of global data are increasing. Both types of meteorological satellite also carry equipment providing dedicated communications facilities for the collection and dissemination of data.

Through EUMETSAT the Met. Office contributes to the maintenance of the Meteosat geostationary satellite system initially developed by the European Space Agency (ESA). The United Kingdom is also making a contribution towards the polar satellite system by designing and building advanced sounding instruments. The Stratospheric Sounding Unit (SSU) was first flown in 1978 and continues to fly on the NOAA series of spacecraft and the last of the eight flight models is due for launch in late 1992. An early development model has been upgraded within the Remote Sensing Instrumentation Branch of the Met. Office for launch in 1993 to ensure continuity of data so providing an overlap and cross calibration with the next generation of operational instrumentation – a key consideration when long-term climate monitoring is considered.

Development of operational space instrumentation

The next series of NOAA polar orbiting operational meteorological satellites, coming into operation in 1994, will carry the Advanced Microwave Sounding Unit (AMSU). There are two components. AMSU-A provided by the USA with 15 channels will derive, primarily, temperature while AMSU-B, provided by the UK Met. Office, has the five highest frequency channels deriving humidity profiles. AMSU-A will replace the four channel Microwave Sounding Unit (MSU) and the SSU, both providing vertical sounding data on the existing NOAA satellites. It will provide superior soundings in cloudy conditions to those from the current payload. Indeed under many cloudy conditions the quality of soundings will be comparable to those available in clear conditions from the current infrared sounding instrumentation. AMSU-B will provide the capability of measuring humidity profiles in the troposphere and should also allow identification of rain cells with an indication of intensity. The improved horizontal resolution, from 110 km of the MSU to 45 km for temperature from AMSU-A and 15 km for precipitation and humidity from AMSU-B, will provide useful image products and aid in the retrieval process for temperature in cloudy areas.

The AMSU-B Engineering model and three Flight models, being built under contract by British Aerospace, are being evaluated and calibrated by the Met. Office in a special calibration facility within the DRA Space Simulation Centre at Farnborough. The Engineering model began its test programme in December 1991. Although evaluation is not yet complete, it is anticipated that no major modification will be needed for the flight models or the calibration facility. The first Flight model is due to begin test in August 1992.

In addition to the provision and calibration of satellite instruments the Met. Office also flies instruments with matching channels on the MRF C-130 aircraft. The Microwave Airborne Radiometer Scanning System (MARSS) comprises two of the AMSU-B microwave channels (89 and 157 GHz). This has been used over the last year to investigate the properties of sea-ice, snow, sea surface and emission from water vapour. Further missions are planned concentrating on the effects of clouds and precipitation. These observations are being used to develop a radiative transfer model which will be at the heart of the retrieval scheme for the new generation of microwave sounding instruments.

ERS-1 meteorological instrumentation

The first European Remote-Sensing Satellite, ERS-1, was launched by ESA into a sun-synchronous orbit on 17 July 1991. Three instruments of particular meteorological importance are carried, a wind scatterometer, a radar altimeter (RA) and an Along Track Scanning Radiometer (ATSR).

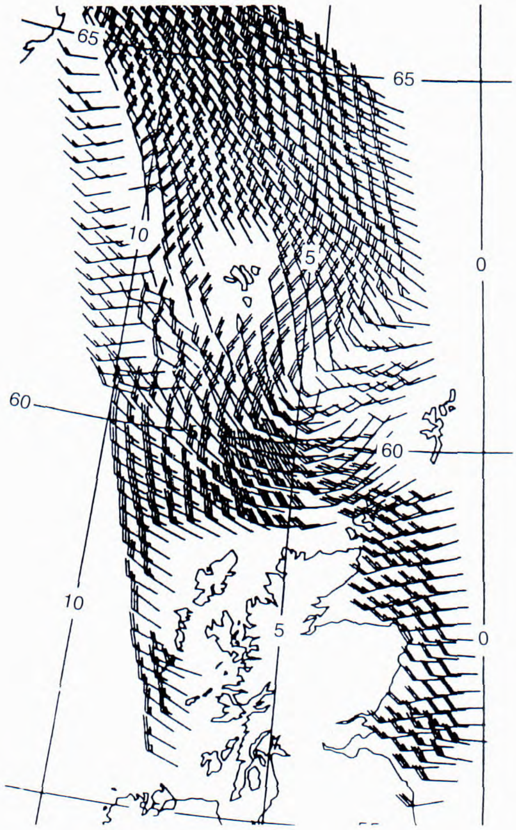

Figure 4 . This is an example of the winds derived from part of a single orbit of ERS-1 on 11 March 1992.

The wind scatterometer detects Bragg scattering from small-scale, wind driven, capillary waves on the ocean surface. Three antennas are used on the instrument, but there still remain certain ambiguities in defining the direction of the wind. The instrument is not operated continuously as it competes for time with the synthetic aperture radar (SAR) which takes high-definition pictures and measures waves. Currently, global coverage by the scatterometer is good except in the Northern Atlantic where the SAR is operated most. The MRF C-130 took part in two ESA organized validation experiments off the Norwegian coast between September and December 1991. The C-130, with other aircraft and a network of buoys, made direct measurements of the wind speed and direction. These measurements are being used to refine the calibration algorithm of the scatterometer.

The best calibration algorithm provides standard deviations of wind speed and direction, compared with the validation data set, of around 2.0 m s^{-1} and 20°; this represents a higher quality than can be obtained from *in situ* methods. Because of the global coverage, assimilation of the data into the forecast model made an impact in the southern hemisphere.

The data from the radar altimeter are processed to provide a number of meteorological parameters. Over the ocean the wave height can be deduced from the slope of the returned signal and wind speed from the power level. Shortly after the launch of ERS-1 the Met. Office received wave data from the altimeter in real time. These were compared with independent estimates of wave height and wind speed from the operational global wave model. By accumulating statistics of the differences between ERS-1 and model data and comparing them with similar data from models and buoys, it was possible to assess the accuracy of the ERS-1 wave data. Weekly reports to ESA from the Met. Office and other wave modelling centres showed that there was an error in the processing of the satellite data. This was found and corrected before the main validation exercises, enabling scientifically useful data to be obtained from the expensive measurement campaign.

The wave data were assimilated into an experimental version of the wave model from November to January. Initial investigations indicated a positive impact, mainly in areas dominated by swell. More detailed studies will be performed later in the year. The trial and other investigations have emphasized the need to cure the systematic lack of swell in the wave model and a programme of work to improve the formulation in the model is under way.

The ATSR is designed primarily to measure sea surface temperature (SST) with an absolute accuracy of less than 0.5 K; part of the instrument was designed and built in the Met. Office. Like other satellite instruments, it makes use of multi-spectral techniques to estimate and hence remove the contribution the atmosphere makes to the received signal. Additionally ATSR views the sea through two different atmospheric paths which enables this estimation to be carried out accurately.

In November 1991, the C-130 aircraft was used to validate products from ATSR during a detachment to Ascension Island, the aircraft being fitted with a radiometer with similar channels. The aircraft and ATSR data is being analyzed. Routine SSTs from ATSR have been evaluated against other systems as part of the sea surface temperature analyses. During this period, there has been a large quantity of volcanic dust (Mt Pinatubo) in the stratosphere that has corrupted all satellite retrievals of SST for the tropics; potentially, ATSR data should provide the best retrieval in such circumstances. The dust levels are now greatly reduced and currently ATSR SSTs are biased overall 0.8 K lower than averages of SST measurements from ships. Much, if not all, of this bias is associated with real differences between the skin and sub-surface temperatures.

The new instruments on ERS-1 are proving to be of high potential value for operational meteorology and the experience gained so far suggests that these new instruments will be required on the future operational polar-orbiting satellites.

Studies of future space instruments

The Met. Office needs to study and understand the requirements, techniques and available technology of future instruments to maximize benefits whilst maintaining tight constraints on costs. Such studiesare essential when seeking to influence the major space programmes. Office staff are members of national committees, delegates to international bodies and active members of associated technical working groups. Studies of future instruments currently include the evaluation of concepts for measurement of precipitation and clouds from space using active and passive techniques. There is also an increasing emphasis on climate and papers have been written for ESA, EUMETSAT, BNSC and DOE covering space instrumentation. Work is increasingly being carried out on a consultancy basis or under contract, e.g. the measurement of winds from space.

It should be technically feasible to observe winds directly from space, using the Doppler shift of light from a series of intense lidar pulses, backscattered from aerosol and cloud. Both ESA and NASA are working on such instruments, called ALADIN and LAWS respectively. The Met. Office is represented on the science teams for both instruments, helping to guide developments so that they meet the needs of data assimilation for numerical weather prediction and studies of the atmospheric circulation.

As part of this development work, under contract from ESA, the Met. Office has just completed a study in preparation for the use of Doppler wind lidar information in meteorological data assimilation systems. A scanning lidar instrument is likely to provide data with special characteristics: line-of-sight components rather than vectors, poor sampling of atmospheric variability and poor signal-to-noise ratio in clear air giving a large proportion of erroneous observations. The report demonstrated that assimilation techniques could be developed to cope with these, and extract useful information. It is planned to continue the work by assimilating simulated Doppler wind lidar observations, along with simulated observations from all other existing systems. The impact of the observations on the accuracy of the analyses will be assessed.

Extensive work has been carried out, again under contract to ESA, on the measurement of precipitation from space. The study defined the meteorological and climate requirements which could be addressed by microwave-based instrumentation and identified potential enhancements to the planned instrumentation. This led to additional studies of requirements common to other imaging instruments which increasingly utilize multispectral 'sounding' techniques. These studies indicate that the current approach, applied to the specification of such instruments, is less appropriate to the new generation of instruments. The studies also offer a new perspective, indicating that relatively small design changes can improve resolution and sensitivity, so significantly enhancing usefulness of the instruments.

Future space programmes

It is planned that after 2000 a new European polar-orbiting satellite will be launched to enable EUMETSAT to take over responsibility for providing the 'morning' polar orbiter from NOAA; they will continue the 'afternoon' series and will also provide some instrumentation. This will be a demanding and challenging development and one in which the Met. Office will continue to play a major role, although the Microwave Humidity Sounder (MHS), effectively the AMSU-B instrument modified for a different platform, will be provided through EUMETSAT. Within Europe the 'morning' payload will probably be demonstrated on an ESA Polar Platform and then continue in operation on a dedicated, derivative platform. The payload will comprise developments of the current operational meteorological instruments, the oceanographic instruments flown on ERS-1 and ERS-2 and several of the other ESA instruments of interest in understanding and monitoring climate change. Advanced infrared sounders are also under development and may be available in time for the first flight to provide a major step forward in sounding with considerable improvements in the vertical resolution. The future operational series of spacecraft provided through EUMETSAT is likely to carry operational climate instrumentation on behalf of other agencies. The EUMETSAT convention has been changed to encompass the secondary objective of operational climate monitoring.

On similar time-scales the existing Geostationary Meteosat Operational Programme (MOP) will be replaced by Meteosat Second Generation (MSG) with improved resolution, additional sensing channels and more frequent data.

The Met. Office is playing a key role in studies aimed at optimizing the instrumentation of European satellites planned for launch in the late 1990s.

DEFENCE INITIATIVES

The role of the Defence Services Division is to provide a comprehensive range of meteorological services to meet the changing needs of the Armed Forces and MOD(PE). Plans are advanced in inject meteorological data into military information systems, which should ensure instant access to a wide range of meteorological products of direct benefit to the RAF and the Army. An increasing research effort is being applied to developing new products, and initiatives have been taken to improve on the quality of meteorological training and forecasts provided to the military customer.

Tactical decision aids (TDAs)

In recent years there has been a growing requirement for more specialized forecasts for the Services and MOD. This has led to the development of a number of specialized models and products, which are generically known as Tactical Decision Aids (TDAs). TDAs incorporate weather and environmental information and predict the impact of meteorology on specific military systems and activities (e.g. electro-optics systems as discussed below and blast-noise propagation as described on page 38) and will lead to better operational advice being provided to Military Commanders and the MOD.

Night vision goggles (NVGs)

NVGs are image intensifiers which amplify the available light at visible (in the red) and near IR wavelengths. Thus NVGs 'see' the contrast of the scene due to reflected moonlight and starlight. Under very low light conditions they can become ineffective. The amount of light available to illuminate the scene depends upon several factors. (a) The phase and elevation of the moon, (b) the presence of cloud can significantly reduce the amount of light reaching the ground. In remote areas, away from cultural lighting, the reduction in light due to cloud can make NVG flying difficult; broken cloud, which can lead to variable light levels, can also make NVG flying demanding and (c) cultural lighting (the light originating from towns and cities) which can be significant, particularly under conditions with low-level layer cloud. TDAs for predicting night-time light levels and moon position have been developed and these provide useful advice to aid NVG flying.

Forward looking infra red (FLIR)

FLIR systems operate in the 8-12 μm window, and respond to the difference in the radiance emanating from various objects. This consists of both emitted and reflected long-wave radiation. The thermal contrast between objects is the major component of the scene signature. However, the thermal contrast seen by FLIR is related to, but not the same as, the difference between the actual target and background temperatures. The scene thermal contrast is very dependent upon the weather conditions. Rain, by cooling the background, can 'wash-out' the thermal contrast. Strong winds also lead to poor thermal contrasts. The thermal behaviour of objects generally follows a diurnal cycle, with heating during the day and cooling at night; the rate of heating/cooling depends upon the thermal characteristics of the object and the surface radiation balance. This diurnal variation is most pronounced under clear skies. Often, around sunset and sunrise, the temperatures of different objects converge, cross-over and diverge. Around this time, generally termed 'thermal cross-over', contrasts are low and the effectiveness of FLIR is reduced. The timing and duration of the cross-over period is dependent upon both the thermal characteristics of the scene and the meteorological conditions. Although the visibility at FLIR wavelengths is generally better than that at visible wavelengths (particularly through haze and mist), FLIR systems cannot see through cloud or thick fog. The FLIR visibility (transmission) is also reduced in precipitation and in conditions with a high absolute humidity due to water vapour absorption.

A TDA has been developed (by the USAF) which can predict the performance (range) of FLIR systems given the meteorological conditions, the nature of the target and its background, and the sensor characteristics. Trials of this TDA, the USAF Mk. 3 IR TDA, are currently being conducted with the RAF Central Tactics and Trials Organization/ Strike Attack Operational Evaluation Unit at A&AEE Boscombe Down. FLIR performance data and TDA predictions are currently being assessed.

Anomalous radio propagation (Anaprop)

Meteorological conditions affect the performance of radar systems in a number of different ways. The most obvious is the attenuation of radio waves by precipitation. However, in addition to this, the refraction (bending) of radio waves can significantly affect the performance of radars. This is due to variations in the vertical profile of radio refractive index (or refractivity). At frequencies up to 100 GHz (3 mm wavelength) refractivity is essentially independent of frequency and is a function of pressure, temperature and water vapour pressure. Significant gradients in the refractivity profile can occur as a result of the vertical structure in absolute humidity and temperature, and these may lead to anaprop. Ducting is the most extreme form of anaprop and occurs when radio waves become trapped in a shallow quasi-horizontal layer. (However, only those radio waves transmitted with an elevation within a few degrees of the horizontal are actually trapped.) In such conditions, significantly extended radar detection ranges can occur when both the radar and the target are in the duct, whilst reduced detection ranges can occur for targets adjacent to the duct (i.e. a radar hole). TDAs are available which can determine the nature of anomalous propagation conditions from meteorological data and which, given the details of the radar, can predict the way the beam is modified, this also depends upon the radar height and beam elevation. The current operational TDA for this type of prediction is the US Navy IREPS (Integrated Refractive Effects Prediction System), although it is anticipated that this will be replaced in the future by the Rutherford Appleton Laboratory Parabolic Equation Model.

During 1991 an assessment of the performance of the Met. Office Mesoscale Model for predicting elevated radio ducts was completed. The results showed that, whilst the Mesoscale Model is capable of predicting some ducting situations, overall the predictions were not sufficiently accurate to be useful. By defining an index to describe the degree to which conditions were ducting/super-refracting it was possible to make probability forecasts which showed a reasonable degree of discrimination. However, the main factor limiting the ability of the Mesoscale Model to predict ducting or anaprop conditions reliably was the way in which the model was initialized. The profiles of temperature and humidity (derived from the Limited Area Model) specified at the start of the model integration were much too bland, and did not contain sufficient detail on the structure of any low-level inversions/hydrolapses, and so poorly represented the refractivity profile. With the expected improvements in mesoscale initialization techniques it is hoped that the performance of the mesoscale configuration of the Unified Model for predicting ducting/anaprop conditions will be significantly improved.

Unified training notes

Approaching 4000 hours per year are spent by Met. Office staff instructing aircrew and ATC personnel at seven locations in RAF Support Command and at the Army Air Corps Centre at Middle Wallop.

The teaching method used to rely partly on a self-teaching package with some instructor-led lessons, but in 1988, with the advent of the Tucano aircraft, the course content became entirely instructor-led. This change in emphasis required the production of new meteorology notes. The notes are in the form of loose-leaf chapters, which are given to students during each lesson, and gradually build up to make a full set of notes.

At the end of the 30-lesson basic course, two examinations are set lasting 3 hours in total. The first exam is essential knowledge (pass mark 100%) and deals with such things as the hazards of thunderstorms and the effects of airframe icing effects on aircraft performance. The second exam is based on general meteorological knowledge (pass mark 70%).

Over the years several other sets of notes have evolved to meet the training needs of various RAF stations. In September 1991, at the annual Support Command Met. Instructors meeting, it was considered beneficial and more cost-effective if a single comprehensive set of notes were used throughout the RAF. After close consultation with the RAF, the 'Tucano' notes were selected to form the basis of the new 'Unified Notes'. Instructors' proposals were incorporated, and additional chapters on subjects such as TDAs, Sea Swell and Helicopter Meteorology were added.

The RAF Flying Training Support Cell are responsible for producing and maintaining the notes. The notes were published in March 1992 and are kept on a desk-top publisher which allows them to be updated easily.

Performance assessment

Agency status provided the impetus to introduce a scheme throughout Defence Services for assessing the quality of the service provided to customers. Initially, a proforma, that was completed at station level by the customer every 6 months, provided a subjective evaluation with comments across a broad spectrum of our activities. The comments provided Line Management with constructive feedback and, where appropriate, have been acted upon. After the first 6 months of the scheme, a simple method of objective analysis was introduced. This objective approach to performance assessment is based on warnings (for example frost and strong wind warnings) that are issued by the station and provides an analysis of the Hit Rate and False Alarm Rate.

Additional methods of objective performance assessment are being tested. One such scheme, known as SCORE, requires the forecaster to predict minimum aerodrome colour states for three 4-hour periods at the end of their shift and to enter the forecasts into a computer program. The actual aerodrome colour states are then entered later by the observer and the results, taking climatology into account, are presented as forecast versus actual contingency tables. A scheme to verify landing forecasts against observations for civil aviation stations by means of a fully automated system on COSMOS is being developed. This project is being extended to include military aerodromes with effect from 1 April 1992. The verification programs use several statistical techniques. The output from these programs is being evaluated to assess their usefulness as a performance indicator.

Networking to the customer: MIST and ALFENS

At least 10 years ago Defence Services saw the need to be able to communicate with their military customers using the computer medium.

The prototype PC-based system, developed in-house, was the Meteorological Information System (MIST). This was tested to wide acclaim at RAF Marham, where it continues to operate following numerous upgrades.

The RAF decided to incorporate the MIST function within a wider-ranging scheme of their own, the Automatic Low Flying Entry System (ALFENS). This system was conceived to try and help avoid mid-air collisions in the congested UK low-level air-space, providing pilots with the appropriate details to plan and complete their low-level sorties safely. It made sense to include meteorology in the system architecture.

ALFENS has become the main IT project for Defence Services. Locations which are not due to be networked into ALFENS will be able to request a MIST terminal. MIST has become a joint project, being developed beyond its prototypical stage in cooperation with BAe, primarily for use in the commercial market.

ALFENS will operate in April 1994. This will form Phase I of the project with initially centrally generated alphanumeric data input to the system. From this data several graphics screens will be developed for the X-Windows environment which ALFENS uses. Phase II will follow, aiming to provide full graphics and textual functionality for meteorological products by mid 1995. At this stage the local forecaster will be able to input products which he has either generated from scratch, or which have been issued centrally and modified by him for his customer. ALFENS will have a network of up to 512 military users both in the United Kingdom and overseas, all of whom will have access to quality meteorological products, where required tailored to specific operations.

FORECASTING, COMPUTING AND MODELS

The Met. Office has the prime responsibility for weather prediction over the United Kingdom. Improvements in these predictions have been made largely through the use of better numerical weather prediction models. Very-short-range predictions on a time-scale up to 6 hours need real-time forecasting systems, driven directly from observed data. In addition, methods of putting the forecast information across to the public continue to be developed, a recent example being the use of probability forecasts.

The Office also has responsibilities for global weather forecasting for defence and civil aviation. In addition there is increasing demand from other customers for weather forecasts in other parts of the world, for example for the routeing of ships. The future defence requirement is likely to include forecasts of the upper ocean structure. To meet these requirements the Office maintains a large global numerical weather prediction system and collaborates with other European countries through the European Centre for Medium-range Weather Forecasts (ECMWF) on new techniques for 4-10 day prediction.

All these methods of prediction depend on observations of the current atmospheric state. A major part of the effort in improving forecasts goes in learning how to make use of the many new types of observation now available.

Operational introduction of the Unified Model

The Met. Office has used a global numerical weather prediction model since 1982, and has used global climate simulation models since the late 1960s. The global weather prediction model was based on the design of the then current climate model. Experience with the two separate models suggested that it would be advantageous to combine them at the next major computer upgrade. The opportunity occurred with the installation of the CRAY Y-MP8 in January 1990.

The global forecast and climate models implemented on the previous CYBER 205 computer had many similarities. They both:

(i) solved the equations of motion using finite difference methods on a grid regular in latitude and longitude;

(ii) used a terrain-following vertical coordinate, with increased resolution near the ground and near the tropopause;

(iii) included representations of the main physical processes such as boundary layer mixing, convection, large-scale precipitation, gravity-wave drag and radiation.

The main differences were that:

(i) lower horizontal and vertical resolution were used in the climate model;

(ii) a different arrangement of the variables on the grid and time integration scheme was used in the two models;

(iii) the representation of physical processes in the climate model was considerably more advanced.

The program structure required for both models was similar. However, the climate model contained a large amount of ancillary software to enable output to be processed automatically during the very long integrations required.

For scientific consistency it is generally desirable to use similar physical formulations of atmospheric processes in both models; this was done previously, but with difficulty. It is much simpler to do this now that both models use the same computer code. Use of a modular program design allows easy testing of alternative formulations, and means that different representations of some processes can still be used if necessary. Either model on its own, together with ancillary programs for processing input and output data, forms a large software system. The unified model system contains about 150 000 lines of code at present.

In order to achieve a unified model, however, several key steps had to be undertaken:

(i) Successful use in the climate model of the very efficient split-explicit integration scheme used in the forecast model; this required modifying it to ensure conservation of heat and moisture, and ensuring acceptable performance in climate mode.

(ii) Modifying the boundary layer scheme to allow use of the longer time-steps permitted by the split-explicit integration scheme.

(iii) Modifying the radiation and cloud scheme to allow use of the higher vertical resolution of the moisture field possible in the unified forecast model.

(iv) Successful use in the forecast model of more elaborate representations of physical processes, particularly the use of explicit cloud water and ice variables and their interaction with radiation.

(v) Design of a single maintainable software system to meet all the requirements, while achieving the same efficiency as a single purpose model.

In June 1991, two forecast configurations of the Unified Model were made operational. The global version uses a grid of 288 × 217 points, giving a N-S grid length of 93 km, and 20 levels in the vertical extending up to 0.5 hPa. The model, including generation of many output products, executes in 7.8 minutes per day on the CRAY Y-MP8. The limited area version uses a grid of 229×132 points, giving a N-S grid length of 49 km and the same 20 levels in the vertical. Compared with previous forecast models there are substantial enhancements to the dynamical and physical formulations. A more accurate form of the equations of motion is used, taking account of terms important for the largest scales of motion. The dynamics satisfies an angular momentum principle and conserves heat and moisture. The surfaces of constant vertical coordinate become flat in the upper atmosphere, reducing numerical errors. The treatment of lateral boundary conditions in the limited area model has been improved. There is a full treatment of surface hydrology, including effects of vegetation. Clouds are taken into account when computing the amount of turbulent mixing in the boundary layer. Water and ice cloud density and amount are predicted, and taken into account in radiation calculations. These enhancements allow a better description of the atmospheric state, and allow a wider range of products to be generated.

Before making the models operational an extensive trial was carried out. An example of a forecast from each configuration is shown. The global model performance shows a marked improvement over the previous model in forecasting upper ridges. This is likely to be because of the enforcement of conservation properties in the integration scheme, and illustrates how enhancing the model to meet climate modelling requirements benefit on operational forecasts. In figure 5 the ridge in the verifying 500 hPa chart developed over the previous 4 days. Though the Unified Model slightly underestimates the amplitude, it is still 12 dam greater than that produced by the old forecast model. This characteristic of the Unified Model seems very insensitive to horizontal resolution, and is also visible in the lower resolutions used for climate and long-range forecast studies.

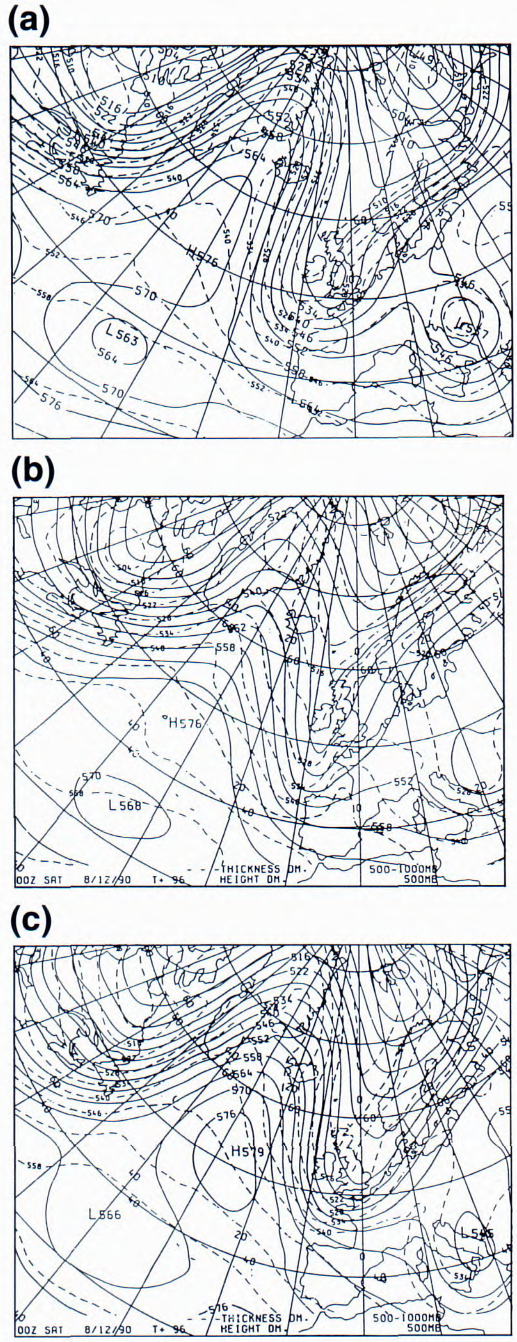

Figure 5. (a) 500 hPa analysis for 00 UTC on 8 December 1990, (b) 500 hPa forecast for 00 UTC on 8 December 1990 made four days earlier using the previous Met. Office model, (c) 500 hPa forecast for 00 UTC on 8 December 1990 made four days earlier using the Unified Model.

Objective measures of the accuracy of the new model show that the errors in the first six hours of the forecast are reduced for all fields. The errors in the winds are primarily reduced because of the increase in horizontal resolution, while those in the temperature and humidity fields are reduced by the better formulations. After the first six hours, the results are better on some, but not all, measures. The new model produces more intense developments which can result in larger root-mean-square errors for a given positional error. The higher resolution and more advanced physical parametrizations of the limited-area version of the unified model allow it to give a more organized representation of regions of precipitation than the previous limited area model. On occasions, the higher resolution also gives a better treatment of pressure systems. In addition, the objective measures of forecast skill calculated for the limited-area model show a marked improvement, largely because of the better treatment of the boundary conditions.

Mesoscale Unified Models

The Met. Office at present runs a very-high-resolution mesoscale model (32 levels and 15 km horizontal resolution) to produce short-period forecasts of weather over the British Isles. The formulation and initialization procedure are different from the global and regional models. The emphasis for this model has always been on prediction of the actual weather elements; temperature, wind, precipitation (rain or snow), cloud cover and base and visibility rather than just the synoptic evolution of wind and pressure systems, and so it had a more detailed treatment of physical processes than the previous global and limited-area models. The initialization of the model concentrates on the use of surface observations of those weather elements as well as satellite-derived cloud cover and tops and radar rain rates to modify mesoscale forecast fields or larger-scale analyses at the start of the forecast. This is in contrast to the larger-scale models where emphasis is placed on the use of upper-air data to continuously adjust or 'nudge' the model fields towards the observations for a period around the data time.

The enhanced physical parametrizations in the unified model have made it very similar to the current mesoscale model; indeed in some of these areas the unified model schemes are more advanced. The versatility of the unified model system means that it is relatively easy to change the configuration and resolution, so trials have been run to assess the feasibility of replacing the current model with a high-resolution version of the unified model to reduce maintenance costs. In parallel, work has started to combine the techniques and data used in the two contrasting initialization schemes.

The benefit of high vertical resolution in the assimilation of radiosonde data in the prediction of the evolution of stratocumulus is illustrated in the figure 6. However, the forecast would further benefit from a full three-dimensional cloud analysis as produced for the current mesoscale model and work has started on methods to 'nudge' model cloud fields towards analysed values.

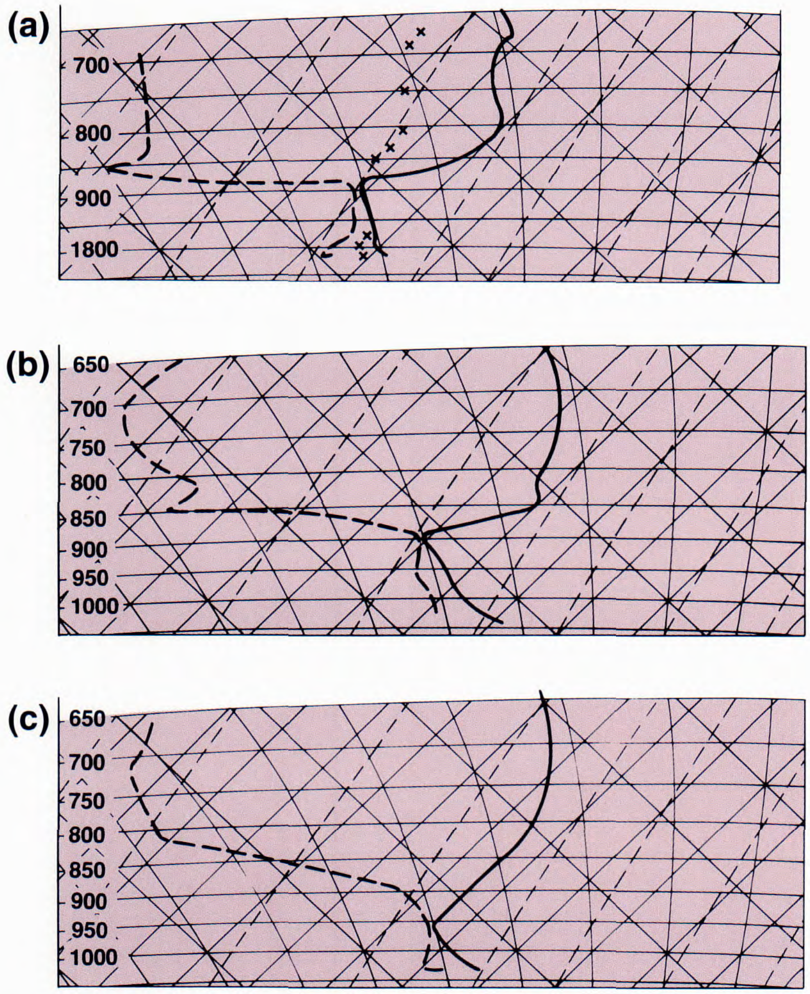

Figure 6. Showing the effect of resolution on forecast upper-air soundings; (a) 12 UTC 4 December 1991 observed sounding from Camborne, (b) 12 UTC 4/12/91 forecast sounding for Camborne using the 12 hr forecast from the mesoscale version of the Unified Model, (c) the same as (b) but from the limited area model. Note the difference in detail at the inversion and cloud base.

Medium-range forecasting

Much of the Office's medium-range forecasting research is undertaken by the European Centre for Medium-range Weather Forecasts.

Since its establishment in the mid -1970s, the Centre has made a great deal of progress in this topic. Using the correlation between the forecast and observed 500 hPa height anomaly as a measure, in 1980, the forecasts at day 5 were barely useful; by 1990 less than 10% of forecasts were very bad and almost half were very good; so that the 5-day forecast is now a reliable product.

The main recent development at the Centre has been the operational implementation of a new high resolution analysis forecast system. The new model has a horizontal resolution of 213 wave-numbers (roughly equivalent to a 100 km grid spacing) and 31 levels in the vertical. In order to implement this model within the available computing time, substantial developments had to be made in the numerical techniques used in the model. The physical processes in the previous model were computed on an approximately regular latitude-longitude grid. In the new model this is replaced by a quasi-regular grid with many fewer points near the poles. This saves about 30% of the cost of the physics in the model. The increased number of levels in the new model, and the increased vertical motions that can be represented by it, resulted in a more severe time-step restriction. The advection in the model therefore had to be replaced by a 'semi-Lagrangian' technique, in which values of physical quantities are transported directly along trajectories and the time-step is only restricted by accuracy requirements.

The new model has been found to perform better than the old model in the early part of the forecast, sometimes predicting significant extra detail. Later in the forecast period, the ability of the model to represent more detail in the evolution can sometimes lead to worse forecasts, as errors develop in the larger-scale pattern.

A major area of research at the Centre is the estimation of predictability using dynamical techniques. The Monte-Carlo (ensemble) forecast is a promising dynamical method for estimating forecast-error growth and providing probabilistic predictions. Dynamic perturbations from a simplified quasi-geostrophic model are used to perturb the operational analyses. An extensive study has been carried out using 24 cases where the operational forecast was poor. A significant correlation between the spread of results from an ensemble of forecasts using perturbed analyses and the skill of the unperturbed forecast has been found throughout a 15-day forecast range.

Long-range forecasting

Global numerical models run as nine-member ensembles continue to provide input in parallel with empirical techniques to the process for producing monthly forecasts (1 to 5, 6 to 15 and 16 to 30 days ahead) for the United Kingdom. During 1991 a switch was made from using a reduced-resolution version of the then operational forecast model, first introduced into operational long-range forecasting in December 1988, to employing the new unified model at climate resolution. Throughout the first half of 1991, ensembles from both models were run in parallel. Average skills of the unified model ensemble means were slightly higher than those of the operational model over the North Atlantic Ocean and Europe, with substantial improvements on some occasions. The unified model replaced the older model for operational 30-day forecasts in June 1991.

One important feature of unified model ensembles is the increased and more realistic variability of solutions, both within an ensemble and from case to case, when compared with the older model, in particular on time-scales of the order of 10 to 30 days. This increased variability has major significance for the ensemble technique in that it should now be possible to simulate a more complete range of atmospheric developments than previously. However, the enhanced variability within ensembles also poses new problems for forecast interpretation.

On numerous occasions ensemble members have been observed to group into two or more distinct sets of solutions, or clusters. For example, one cluster may predict westerly flow over the United Kingdom while a second suggests high-pressure blocking in the same area. The ensemble mean, which combines these clusters, produces 'washed-out' patterns in such circumstances and so provides limited forecast guidance. Techniques need to be developed either to select the most likely cluster or, more tractably, to express the forecast in terms of probabilities.

Several approaches to probability forecasting are currently being explored, probabilities being the optimal way to express long-range forecasts. For example, probability forecasts may be obtained directly from ensembles by considering the

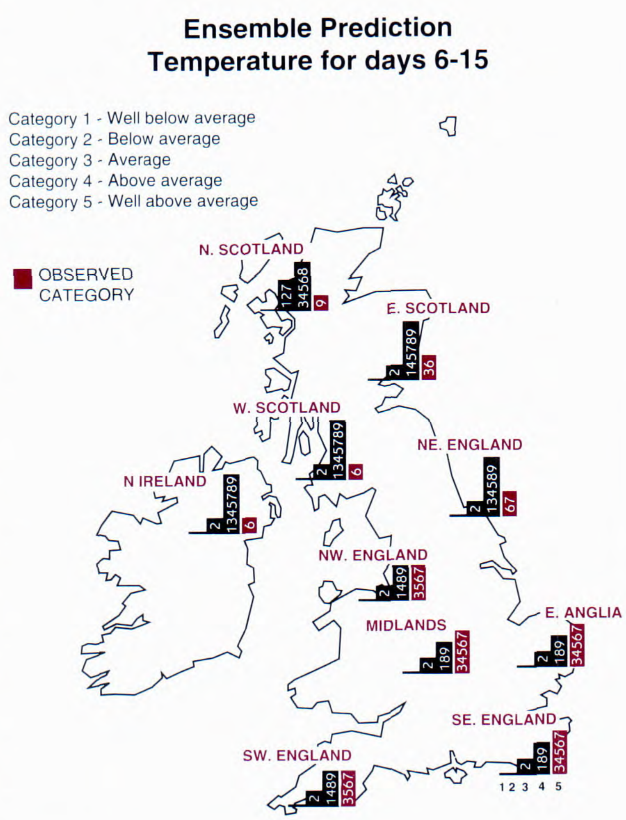

Figure 7. The numbers in the boxes indicate which of the nine runs fell in each category.

temperature and rainfall anomalies associated with each member, as illustrated for temperature in figure 7. Here, probabilities assigned to each category are determined simply by the number of members in that category. In this example the ensemble guidance is that temperatures will most probably be above or well-above average everywhere (in this case a good forecast!). One alternate approach is to use distributions of, say, temperature associated with previous occurrences of fields similar to a predicted field as an estimate of the probability distribution. Preliminary work in this direction has also provided encouraging results.

Forecast skills reached record levels during 1989 and 1990, although they have moderated somewhat since. Forecasts have been provided to external users (mainly water authorities and food and drink producers and retailers) since summer 1989 in a cooperative project with the marketing division of the Office.

Verification and monitoring of operational services & products

Verification of the forecast is an essential procedure which is carried out not only for the benefit of customers, but also in order to help forecasters to improve their performance and to give an objective assessment of the way in which the computer models behave.

Annual mean results

Verification of the computer model is achieved by comparing the numerical forecast field with either the model field as analysed at the validation time or a set of observations. The mean and root-mean-square errors are then evaluated for a number of fixed areas over the globe for a chosen period of time, usually one month. Some of these areas have been agreed within the WMO's Commission for Basic Systems and results from them are exchanged with other participating countries.

One fixed area covers most of the North Atlantic and Europe, including the United Kingdom. The results for pressure at mean sea-level over this area show how the model performance has improved throughout the last decade (see Fig. 8). The improvement has been brought about by advances both in the treatment of the available observations and in the forecast model itself, including the introduction of the Unified Model into operational use at 12h on 12 June 1991.

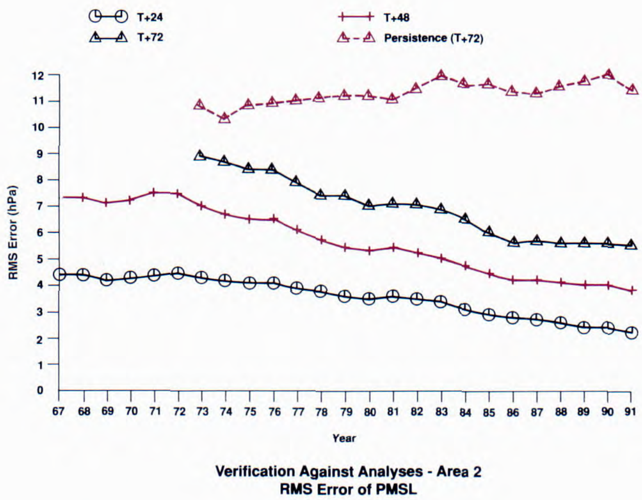

Figure 8.

Verification also has the advantage of drawing attention to some weaknesses in the model, for example to an increased cooling throughout the troposphere. Identification of these features is the first step to removing them, thereby achieving a further improvement in performance.

Aviation winds

The forecast of winds near the tropopause is of particular concern to aviation, which the Office serves in its capacity as a World Aviation Forecasting Centre. Winds, being vectors, are verified by computing the mean error of the wind speed and the root-mean-square vector wind error (the latter indicates the amplitude of the scatter of the forecast). Results for the 24-hour forecast of winds at the flying levels, typically at 250 hPa, have shown an improvement in both parameters every month since the introduction of the Unified Model, compared with the corresponding month in the previous year (see Fig. 9).

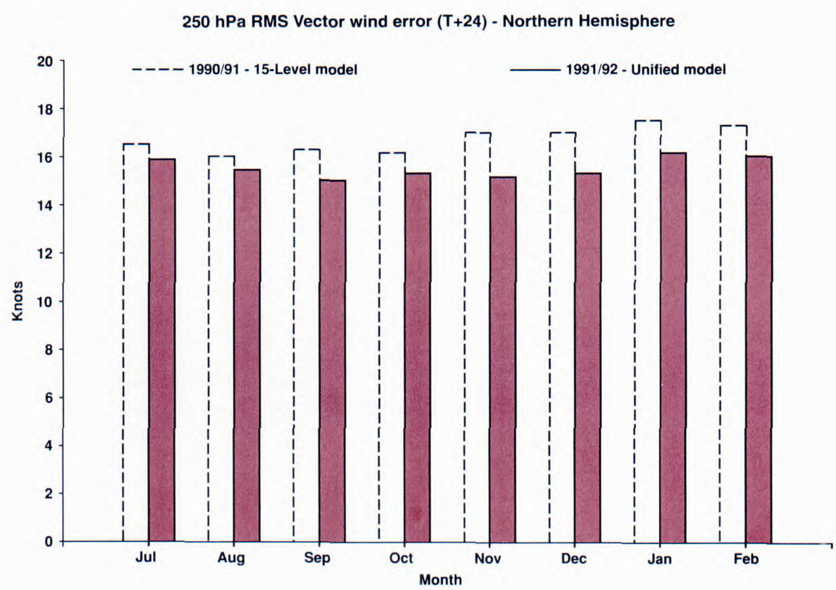

Figure 9.

Precipitation

Verification techniques have been designed to assess both the incidence of rainfall events and the quantitative prediction of the amount of rain that occurs. Contingency tables are used to compare the treatment of rainfall in the Limited Area Model (LAM) with what is actually observed at reporting stations over the whole of the United Kingdom. Results for forecasts 6 to 12 hours ahead show that approximately 80% of events are correctly forecast as either rain or no rain. On splitting up the rain events into categories of light and moderate it becomes apparent that most of the remaining 20% are borderline cases.

Worded forecasts

Verification of many worded forecasts is carried out on a subjective basis. The results can be quantified by using them to construct a contingency table. For example, the forecast on BBC Radio 4 is assessed by applying such a method to the predictions of temperature, weather, cloud and wind. Through the year the evening forecast (for 'tomorrow', broadcast at 1755) has consistently achieved 83% of the maximum score, or better.

In the assessment of gale warnings, the performance showed some variation through the year. However, the success rate averaged 80% overall, while the false alarm rate was never worse than 21%. Other warnings, for example for frost, are also verified. Forecasts of temperatures for up to 3 days ahead, for British Gas, were found to be within the required accuracy of 3 °C on 97.6% of occasions during the year.

Probability forecasts for the occurrence of rain, snow, gales, frost and above or below normal temperatures (4 °C or more) for specific 12-hour periods were incorporated into the guidance issued by CFO during 1991. The probabilities are estimated for twelve specific sites in the United Kingdom from which routine hourly observations are obtained allowing for the subsequent verification of the forecasts. In particular, the probabilities of 12-hour rainfall of greater than trace (wet), and equal to or greater than 5 mm (very wet) are estimated. For snow, the probability is an estimate of the likelihood of precipitation falling as snow if precipitation occurs.

During the year a scheme has been set up for the verification of Terminal Aerodrome Forecasts (TAFs). A simple yes/no scheme suggests that about 90% of these forecasts are correct. A more detailed scheme to consider each element of the forecast is being set up to include both civil and military aerodromes from April 1992. Verification of forecasts for military aerodromes is also performed by means of contingency tables.

Customer satisfaction

Evaluations of services in both the public and defence sectors are carried out at regular intervals by means of customer satisfaction questionnaires. Results are analysed and may be used as the basis for recommending improvements to the service. Some of the most striking features of these surveys are that 78% of the public felt that the forecasts were useful to them; and that, although 5% thought there had been a deterioration, 67% thought the accuracy of the forecasts had improved over the last 5 years.

Development of other forecasting aids

The numerical models provide much of the guidance for forecast products, they are not yet able to meet all the needs for real-time forecasts on a local scale. Other techniques more directly related to observations have therefore been made available to forecasters. Two of these are described below.

Air-mass transformation modelling

Output from the operational numerical weather prediction models is one of the most important sources of guidance to outstation forecasters on likely weather developments for 24 hours and more ahead. However, it is not, as yet, sufficiently well resolved to assist with the problem of local forecasting of low cloud base and fog development less than 24 hours ahead. Also, the large-scale models cannot be rerun to explore the sensitivity to small changes in the initial conditions, something that would be extremely useful in certain weather situations.

In order to fill this gap in the tools available to forecasters, a simple model has been developed to predict short-term changes in temperature, humidity and cloud under conditions of fairly uniform air mass: hence the title Air Mass Transformation (AMT) model. A one-dimensional, mixed-layer model of the atmospheric boundary layer (provided to the Met. Office in a basic, dry, version by the Dutch meteorological service) has been extended to include moisture variables such as cloud water and water vapour. In addition, routines have been added which compute temperature changes through the atmospheric column resulting from short- and long-wave radiation. The model is initialized by computing back-trajectories at various levels in order to identify the region of origin of the air mass which will affect the station, and then by setting up the initial vertical temperature and moisture profiles from representative radiosonde data.

The model has recently been adapted to run on desk-top computers, and will be supplied to a small group of outstations for trials during 1992/93. Although it is inevitable, in view of the complexity of the atmosphere, that the model can only represent fluctuations in low cloud base approximately, it has the great strength that it can be run repeatedly, incorporating any modifications to the initial profiles which the outstation forecasters consider helpful. With sensitivity studies of this kind they should be able to learn much about the potentialities and variability inherent in the situation.

Nowcasting of precipitation using the FRONTIERS system

The production of a precipitation forecast from radar and satellite data using the FRONTIERS system is a three-stage process. During a 30-minute cycle, the forecaster applies further quality control to the radar data if necessary (the radar analysis), uses Meteosat satellite data to derive likely areas of precipitation beyond radar range (the satellite analysis) and finally produces a forecast for up to 6 hours ahead.

The original forecast scheme allows the forecaster to track areas of precipitation and derive their velocity semi-automatically. An extrapolation forecast is then produced by moving the precipitation in a straight line at its recent velocity. To try and account for more complex motion (e.g. curved motion) it is possible to move specified areas of precipitation with different velocities. However, there is often insufficient time to define enough areas and it is still not possible to represent curved motion properly. After the forecast is computed, the forecaster is permitted to modify each forecast field, e.g. delete showers moving from a warm sea to cold land at night. However, there was generally insufficient time to do this on the original system, within the half-hour forecast cycle.

In order to mitigate these problems, a new forecast scheme was developed which uses forecast wind fields at two levels from the mesoscale model to produce two advection forecasts based on the current radar/satellite rainfall field. These automatically include the rotation implied by the wind field and very complex patterns of motion can occur when a circulation centre moves across the United Kingdom. Such advection forecasts are not a complete solution because the height of the winds which correlate best with the actual motion of the precipitation may vary across the field. As the forecast winds may be in error, the original extrapolation procedure is retained as an option. The new forecast scheme also incorporates the calculation of accumulations over a 15-minute period. A very important recent change has been the upgrading of the system from a VAX 11/750 to a VAX 4000: the subsequent dramatic speed-up has given the operators time to implement options that were previously frequently shut off by time constraints.

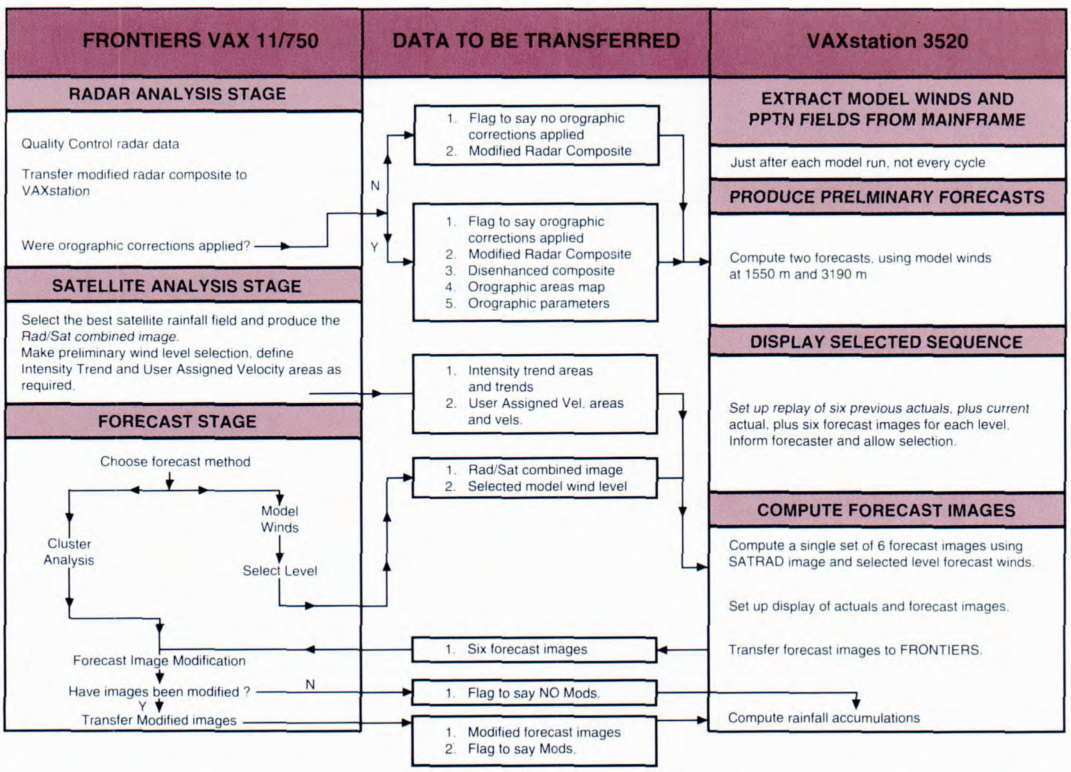

Figure 10. Outline of the structure of the new Forecast Stage, showing the data to be transferred between the FRONTIERS VAX and the VAXstation 3520 at each stage of the FRONTIERS cycle, and the main tasks to be performed on the VAXstation.

In March 1990 the Office invited the Thames and North-West Regions of the National Rivers Authority (NRA) to take part in a pilot operational service to receive and assess FRONTIERS rainfall forecasts. The trial period began on 1 October 1990 with a duration of one year, later extended to 18 months. One motivation for this work has been to assess whether or not the potential financial savings from a 3-hour advance warning of flooding, specified by a joint study undertaken by the National Water Council and the Office in 1983, are likely to be achievable using FRONTIERS forecasts. In the Thames region these savings ranged from £25K per annum (1992 prices) in rural catchments to in excess of £800K per annum in urban catchments, whereas in the North West the savings ranged from less than £1K per annum in coastal areas, to in excess of £170K per annum for steep, hilly catchments like the Irwell's.

Overall, it proved difficult to assess the quality of the FRONTIERS product for flood situations during the trial year. The year 1991 was unusually dry with the average rainfall in the Thames region about 86% of standard average and in North West region 73%. It was characterized by very few flow events that gave rise to significant river flows of the scale for which flood forecasting models have been calibrated. The service has been developed as a result of feedback from the first year in which FRONTIERS data have been made available outside of the Met. Office. The trial will therefore be extended a further 12 months, in the hope of obtaining more significant precipitation events, and of assessing the current improved version of FRONTIERS over a longer period. Further improvements to FRONTIERS forecasts will be sought by developing automatic techniques, including the ability to use model forecasts directly in situations where the model out performs extrapolation techniques.

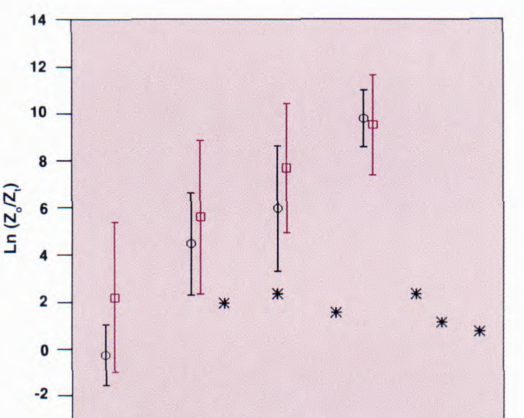

Figure 11. Showing the dependence of $\ln(z_o/z_{ot})$ on roughness Reynolds number. The squares represent observations made at Cardington, the circles experimental and model results for a bluff-rough surface and the stars observations taken over permeable, vegetated surfaces.

Process studies to improve atmospheric models

The numerical models are unable to resolve small-scale atmospheric flow. They therefore incorporate statistical representations of the effects of small-scale features. In order to design and calibrate these representations, it is necessary to carry out research studies in which the small-scale features can be represented and understood properly. A number of these studies are described below.

Roughness lengths over inhomogeneous terrain

The accurate representation of surface fluxes (e.g. of momentum, heat and moisture) is an important element of atmospheric numerical modelling. The framework of common parametrization schemes derives from results applicable to flat homogeneous terrain. However, the Earth's surface is a complex mixture of topography and terrain types, with substantial inhomogeneity on length scales shorter than the resolution of numerical models. To overcome this problem considerable attention is being given to the definition and measurement of effective roughness lengths to characterize the effect of the terrain on sub-grid length scales and hence allow models to generate the correct area-averaged fluxes.

Over a rough surface, momentum transport is dominated by pressure forces and it is possible to relate the roughness length to the size and density of the surface obstacles. However, at the surface the transport of a scalar, such as temperature, is dictated by molecular processes. This creates problems in the definition of the surface boundary conditions and suggests marked differences between surfaces with large, bluff roughness elements and those with densely vegetated areas. Recent theoretical work has examined the area-averaging of roughness lengths for momentum and heat transfer. For typical rural and agricultural land where the fractional cover of large roughness elements (e.g. trees and hedges) is fairly low, perhaps 10% to 20%, the effective momentum roughness (z_o) is predicted to be greater than a simple logarithmic average of local roughness lengths. However, the converse is true for roughness lengths for heat transfer (z_{ot}). This inequality is illustrated in Figure 11 which shows the experimentally dependence of $\ln(z_o/z_{ot})$ on roughness Reynolds number (defined as $u_* z_{ot}/\nu$ where u_*, is the friction velocity and ν the kinematic viscosity) from observations made at the Met. Office field site at Cardington . Also shown is a compilation of data applicable to more uniformly vegetated areas of grass land, crops and forest and which contrasts markedly with Cardington data.

Modelling turbulent flow over hills

Most of our current understanding of turbulent flow over hills has been derived from two-dimensional theoretical and numerical studies. This limitation to two-dimensions considerably restricts the type of flow with only cross-stream vorticity occurring and convergence confined to the vertical plane. To investigate the effects that three-dimensions may have on present ideas and parametrizations a three-dimensional numerical model, employing terrain-following coordinates, has been coded that is capable of simulating the mean flow over three-dimensional hills.

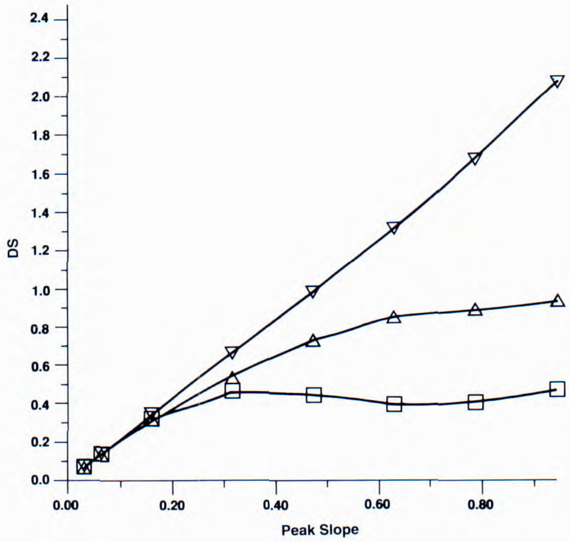

Figure 12. Values of the maximum fractional speed-up at the crest of the hill (DS) as plotted against the peak slope for each of the three series of model simulations performed. The squares are for two-dimensional hills, the upward pointing triangles for closely-packed three-dimensional hills, and the downward-pointing triangles for isolated hills.

The results of simulations of flow over either two-dimensional ridges or circularly symmetric, cosine-squared hills, with various values of maximum slope, have been compared with each other and with results of linear theories, observations and other two-dimensional numerical model results. A theoretical formula for the pressure force induced by a two-dimensional hill has been generalized to three dimensions and extended to give a more general formula for the pressure force at slopes large enough to generate separation. The pressure field induced by the hill generates a speed-up in the velocity near the crest of the hill. At small slopes, the speed-up behaves very similarly for the three different types of hill configuration considered. At steeper slopes the pressure force slows the overall flow and reduces the speed-up at the crest of the hill. For a given slope the pressure force is largest for the two-dimensional hills. Thus, the speed-up is found to be greatest, for a given slope, for the more isolated, three-dimensional hills. On steep slopes the adverse pressure gradient is large enough to cause flow separation. Using linear solutions for the fractional speed-up, an expression for the slope at which separation occurs over two-dimensional hills is obtained, which shows good agreement with reported values of this critical slope. Finally, it has been shown that for all the hills considered, the areally averaged velocity profile and the total surface force are well described via an effective roughness length. An expression for this roughness length has been obtained which agrees well with the model results for both the two- and three-dimensional hills under consideration.

Gravity wave drag

A combination of observational and numerical modelling techniques have been successfully employed to study the form and intensity of lee wave motion over the Lake District and northern Pennines. Orographically- forced gravity waves were observed on most days of a field experiment held in November 1991 at Eskmeals on the Cumbrian coast. Wave activity was revealed by ascent-rate fluctuations evident in groups of five radiosondes release in rapid succession. On two days in November, the C-130 aircraft was flown along the approximate path of the sondes at up to five levels in the troposphere and a comprehensive picture of the lee wave structure was obtained.

In a case-study of the trapped lee wave found on 26 November, the non-hydrostatic Mesoscale model was run on a 2 km grid (covering a 180 km square region of northern England) with 43 levels in the vertical extending up to a height of 24 km. Above 18 km a damping layer was implemented so that upward-propagating gravity waves at this level would be absorbed. The model was initialized with a single upstream profile derived by merging an aircraft descent profile with a sonde profile. After four hours of model integration a quasi-steady trapped lee wave field resulted with a vertical velocity maximum of 3.5 m s^{-1} at a height of 3 km and a dominant wavelength of 20 km. Figure 13 shows a comparison of the vertical velocity observed by the aircraft compared to that in the model along the path of the aircraft and at a height of 3.7 km.The agreement, in both amplitude and phase, is very good, particularly in view of the difficulty in measuring vertical velocity. The total pressure drag due to resolved motion over the model domain was found to be 0.4 to 0.5 N m^{-2} and most of this is likely to be gravity-wave drag. The sub-grid shearing stress on the surface was found to be even larger than this and dependent on the assumed roughness-length.

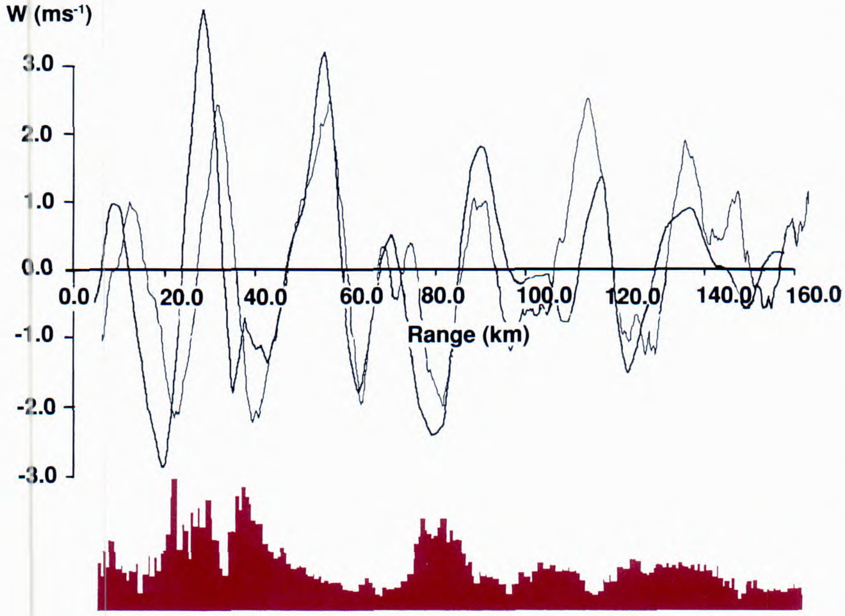

Figure 13. Showing a comparison of the vertical velocity observed by the aircraft compared to that in the model along the path of the aircraft and at a height of 3.7 km.

Fronts

During the year major papers were published on the conclusions of the FRONTS 87 experiment, and preparations made for a further campaign, FRONTS 92, during March and April. The earlier experiment showed some of the most detailed evidence yet obtained on the interaction of dynamical processes with latent heating in fronts. In particular, mesoscale patterns of potential vorticity were resolved and indications of circulations induced by the evaporation of snow were substantiated by microphysical calculations.

The FRONTS 92 programme is intended to study the dynamics of frontal waves, which are a substantial forecasting problem in the United Kingdom. Several theories now relate to the development of waves below the synoptic scale, and the primary aim of the project is to study the mesoscale structure and evolution of waves on fronts.

Modelling deep convection

Research is continuing on deep cumulonimbus convection because it is such an important physical process that has to be parametrized in numerical weather prediction and climate models. It plays a fundamental role in the redistribution of heat, moisture and momentum in the atmosphere and is responsible for a considerable fraction of global precipitation. Cloud fields associated with convection interact with solar and infrared radiative fluxes in the atmosphere which, together with latent heat release, play a major role in dictating the distribution of diabatic heat sources and sinks in the general circulation. An understanding of how to include their effects on the large scale of the model is essential for climate prediction.

Only a limited amount of observational data is available to help validate the parametrizations, primarily because of the difficulty and expense of making observations on the wide range of scales necessary – from the microphysical scale to the scale of cloud clusters. Numerical modelling of convective systems offers a relatively cheap way of gaining a better understanding of the processes involved; such an approach is being pursued. The model is an extension of the Large Eddy Simulation model which has been used for boundary-layer studies over a number of years. It is non-hydrostatic, anelastic, and uses conservative thermodynamic variables. It has a sophisticated, shape-preserving advection scheme and a stability-dependent first-order turbulence closure. The main development this year has been the implementation and testing of a microphysical parametrization of warm rain processes: autoconversion (growth of raindrops by condensation), accretion (coalescence of raindrops and cloud droplets), and evaporation of rain. Test simulations of the growth and decay of single cumulonimbus clouds show considerable realism.

Improved use of observations in models

In order to improve the analyses used in the numerical models, it is necessary to extract the maximum possible information from available data. Considerable effort is required to make the best use of satellite data, and two areas of this research are described below.

Use of satellite cloud-motion winds

Satellite cloud-motion winds (SCMWs) are produced operationally by all the operators of geostationary meteorological satellites. The low-level SCMWs produced operationally by ESA from Meteosat data are extremely accurate; when verified against numerical analyses the accuracy is very close to that of radiosonde winds. However, high-level winds are not so accurate, and it is believed that the major source of error is the height assignment; in particular cirrus clouds are semi-transparent and radiation may be received from a considerable depth through the cloud, or indeed a surface below. A further complication is that clouds may not move with the wind at the cloud top (they may be tied to topography, move with a mean wind in deep convection, or transfer through dynamical developments). Thus complete understanding of the problem involves dynamics, microphysics and radiative-transfer theory.

During the International Cirrus Experiment (ICE) in 1989, measurements of wind, temperature, humidity and a number of microphysical and radiative parameters were made by up to five aircraft, including the MRF C-130, flying simultaneously in cirrus cloud. Thus the data obtained provided the best opportunity to study the problem of the semi-transparency correction using contemporaneous observations of all the relevant variables. The study described here is being performed under contract to EUMETSAT, the European body which finances Meteosat operations.

The first stage of the study consisted of generating CMWs on a number of scales for the areas and times of the experimental aircraft missions. The issue of scale is a significant one. The operational production of SCMWs uses as a template size an array of 32 × 32 infrared pixels, but studies of low-level winds have shown that a smaller template size produces better results.

The process of generating SCMWs involves firstly the construction and interpretation of the histogram of infrared in the relevant portion of the image. Radiances outside the specified thresholds are considered to arise from the background and those pixels are eliminated so that only motions in the relevant cloud layers are tracked. Correlation surfaces are then generated between one image and the next for a range of possible displacements.

The second stage of the study was an analysis of the aircraft wind and temperature data. The analysis was performed on a grid of 40 km in the horizontal by 2000 feet increment of flight level in the vertical, and separate analyses were performed for all the times for which the SCMWs were produced.

The third stage of the study is to produce an empirical level of best fit (ELBF) – this is the level at which the CMW agrees best with the aircraft data. Of course an ELBF will be produced for each SCMW at each scale.

Calculation of the ELBF takes into account the vertical vector wind shear and the shape of the correlation surface. For a number of the SCMWs for mission 207 it was apparent that there were two ELBFs, one corresponding to a layer of cloud at about 400 hPa moving relatively slowly and a second corresponding to a layer at about 300 hPa moving somewhat quicker. This was a surprising result as it was impossible to discern the two layers from the histogram of infrared radiances. However, it was probably due to the variable density of the cirrus cloud sheet.

The next stage will be to tune the semi-transparency correction to agree with the ELBF. Data additional to that used operationally will be used at this stage, e.g. a second water-vapour image, visible channel data, aircraft radiometric data. The final stage of the study will be to make recommendations for changes to the operational semi-transparency correction.

Satellite soundings

The starting point for Met. Office research into the use of satellite sounding data in NWP is the Local Area Soundings System (LASS) that is run routinely at Bracknell. Raw sounding data for the local area are received at Lasham directly from the US operational polar orbiting satellites when they are in line-of-sight.

Currently, the processing of the data proceeds in three main stages. Firstly, the raw instrument counts are converted to basic radiances, and the latitude and longitude of each sounding is calculated. Up to now this first stage of the processing has been performed on the HERMES minicomputer at Bracknell, but during the year most of the work has been done to enable this task to be transferred to the AUTOSAT-2 system at Lasham. Next, estimated values of an idealized set of radiances are calculated. The idealized set consists of collocated radiances from the infrared and microwave sounding instruments at nadir viewing through a cloudless atmosphere to a surface with emissivity of unity. Finally, temperature and humidity profiles are retrieved from the idealized radiances. In fact, temperature and humidity profile increments are calculated from radiance increments using a linear inversion technique. The profile increments are the differences from space and time interpolated NWP profiles, whilst the radiance increments are the differences between the idealized radiances and background radiances calculated from the NWP profiles using a forward radiative transfer model.

During the year changes were introduced to take advantage of background profiles available to a higher level (15 hPa is used) following the implementation of the Unified Model for operational NWP. Two major lines of development are proceeding from the base outlined above.

A non-linear inversion technique is available from previous research and this has been tested during the year in parallel runs of the LASS. In this approach the idealized radiances are not calculated, though the basic microwave radiances are still mapped to achieve collocation with the infrared radiances. Temperature profiles, humidity profiles, cloud amount, cloud-top pressure and surface emissivity are then retrieved directly from the basic radiances. A significant improvement in performance was demonstrated during the year by imposing a constraint on the horizontal variation of the cloud top-pressure. New research was started on the representation of the effects of cloud reflectivity, hitherto neglected. The capability now exists to retrieve cloud reflectivity at a particular frequency and to relate this to the reflectivity at other frequencies through theoretical Mie scattering calculations.

The second major line of development concerns the establishment of a Global Soundings System (GLOSS). The input data at present are idealized radiances (often referred to as cloud-cleared radiances) for the globe received from the United States. During the year studies of these data have been carried out to establish suitable quality control procedures. Even working with idealized radiances, the linear inversion method is unsatisfactory for global data. Consequently, the non-linear inversion technique has been installed on the CRAY supercomputer for the global retrieval of temperature and humidity profiles.

These developments are expected to come together in future years when global basic radiances become available from the United States. The methods being developed will be applicable to the improved microwave data available from the AMSU instruments (expected in 1995) and to the data from advanced infrared sounders (expected around the turn of the century).

CLIMATE VARIABILITY AND CHANGE

Introduction

Climate change has attracted growing attention over the last several years and interest continued at a high level during the year under review. **The Hadley Centre, funded jointly by the DOE and the Met. Office, is the main centre in the United Kingdom for research on climate change.** The research focuses on the understanding and monitoring of climate and on the modelling of climate change. Improvement of the climate model used for these activities is an important part of the programme. A major task this year has been to bring the Unified Model built for use both for short-range forecasting and climate simulation to a standard suitable for climate research. Low temperatures, unrealistic flow patterns over the North Atlantic and excessive continental aridity have been the target of model improvements which, by the end of the year, had brought the model simulations to a much more acceptable state.

Climate prediction research is very dependent on the availability of large computers. Through DOE funding, the Hadley Centre has one of the largest supercomputers currently available, a CRAY YMP-8/64. This machine was installed in March 1991 and is dedicated to climate research. Linked to the supercomputer is a graphics workstations system which allows easy and relatively rapid analysis of the output from the models. This was installed in November 1991 and is now operational. The workstations allow the model results to be displayed directly in graphical form on the screen and this has dramatically speeded up both model development and data analysis.

Observed climate change and variability

Observations of land and sea surface temperatures are valuable components of the climate data base used for studying climate. Monitoring of surface temperatures has revealed continuing evidence of global warming, with 1990 and 1991 the two warmest years to date; there was weak cooling later in 1991, possibly due to the reflection of solar radiation by the stratospheric dust cloud from the eruption of Mount Pinatubo in June; the last decade has been the warmest decade of the record (Figure 14).

A valuable application of the database for climate studies is to force a climate model by the best available analysis of sea surface temperature (SST) and sea-ice. This is already being done for recent years in the Atmospheric Model Intercomparison Project (AMIP), sponsored by the World Climate Research Programme, in which many atmospheric models will be integrated for the period 1979-88 using observed SSTs and sea-ice. Understanding of climate variability could be improved by similar experiments for other periods of the last 100 years; unfortunately, the required data are very incomplete so new interpolation methods are being devised to create a nominally complete data set since the 1870s. The SST data have been expanded using the Comprehensive Ocean–Atmosphere Data Set (COADS). In addition, many millions of hitherto inaccessible marine observations dating back to the late nineteenth century are slowly being digitized abroad and plans are being made to incorporate them into our archives. Corrections are needed to allow for biases in older data due to the way they were collected; these corrections, and the theory behind them, have been further developed. Analyses of the improved data have contributed to the 1992 Supplement to the IPCC Scientific Assessment. It has not yet been possible to use satellite data on SSTs because of their biases, as shown by earlier Met. Office analyses. This problem was again highlighted during the year following the eruption of Mount Pinatubo.

Work has started on an expanded database of air temperatures measured near the ocean surface from ships. Daytime data are unreliable because of the solar heating of ships' decks, so emphasis is placed on measurements made at night. Such data are a valuable cross-check on SST and are needed for better estimates of heat exchanges between the atmosphere and oceans.

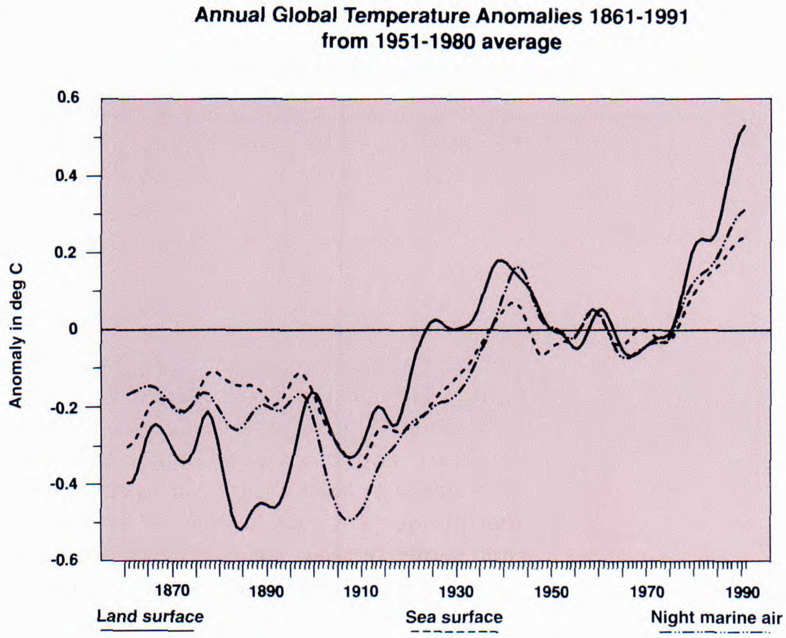

Figure 14.

The mostly good agreement between global trends in SSTs and air temperatures, measured near the surface over land and sea, is shown in figure 14.

There has been concern that reported increases in the strength of the wind near the ocean surface over the last few decades may not be real. Such a trend would be important to our understanding of the possible impact of increasing greenhouse gases. Methods have been devised to correct the wind data for changes in the way winds are measured.

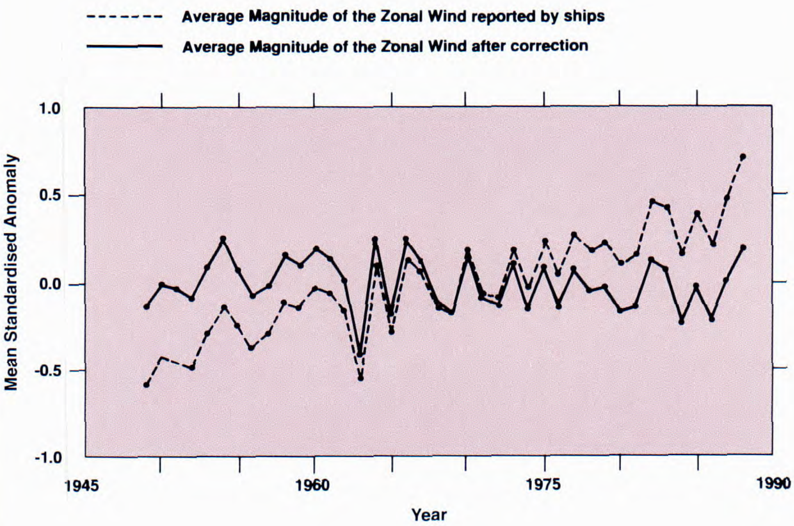

Figure 15.

The corrected winds show little or no globally averaged trends, though trends remain in some regions, related to regional climate variations, particularly in the tropical Atlantic Ocean.

Routine quality-control of land-based monthly air temperature and rainfall data continued in collaboration with the University of East Anglia's Climatic Research Unit. An International Temperature Workshop was organized which helped to identify new sources of data, including measurements of daily maximum and minimum temperature needed for more detailed studies of climate change. To help with studies of climate variability over the United Kingdom, a more homogeneous daily Central England Temperature data set for 1772-1991 is now complete.

Measurements of temperature and wind in the troposphere and lower stratosphere derived from radiosondes are available for about the last 40 years and have great importance for understanding climate change and variability over that period. Warming trends shown by the radiosonde temperature data are generally consistent with changes observed at the surface. However the data suffer from instrumental and procedural changes and other errors. A limited study of these problems is nearing completion.

The most complete data on tropospheric and lower stratospheric climate for recent years can be obtained from analyses created by weather forecasting models. However, these have considerable inhomogeneities which must be understood before the analyses can be used for climate studies. Monthly global tropospheric analyses for the period since 1979 are being extracted from the ECMWF archives for comparison with simulations, now in preparation, using the Unified Model in AMIP, while Met. Office archived data have been used to create climatological data for validation of climate simulations.

Prediction of climate change

A primary cause of the recent concern over climate change has been the results of climate models which over the last 20 years have been showing that the Earth should warm as greenhouse gases increase. Until recently, attention has been focused on the equilibrium response of climate to doubling CO_2 using atmospheric models coupled to a mixed-layer ocean. Such experiments show increases in annual mean surface temperature which are a maximum over the Arctic and around Antarctica and a minimum in the tropics; the warming over land is generally greater than over the ocean.

To assess the effects of a gradual increase in greenhouse gases, a coupled ocean atmosphere model has been run in which CO_2 concentrations were increased at the rate of 1% a year, giving a doubling of CO_2 after 70 years. This gives a decadal change in radiative effect which is slightly larger than that due to the estimated increases in all greenhouse gases over the last decade. The large thermal inertia of the ocean slows the warming, so that at the time of doubled CO_2, the warming (1.7°C) is generally smaller than the equilibrium response with a mixed-layer ocean model (2.7°C). Although the radiative forcing increases linearly, the model shows little warming over the first two decades or so, and then a broadly linear increase of about 0.3°C/decade. The initial delay appears partly to be an artifact of the experimental design so that one cannot relate the results directly to the observed temperature record. A similar delay occurs in the increase of sea-level due to thermal expansion which reaches about 3 cm/decade at the end of the experiment, consistent with the IPCC Report.

Many of the features in the transient experiment are qualitatively similar to those in equilibrium experiments, including the land-sea contrast and the maximum warming over the Arctic. However, around Antarctica and in the northern North Atlantic, there is little or no warming in the transient experiment. In these regions mixing occurs throughout the depth of the ocean (typically several kilometres) rather than the few hundred metres typical of lower latitudes. Thus the greater thermal inertia in these regions leads to a much smaller warming than elsewhere.

The broad regional patterns of the seasonal changes in temperature, precipitation and soil moisture become established over the first few decades. In the northern hemisphere, these patterns are generally similar to those found in equilibrium experiments—for example, precipitation increases in middle and high latitudes in winter and soil moisture decreases in mid latitudes in summer. However, like the real atmosphere, the model displays substantial 'natural' variations from decade to decade. Changes in temperature over western Europe exceed these interdecadal fluctuations after 20 to 30 years. For precipitation and soil moisture the changes are of consistent sign after the first decade, with increases in winter and decreases in summer as in the equilibrium experiment; sizes approach the level of the interdecadal fluctuations after 30 years but do not increase consistently thereafter.

Equilibrium experiments with mixed-layer ocean models continue to be of use because they are cheaper to carry out and simpler to analyse than transient experiments. The simulation of the diurnal range of temperature in a low-resolution model has been found to compare quite well with observations though it is underestimated in wet climates. On doubling CO_2, the global mean diurnal range is reduced slightly, due to increases in the solar absorption by CO_2 and in the ratio of evaporation to sensible heat. Locally, changes in diurnal range are dominated by changes in cloud, snow cover and soil moisture. Observations of diurnal range have been analysed for about a quarter of the land surface and mainly show a reduction in diurnal range during this century, with the warming mostly due to increased minimum temperatures. This is not the case in the model where both maximum and minimum temperatures increase substantially and the reduction in diurnal range is small. (The increase in observed maximum temperatures expected, due to increases in greenhouse gases, may have been suppressed by increases in sulphate aerosols, which are not represented in the model, or by increases in cloud which in turn may have been caused by increases in trace gases.)

Climate models-development and validation

The climate is generated by the interaction of the radiative forcing with the dynamical and physical processes of ocean and atmosphere, modified by the Earth's geography. In a climate model the processes affecting the absorption and emission of energy (radiation, clouds, surface characteristics) and its transfer in the atmosphere and ocean by large-scale and small-scale (turbulent and convective) motions must all be realistically represented. The following subsections review the year's research on these and other related topics.

Radiation and clouds

Work on the Unified Model radiation code has focused on identifying and removing systematic errors, as well as adding additional diagnostics. New data were included for the gaseous transmissions in the short-wave region of the spectrum. Excessive cooling in the upper troposphere was reduced by replacing the long-wave transmissions by data from the ECMWF model. A version of the code which includes the minor trace gases methane, nitrous oxide and the two most important chlorofluorocarbons has also been developed, so that changes in these gases can be properly represented in climate change experiments. A parametrization of the radiative effects of ice clouds was developed, which takes account of the different scattering properties of ice crystals compared with water drops. Integrations of the model have been compared with data from the Earth Radiation Budget Experiment (ERBE), to provide assessments of the model as it has evolved, and further ERBE data are being obtained for the more extensive comparisons to the simulations for 1979-88 to be run as part of AMIP as discussed earlier.

Liaison has continued with the Atmospheric Physics Research Group at UMIST. A simple parametrization developed at UMIST for the 'effective radius' of water clouds using data from a wide range of conditions, including the mid-continental USA, has been programmed into the model. A series of experiments is being run to examine the impact of changes in effective radius on the cloud radiative feedbacks operating in the model as the sea surface temperatures are raised.

Work has proceeded well with the development of a new radiation code. This will replace the out-of-date codes presently used for stand-alone comparisons with experimental data and provide an alternative to the existing Unified Model radiation scheme. The code has variable spectral resolution and the effects of atmospheric gases, aerosols and clouds can be turned on or off. Several methods are supported for representing the overlap between partially cloudy layers. Detailed tests of the code in single column mode are producing encouraging results.

Development of the system for the Simulation and Analysis of Measurements from Satellites using Operational Analyses (SAMSON) has continued. Simulations of the clear-sky, outgoing, long-wave radiation over the oceans were made with a high spectral resolution radiation scheme provided by the University of Reading. Atmospheric temperatures and humidities came from both the ECMWF and Met. Office operational analyses. The simulations are close to the ERBE data, suggesting that this approach may be able to supplement or even replace the clear-sky fluxes currently retrieved from satellite data.

Experimental studies of clouds and radiation

Numerical weather prediction and global climate models have grid spacings which are too coarse to resolve explicitly processes associated with clouds. Thus the effects of clouds have to be expressed in terms of the bulk parameters of the model. In general, these parametrizations are simplified and they are often based on very little observational data.

Analysing and interpreting *in situ* measurements of cloud and radiation in a way that is representative of a model grid box, say 100 or more kilometres square, is a non-trivial task. However, a well-instrumented aircraft, which can survey large areas in a short period of time, can provide more directly usable observations. During the last year the C-130 Hercules of the MRF has been making measurements in and around clouds to improve our understanding of the physical processes, and to validate and improve some of the parametrizations that are being used.

Radiation schemes in numerical models are sensitive to the effective radius, r_e, of cloud drops. Measurements have been made in stratocumulus clouds off the coast of California during the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE) in 1987, in maritime and continental air masses around the British Isles, and over the South Atlantic during the First ATSR (Along Track Scanning Radiometer) Tropical Experiment (FATE). These data have been analysed to investigate the variation of r_e with liquid water content, droplet concentration and cloud condensation nuclei concentration. Figure 16 shows relationships from these data which, together with the UMIST data referred to earlier, will form the basis of a new parametrization for layer clouds to replace the single value of r_e that is currently used in the radiation scheme for all water clouds in the Unified Model.

Microphysical measurements have been made in frontal and jet stream cirrus over and around the British Isles, and also during the International

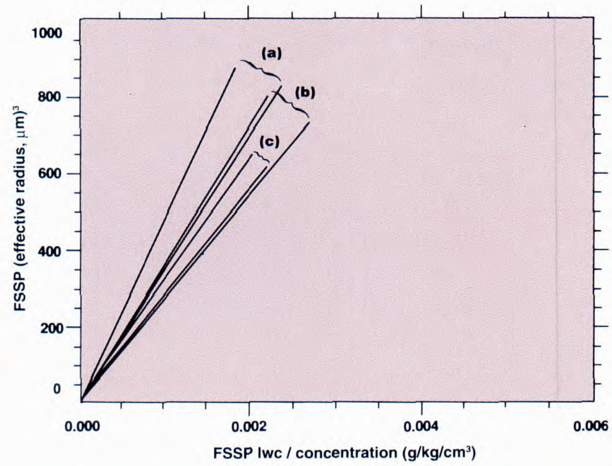

Figure 16. This figure shows relationships found by the Forward Scattering Spectrometer Probe (FSSP) in (a) continental air masses, (b) maritime air masses and (c) maritime air masses in FATE.

Cirrus Experiment (ICE), in order to improve the simulation of cirrus clouds in models. The analysis has concentrated on determining the ice water content of these clouds, the r_e of the cloud particles and the precipitation rate, and on relating these to bulk parameters such as the ambient air temperature.

Numerical model precipitation and radiation schemes are significantly affected by the presence of ice and there are a number of different parametrizations being used for the conversion of liquid water to ice. Data have been collected from a wide variety of different cloud types in both maritime and continental air masses and the ratio of ice to water in these clouds, averaged over areas representative of model grid boxes, has been related to the ambient air temperature and the cloud-top temperature. Figure 17 summarizes all

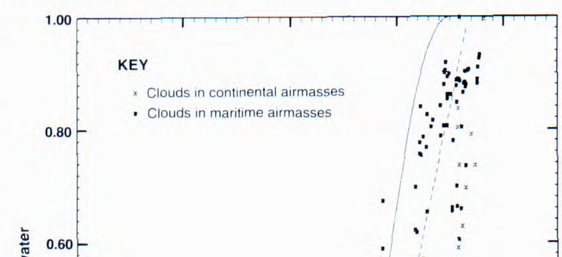

Figure 17. This figure summarizes all the flight data and shows how the ratio of ice to liquid water mass (for particles greater than 150 µm in diameter) varies with ambient air temperature.

the data from these flights and shows how the ratio of ice to liquid water mass (for particles greater than 150 μm in diameter) varies with ambient air temperature. The results indicate that, for these relatively large particles, the parametrization currently used in the Unified Model converts water to ice at too low a temperature.

Surface, boundary-layer and convective processes.

Changes in the climate are expected to have effects on vegetation which, as well as being directly important for human activity, may in turn affect the climate. Climate models represent the land surface through model parameters which depend on vegetation type. Currently these do not vary with time but work is in progress to allow them to interact with atmospheric and soil variables on a range of time-scales. On the time-scale of minutes to hours the resistance to evapotranspiration varies as the leaf stomata open and close in response to environmental factors such as soil moisture and radiation. A parametrization of this resistance, calibrated with data measured by the Institute of Hydrology, is being incorporated in the model. On the time-scale of months to years vegetation grows or decays. A parametrization linking these processes with the carbon cycle, as influenced by the model's changing climate, is being developed with guidance from ecological modellers.

The model's representation of the transfer of heat and moisture at the land surface is being reviewed. There are several problems with the present methods: surface temperature represents a finite layer of soil, whereas an interface temperature would be more appropriate for radiation and for inclusion of a vegetation canopy; snow should be allowed for as a separate layer in order to predict the seasonal snow cover realistically; and seasonal soil freezing and the permanently frozen soil (permafrost) which covers large areas of the land surface need to be represented – this last topic may be important for the atmospheric methane balance if permafrost melts due to climate change. Research on these topics has included development of a method for calculating surface fluxes, based on the approach devised by Penman and Monteith, which avoids using a prognostic equation for surface temperature and can be extended to include a separate energy balance for a vegetative canopy. A numerically accurate way of calculating heat flux through a layer of snow is being developed, and problems of representing permafrost and associated methane release are being studied in collaboration with the University of Cambridge.

Boundary-layer turbulent mixing and convection are the main processes which link the surface to the troposphere. The way the model's boundary-layer mixing and convection schemes interact is being studied with the aim of improving both the simulated boundary-layer structure and the initiation of convection. A promising revision to the way turbulent mixing is done in unstable conditions is being tested. An important feature is the scheme's ability to recognize when the unstable layer can deepen within a model time-step. A version of the convection scheme incorporating a representation of downdraughts associated with deep clouds has been tested in the climate configuration of the Unified Model. In convective regions the boundary layer is warmed and dried by inclusion of downdraughts; model temperature biases are reduced in mid-latitudes and in the upper tropical troposphere. Another important but unrepresented convective feature is anvil cirrus associated with cumulonimbus clouds. Initial results of representing these show that the scheme can simulate the upper-level heating associated with anvil clouds and the lower-level cooling due to evaporation of precipitation.

Global Precipitation Climatology Programme

Development of physical parametrizations, especially for convection, requires reliable data on the distribution of precipitation. Provision of this is the aim of the World Climate Research Programme (WCRP) Global Precipitation Climatology Programme (GPCP). Satellite imagery data, with their excellent global coverage, can be used to augment the sparse network of rain-gauge measurements of precipitation. It is crucial for the success of the WCRP Global Energy and Water Cycle Experiment (GEWEX) that these space-based estimates of precipitation are as accurate as possible and that their error characteristics are well understood. A project to compare various methods of estimating precipitation from satellite imagery was started in the Short-Range Forecasting Research division of the Met. Office, in conjunction with the GPCP. This project focuses on weather patterns in extratropical regions; another, run by the Japan Meteorological Agency, concentrated on tropical weather conditions.

Satellite images covering much of north-west Europe during the period 1 March 1991 to 9 April 1991 were received, processed, quality-controlled and dispatched to the 19 laboratories participating in the project. The data comprised conventional images from polar-orbiting satellites and from Meteosat, the European geostationary satellite. Also provided, by courtesy of the US National Oceanographic and Atmospheric Administration, were data from a special microwave instrument with channels chosen especially to measure precipitation. Other supporting data were also provided, including numerical weather analyses from a number of global centres.

Most of the images were collected in near real-time using the Met. Office's dedicated satellite images processing system, known as Autosat-2. Additional raw data were provided by the University of Dundee and by the European Space Operations Centre in Darmstadt, Germany, before being processed by the Met. Office.

Each laboratory will provide estimates of hourly and daily rainfall, or instantaneous rainfall rate, depending upon the type of the imagery. These estimates will then be compared with an extensive set of ground-truth data based on rainfall radar measurements and rain-gauge observations. It is expected that the information obtained will enable researchers to improve their algorithms, and hence allow better estimates of global precipitation to be determined.

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

A current concern in climate modelling is the low horizontal resolution employed for the oceanic component of the present generation of global models. In the Met. Office model, for example, this is the same as that of the atmospheric model, 2.5° latitude × 3.75° longitude. Ocean models run on such coarse grids cannot resolve important oceanic features such as the Gulf Stream. Increased computing power means that we can now look to improving the resolution of the oceanic component of coupled models. For this reason a 1° × 1° global model has been developed, and is currently being used in parallel integrations with the coarse resolution model. Figure 18 shows currents in the North Atlantic from both models, illustrating the much more realistic definition of the Gulf Stream in the 1° model. This improved representation of boundary currents should, in turn, lead to improved horizontal heat transports by the ocean model and, when coupled, to improved climate simulations. Work to include ice dynamics in the coupled model is also underway, based on a model of free drift, modified by a simplified representation of the ice pack's internal stresses .

A major task over the past year has been to finalize work to incorporate the ocean models into the unified model framework within which they may be run in stand-alone mode or coupled to the atmospheric model. As part of the Unified Model

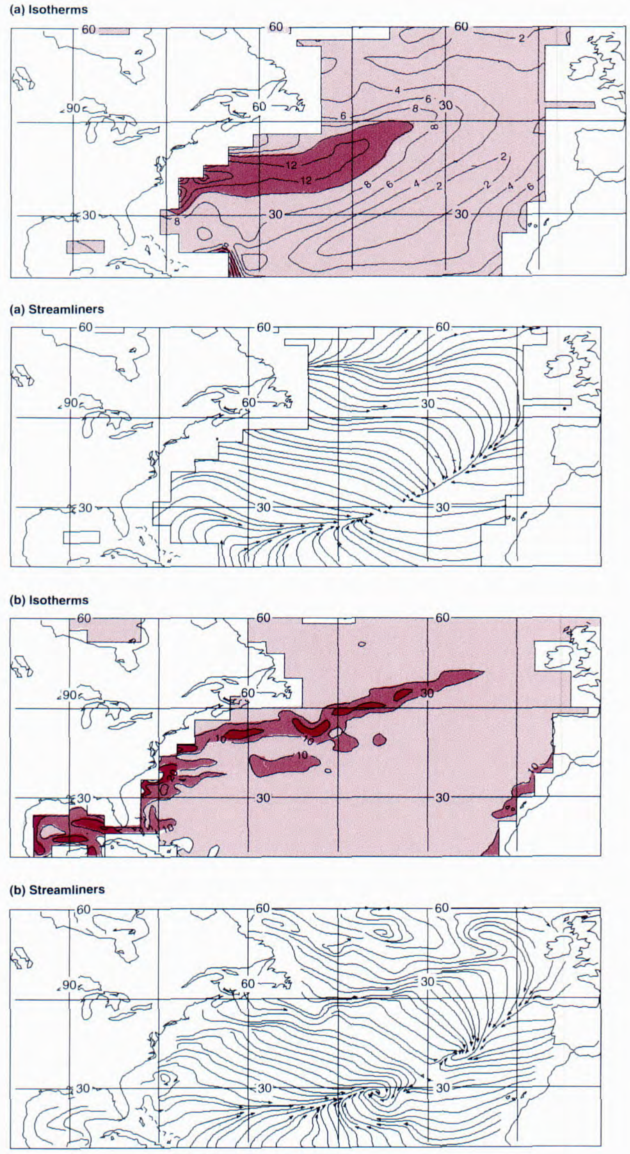

Figure 18. The currents in the North Atlantic from both models, illustrating the much more realistic definition of the Gulf Stream in the 1° model (b) when compared with the old model (a).

development, the number of vertical levels in the ocean model has been increased from 17 to 20. The additional levels have been positioned to give better resolution of the bottom topography and thus of the flow around it. Alternative formulations of the vertical coordinate system used in ocean models are being explored in a collaborative project with the James Rennell Centre for Ocean Circulation, Southampton, in which models formulated in 'isopycnic' and 'level' coordinates are being intercompared on a 1° resolution grid for the Atlantic Ocean.

An increasingly important component of studies of climate change is modelling of the carbon cycle. Work is being carried out to develop an ocean carbon cycle model suitable for use in GCM experiments. This also forms a collaborative project with both the James Rennell Centre, and Plymouth Marine Laboratory.

The long time-scales (decades to centuries) associated with processes in the deep ocean mean that integrations of global ocean models are costly. A more economical version of the ocean model for a limited domain (60° longitude × 70° latitude) and with a simple geometry has therefore been developed to provide a test-bed facility. This simplified version is currently being used to study techniques to speed up the approach of the model to equilibrium, to explore other eddy viscosity formulations and to assess sensitivity to vertical and horizontal resolution, prior to implementation in the full global model.

A major signal in the variability of the climate system on interannual time-scales, important for seasonal prediction, is that of the El Niño-Southern Oscillation (ENSO). It involves coupled interactions between the tropical ocean and global atmosphere. These are being studied using high-resolution ocean models of the Indian and Pacific Oceans, a fully coupled Tropical (Pacific) Ocean-Global Atmosphere (TOGA) GCM, and simplified models of the coupled system. The work is carried out in collaboration with the Robert Hooke Institute, Oxford.

Earlier results with the coupled TOGA GCM run on the Cyber 205 showed good simulation of the seasonal cycle of tropical Pacific sea surface temperatures, but did not reproduce the expected ENSO signal. Work to carry out similar experiments, including hindcasts of ENSO events, with the new unified model version is currently under way. As part of the preparation for these coupled runs, the response of the atmospheric model to anomalies in sea surface temperature fields has been studied and shown to be satisfactory, in particular in respect of responses in the surface wind fields over the tropics. The unified model version of the Pacific Ocean has also been used to contribute to an international intercomparison study of tropical ocean models.

Work on simplified models of the coupled system has proceeded along several fronts. It has included further development and testing of a new two-layer ocean model, which was shown to reproduce the major ENSO events of the 1980s successfully, development of a new simplified atmospheric model and work on basic ENSO mechanisms.

Coupled model development

A new coupled ocean-atmosphere model has been developed to run on the CRAY computers. The atmospheric model, developed for both numerical weather prediction and climate research, has 20 levels and uses a more efficient dynamics scheme. New physical parametrizations of cloud, boundary layer and convection are being introduced as they become available. For climate work, a horizontal grid of about 280 km will generally be employed, though short experiments have been run at higher resolution. The ocean model also has 20 vertical layers, and now includes the effects of river run-off on salinity. Initially, the ocean component is being run at the same horizontal resolution as the atmospheric model, though the grid length can be reduced if it is found to lead to a sufficient improvement in coupled simulations.

Coupled climate models commonly exhibit a tendency for their climates to drift towards an equilibrium different from the observed. By improving the models it is hoped to reduce this drift to an acceptable level. In the meantime, it is necessary to correct for the drift. This is achieved by modifying the energy transfers between the atmosphere and ocean so as to maintain the observed climatology with present-day radiative forcing. The same 'flux corrections' are applied when the forcing is perturbed, for example with an increase in CO_2. Implicit in this approach is the assumption that the model errors responsible for the drift remain the same in the perturbed climate. Much attention has been given to the best way of specifying these corrections near the sea-ice edge.

Regional climate modelling

Current global climate models (GCMs) have horizontal spatial resolutions limited by computer resources to a few hundred kilometres. Though this is sufficient to capture large-scale flow features, many climatically significant surface features are not resolved. Also, for climate change studies it is insufficient for direct predictions on scales applicable to the biosphere.

The Met. Office is addressing this problem by considering ways of obtaining finer-scale information. One method is to nest a higher-resolution regional model within the climate GCM; this is being implemented by deriving boundary conditions from the GCM to drive a version of the limited area forecast model. A second method being investigated is to use empirical formulae derived from relating large-scale flow patterns to surface observations.

The regional model has a 50 km resolution which allows a much more realistic representation of mountains and coastlines. Soil and vegetation variations are better resolved and climate change predictions on this scale are more useful in impact studies. Initial work has been encouraging with the model producing a broadly similar large-scale flow in the two models, but with more detailed features in the regional model; for example, rainfall is enhanced on the upwind, and reduced on the lee side of the Scottish mountains.

Seasonal forecasting

Seasonal forecasting research is currently confined to the tropics and has been developed because of increasing evidence that interannual variations in the tropics are linked to variations in sea surface temperature (SST). Research has concentrated on rainfall in the sub-Saharan region of North Africa, which has a wet season mainly from July to September, and the northern Nordeste of Brazil, where the wet season peaks in March to May. Both regions are subject to large interannual fluctuations in wet season rainfall and the Sahel also experiences longer-term variations.

A large number of climate model experiments indicate that Sahel rainfall can be well simulated in most years when the global patterns of SST anomalies are known. The atmospheric mechanisms producing Sahel drought in the model have been studied. There is evidence for a pattern of atmospheric variability extending throughout the tropics, hitherto little suspected, which includes the Sahel, the Caribbean, the Indian Ocean and the tropical West Pacific.

Empirical studies support the link with global SST patterns. Statistical prediction models have been developed based on SST patterns observed in the months before the main rainfall season. However, although these patterns often persist for several months, the statistical methods may fail when SST persistence is poor. A statistical method has therefore been devised, for predicting sea surface temperature in the Sahel wet season from temperatures and surface pressure patterns measured in the previous spring. The climate model has also been used to make predictions of Sahel rainfall, but it is more sensitive to SST changes. It is most useful near the beginning of the rainfall season when its skill is quite high. For the northern Nordeste, only statistical models are used.

The forecasting techniques have been tested on past data and useful levels of predictability have been found for rainfall in both regions. Forecasts have been issued in real-time for the Sahel since 1986 and for the northern Nordeste since 1987 in terms of five climatologically equiprobable rainfall categories. The real-time forecasts now consist of a preliminary forecast issued several weeks before the rainfall season starts followed by an updated forecast issued as the season starts. All five Nordeste forecasts show skill (Figure 19a) but the skill of the Sahel forecasts is more mixed (Figure 19b). The failure of the Sahel forecast in 1988 was linked to large and rapid changes in SST anomalies in the tropical Pacific Ocean and elsewhere. Such failures highlight the need for accurate SST prediction.

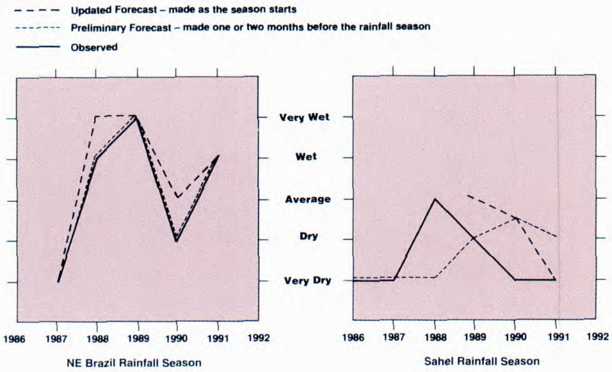

Figure 19. Results of recent seasonal forecasts.

Middle Atmosphere

The dramatic thinning of the ozone layer in the stratosphere over Antarctica during spring is a clear sign that man's activities are having a long-term damaging effect on the Earth's atmosphere. The discovery of this 'ozone hole' has led to international agreements to ban or limit the release of CFCs which contain the chlorine that does the damage. However cut-backs in emissions will not quickly reduce concentrations of these gases in the stratosphere, because of their long lifetime. Research has therefore continued apace to study the phenomenon in order to learn whether an ozone hole will form over the Arctic, and whether serious ozone depletion might also occur over populated regions at lower latitudes.

In response to concern about the ozone layer, the US space agency, NASA, led a project to develop an Upper Atmosphere Research Satellite (UARS). Several teams of UK scientists have participated. The satellite, launched from Cape Canaveral in September 1991, carries instruments which make measurements in the stratosphere and mesosphere (roughly 8 to 80 km) of temperature, wind, and the concentrations of a range of trace chemicals including ozone and chlorine-containing compounds. Simultaneous observation of a wide range of meteorological and chemical data provides unprecedented opportunities for research into the complicated interplay of meteorological and chemical processes that determine the ozone distribution.

As its contribution to the UARS project, the Met. Office undertook the challenge of combining all available meteorological data from the UARS and other sources, and some of the chemical data to produce a three-dimensional view of the evolving state of the middle atmosphere. The technique used is that of data-assimilation in which observations are combined with data from a numerical model as the model marches forward in time. For the UARS project, a version of the Office's Unified Model was developed, which has 42 levels from the ground to the lower mesosphere (about 50km, and a horizontal grid of 2.5° latitude 3.75° longitude.

As a prelude to assimilating UARS data, observational data from radiosondes and weather satellites are currently being assimilated. Global analyses of the troposphere and stratosphere are produced daily and sent by electronic link to NASA's Goddard Space Flight Center. Scientists involved with instruments on UARS are using the data to help validate their measurements (a useful by-product of data assimilation is error statistics for both the observational data and for the numerical model). Theoretical investigators, including those at the Met. Office, are using the data for studies of transport, dynamics and photochemistry.

In the near future, such maps will be augmented by data from the UARS. The immediate goals are to assimilate data from temperature and wind measuring instruments into a new version of the Unified Model which extends well into the mesosphere. Later on, long-lived chemical species will also be assimilated. One of these will be ozone in the lower stratosphere.

Basic dynamical processes in rotating fluids

The Met. Office research on the basic dynamics of rotating fluids, started in 1967, was transferred to Oxford University at the end of the year. Raymond Hide founded his laboratory for research into geophysical fluid dynamics for projects involving:

(a) laboratory experiments with thermally or mechanically driven fluids;

(b) associated numerical modelling and theoretical studies of non-linear dynamical systems,including chaos;

(c) studies of the dynamics of planetary atmospheres (Venus, Mars, Jupiter, etc.);

(d) studies of irregular fluctuations in the Earth's rotation (and their implications for dynamical meteorology, oceanography, etc.).

The work on Earth rotation fluctuations and their meteorological implications ((d) above) has been pursued in close collaboration with meteorologists, geodesists and oceanographers in various

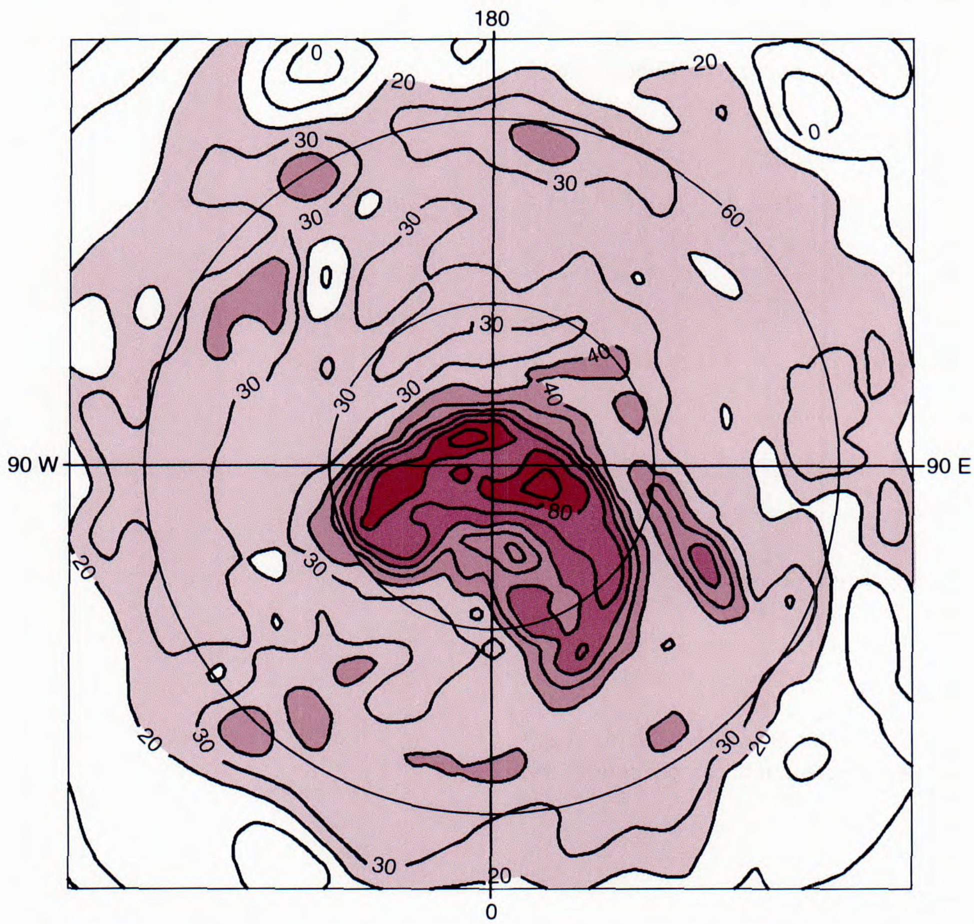

Figure 20. The figure shows a large tongue of air being severed from the main westerly vortex. If significant ozone loss were to occur in the polar vortex in the northern hemisphere, such a process could take ozone-depleted air to lower latitudes.

institutions. New lines of research in this area were opened up about 15 years ago, which led to developments in international cooperation under the auspices of IUGG and IAU. The work exploits technical advances in practical meteorology and geodesy and continues to produce significant findings in meteorology, oceanography and other branches of geophysics. In the past year, for example, a dynamically significant phenomenon in the atmosphere, namely global teleconnections on interannual time-scales involving the slow propagation of signals from tropical regions to higher latitudes in both hemispheres, has been discovered. Current investigations focus on whether the phenomenon is excited by fluctuations on much shorter intraseasonal time-scales. The ability to reproduce these interannual and intraseasonal fluctuations in the numerical climate prediction models being developed in various meteorological centres would constitute a stringent test of the models.

External liaison

There are active links between the Hadley Centre and other groups in the UK involved in research on climate change. These groups may contribute to the development of the models; they may provide data needed for monitoring climate; or they may require output from model predictions for their studies of the impacts of climate change.

As part of the DOE-funded Climate Prediction Programme within the Hadley Centre, there is an active programme of exchange visits. During 1991 the main effort was to summarize the research currently being undertaken on climate prediction by institutions throughout the world. Visits were made to the USA, France, Germany, China and Japan and, together with information obtained from visitors to the Hadley Centre, a report was prepared summarizing the international work on this topic.

During these visits the opportunity was taken to establish and build on existing collaboration. In subjects where there is common interest and research there are particular benefits in exchange visits. During 1991 some eight scientists (representing Australia, Kenya, Poland, Spain and the USA) made extended visits to the Hadley Centre and a further ten visitors are planning to come for periods of a month or more during 1992.

Intergovernmental Panel on Climate Change

The secretariat for the IPCC (Intergovernmental Panel on Climate Change), which is funded by DoE and located at the Hadley Centre, co-ordinated the production of a supplement to the 1990 IPCC WGI (Scientific Assessment) report. The supplement covered three main topics:

Greenhouse Gases, Sources and sinks, global warming potentials and emission scenarios;
Climate Models, Validation and climate prediction;
Climate Variability and Change.

It was issued in April 1992 with the supporting material due for publication in early May. During its preparation, three international conferences were organized - Taskforce on Greenhouse Gases (Shepperton, United Kingdom, July 1991), Modelling Lead Authors' drafting session (Bristol, UK, November 1991) and Climate Variability and Change Lead Authors' drafting session (Melbourne, Australia, November 1991). There were 118 lead authors and contributors from 22 countries, and the supplement was reviewed by a total of 380 specialists from 63 countries and 18 UN and non-governmental organizations.

POLLUTION ASSESSMENT AND PREDICTION

Noise pollution

Noise pollution is a problem for a number of MOD ranges. It is particularly pressing at Shoeburyness, where noise complaints have been received from as far as 50 km away. To assist the range authorities in minimizing noise nuisance, a noise assessment model is run routinely by the range met. office to help predict the noise levels in the vicinity of the range.

Since 1987 the Defence Services Division have been collaborating with the Department of Applied Acoustics, Salford University on a project sponsored by the MOD Directorate of Defence Health and Safety for the 'Development of an improved system for the prediction of atmospheric focusing of impulsive blast noise'. This work has led to the development of an improved acoustic prediction model. The new model is a hybrid ray invariant/parametric model and is expected to give more reliable predictions.

During spring 1992 the new model was installed at Shoeburyness met. office for a validation trial. Remote Monitoring Units (RMUs), developed by Salford, were set up on the range to give noise measurements along a 10 km line. The RMUs, together with the new Shoeburyness noise monitoring system, will enable the various noise models to be assessed.

In parallel with this trial, the impact of low-level wind data from a Doppler sodar on the acoustic predictions is being evaluated. It is expected that these data will be needed to realize the benefits from the more sophisticated models being developed by Salford, i.e. the hybrid model and the more advanced field (Fast Field Prediction and Parabolic Equation) models which are currently under development. Also, it is planned to assess the usefulness of profiles from the Mesoscale Model for acoustic forecasting. These trials are progressing and the data are being collected; it is expected that the results will be available by autumn 1992.

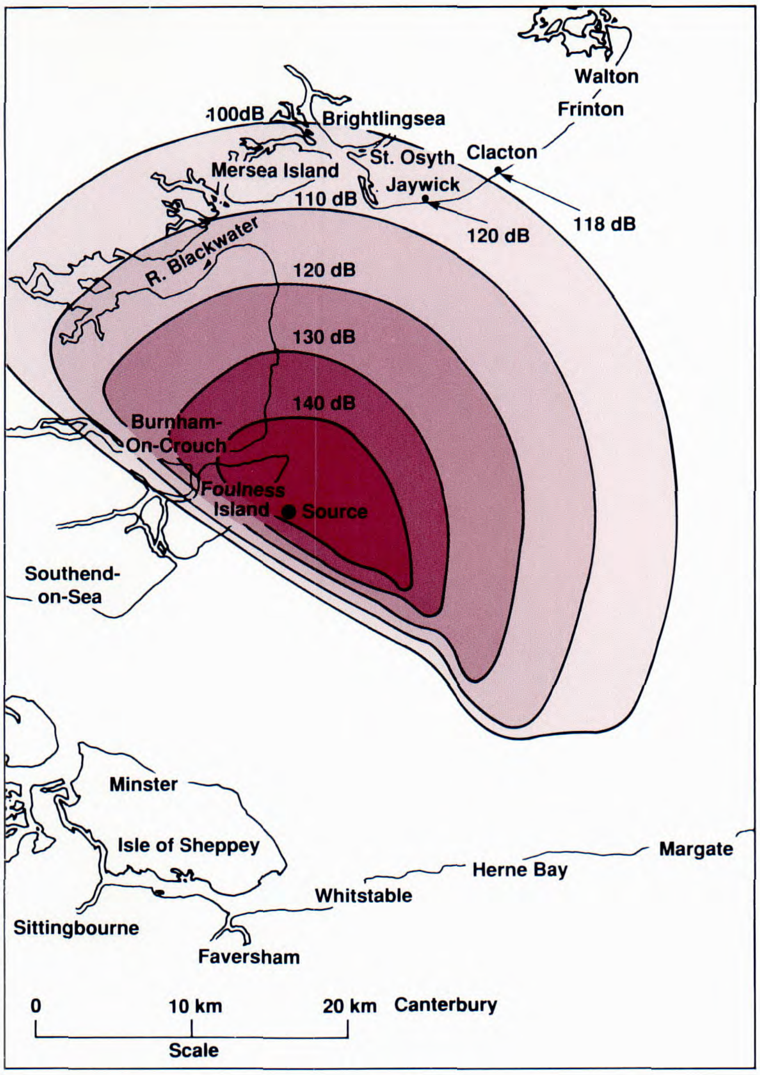

Figure 21. Showing the acoustic model prediction for Shoeburyness for 1200 UTC on 12 February 1992. Contours show the predicted peak sound pressure levels (in dB) around the source. Actual noise measurements made at Clacton and Jaywick are shown.

Short-range dispersion modelling

A collaborative project is being undertaken with Cambridge Environmental Research Consultants Ltd. and National Power PLC to develop a general purpose short-range dispersion model. The model, which is known as the UK Atmospheric Dispersion Modelling System (UK-ADMS), will be completed later this year. It is designed to run on IBM-compatible PCs and is modular in form, both in order to make the model flexible and to enable future improvements to be incorporated easily. It is a development of the Gaussian-plume type of model in that analytic profiles are used rather than solutions to differential equations. The modular nature of the code (which means, for example, that the terrain module can be omitted if one is considering flat ground) enables the model to run reasonably quickly. As a result many different weather conditions can be simulated to build up dispersion climatologies. However, in contrast to most Gaussian plume models, it takes advantage of a number of recent improvements in our understanding of dispersion and of the atmospheric boundary layer. Perhaps the most important, example of this concerns the scaling of the boundary layer; this is now well understood and has been incorporated in UK-ADMS. This is especially important in convective conditions as traditional models can be very inaccurate. The prediction of fluctuations is also included – perhaps for the first time in such a model.

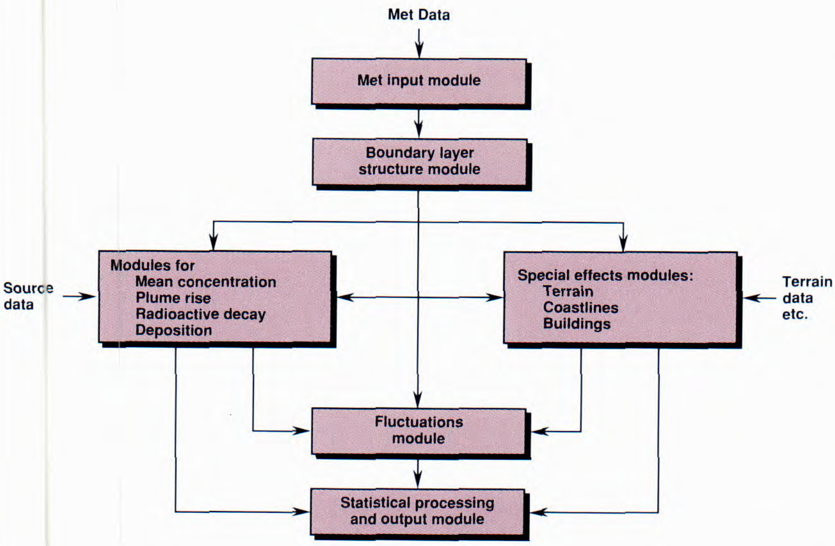

Figure 22. Schematic illustration of the modular structure of UK-ADMS and of the data-flows within it. All the data transfers are actually carried out via the main control module (not shown).

Mean and fluctuating pollution concentrations

The investigation of short-range dispersion has continued with both ensemble mean concentrations and fluctuations about the mean being investigated. Mean concentrations have been investigated using large-eddy simulations and random-walk models. In the course of this study a new random-walk model has been developed to simulate dispersion throughout the depth of the atmospheric boundary layer in a range of atmospheric stability conditions from free convective to neutral (previous models have only been able to deal with certain limiting cases). One surprising result is that adding a mean wind to a free convective boundary layer tends to decrease the rate of vertical dispersion, despite the fact that the rate of production of turbulent energy increases. This is because the wind shear tends to disrupt the large-scale convective motions and so reduce the turbulence length-scale.

A knowledge of concentration fluctuations is important for many applications in which short-duration peaks of high concentration are more significant than the long-period average. Examples of such applications include the dispersion of flammable or odorous gases, and of many toxic gases, such as chlorine, for which exposure to such short peaks is far more hazardous than longer periods of lower concentration. Work in the 1991/92 period has been directed at extending our general knowledge of concentration fluctuations to include conditions of particular importance in practical applications and certain detailed features of plume structure.

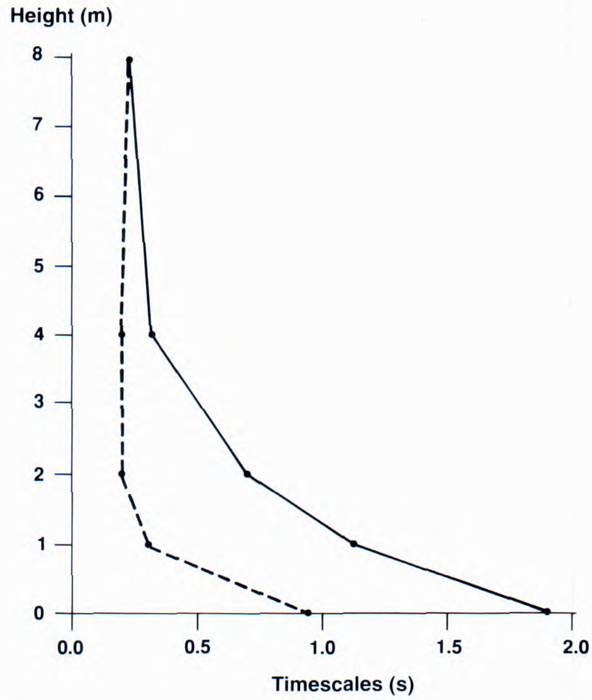

Figure 23. Vertical profiles of the integral time-scale of concentration fluctuations through two dispersing plumes from sources at heights of 0 m (solid line) and 4 m (dotted line). The measurements were conducted at 50 m downwind of the sources in a wind of about 10 ms^{-1}.

The highest peak and time-averaged concentrations occur in light wind conditions at night, and a detailed analysis of experiments conducted in such conditions has been completed. Fluctuations were found to be very similar to those in daytime windy conditions in many respects, but peak concentrations were found to be higher relative to the mean and also to last longer, making them significantly more dangerous. Most experimental measurements of concentration fluctuations have been made over flat open terrain to minimize their complexity. However, many practical dispersion problems occur in urban areas, and experiments measuring the effect of a group of building-like obstacles on plume dispersion, conducted in collaboration with the University of Cambridge, have been analysed. The intense turbulence within the wake regions downstream of the obstacles was found to have a major effect in reducing concentration fluctuations in the plume. Time-averaged concentrations were not significantly affected.

Analysis has also been completed of experiments designed to measure the variation of concentration fluctuations with height above the ground. The fluctuation time-scale is much longer low down, and indeed the increase near the ground is greater than that due simply to the change in wind speed with height. This is believed to be due to enhanced small-scale turbulence which has smoothed out much of the fine structure of the plume. Time-scales are also generally longer for a source near the ground than for an elevated source, due to greater small-scale mixing near the release point.

Other experiments have measured fluctuations at very high frequencies using a different detector from the type normally used, and analysis of these has helped to confirm the validity of results from previous experiments.

Tropospheric chemistry

Atmospheric chemical processes can influence radiatively active (greenhouse) gases in two main ways. Firstly, the atmospheric lifetime of some gases (e.g. methane, HCFCs and HFCs) is governed by the concentrations of highly reactive species, principally the hydroxyl radical (OH). Secondly, the local concentration of ozone depends on a complex combination of photochemical reactions leading to net ozone depletion in the stratosphere but net ozone production in the troposphere.

The chemistry programme at the MRF is aimed at identifying the distribution of several of the chemically significant species and elucidating their role in the chemistry of the troposphere. This is being done by a combined programme of aircraft measurements from the C-130, data interpretation and Lagrangian photochemical model studies constrained by the aircraft observations. To the MRF airborne measurements of hydrocarbons, ozone, and other photo-oxidants, are added those of hydrogen peroxide made by the University of East Anglia, and nitrogen oxides and actinic flux made by the Forschungszentrum in Julich (Germany).

Work during 1991 concentrated on four topics:

1. The continuing analysis of flights in 1990 over the North Atlantic, where aircraft measurements of ozone and its precursors have been compared with Lagrangian model simulations.

2. An investigation of the differential removal of reactive hydrocarbons by hydroxyl radical attack, using samples collected in the smoke plume from Kuwait.

3. An observational study of the summertime transport of ozone from the stratosphere during tropopause folding and cut-off low events, as part of the EC 'Transport of Ozone and Strat-Trop Exchange' project.

4. The relationship between photochemically active gases in different meteorological situations (vertical transport in clouds, low-level transport in anticyclonic conditions) measured in a number of successful flights in June/July 1991.

The EC have recently selected the 'Oxidising Capacity of the Tropospheric Atmosphere' project for funding, which will allow Dr D. McKenna of MRF to coordinate the participation of several European countries in the North Atlantic Regional Experiment in 1993.

Nuclear emergency response system

In January 1988, following review of the Chernobyl incident, the Government published a National Response Plan (NRP) to deal with the consequences for the United Kingdom of overseas nuclear accidents. The main component of the NRP is a national radiation monitoring network and nuclear emergency response system known as RIMNET (Radioactive Incident Monitoring NETwork). A number of Government Departments and Agencies are involved in the NRP, including the Met. Office, with the DoE (HM Inspectorate of Pollution) nominated as the lead authority.

The Met. Office is involved because of its (relatively) evenly distributed network of observing stations, at which sensors monitoring levels of gamma radiation are located. Under RIMNET Phase 1 (which became operational in August 1988) 46 UK Met. Office observing enclosures were fitted with sensors. Phase 2, due to become operational in summer 1992, has sensors installed at 85 Met. Office and 2 Royal Navy locations with a further 5 at various MoD establishments.

Under Phase 1 the reading was taken manually once an hour and attached to the routine observation. Phase 2 is fully automated, with the sensor polled once an hour by a central computer at the DoE where the data are stored in the Central Database Facility (CDF). The sensors can be interrogated more frequently, should the need arise.

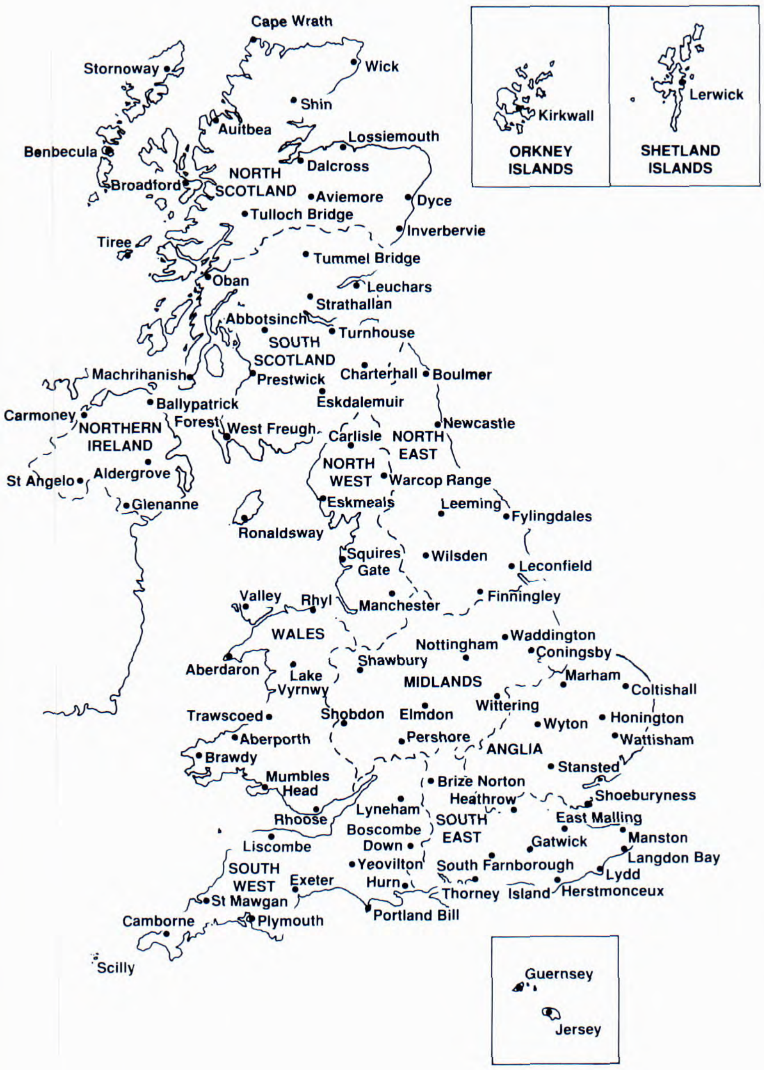

Figure 24. Phase 2 RIMNET monitoring sites and bulletin regions.

In the event of an overseas nuclear accident threatening the United Kingdom, an emergency briefing centre—the Technical Coordination Centre (TCC) would be opened and manned by the Department of Environment and various other Government Departments, including the Met. Office. The purpose of the TCC is to collate all relevant information (including that from the 92 RIMNET sensors) and to brief Government ministers, emergency services and media accordingly.

A further role of the Met. Office under RIMNET Phase 2 is to make output from the NAME model available to the TCC. This model is run on the Met. Office central computer, and provides plume analysis, its expected movement and deposition up to 6 days ahead, and, if necessary, hindcast analysis as well. Data from this model will be sent to the CDF and displayed on the computer system in the TCC. Advice on this output, along with comment on the routine weather forecasts, will be provided by the Met. Office representative.

The Nuclear Accident Modelling Exercise: 'NAME' model

NAME is an essential component of the contingency plans (a) to provide early warning for the guidance of emergency services and (b) to predict concentrations, depositions and dosages of radionuclides as input to risk assessment models (e.g. for foodstuffs). It is an important tool for accident analysis, and available for use in major emergencies of a non-nuclear nature—for example, the release of toxic or hazardous chemicals, or volcanic effluents of concern to civil aviation.

NAME is a 3-dimensional Lagrangian model based upon on-line meteorological data from the operational NWP models, which uses particle methods to simulate the spread of pollutant plumes in the atmosphere. The use of large numbers of particles allows for both turbulent diffusion and, over longer times, the effects of the synoptic-scale distortion of the motion fields, to be represented in a realistic way. The particles are released, suitably weighted, into the 'model atmosphere' in accordance with a reported or estimated emission profile. Concentrations in air are calculated at various levels, together with both wet and dry deposition to the surface. The model can be run in hindcast or forecast mode, and repeatedly updated as fresh meteorological data become available. A back-trajectory facility can be used to give guidance on the possible origins of a cloud of radiation.

The Chernobyl incident underlined the critical importance of the wet deposition processes. In order to provide a timely analysis over NW Europe, hourly rainfall rates for the last 10 days are stored on-line. This archive combines weather radar imagery of about 5 km resolution and satellite imagery, supplemented as necessary by NWP products. Surface observations are used in a verifying role. This facility is updated in near real time. Indeed, the on-line facilities available to NAME taken with the operational backup provided by the Met. Office are probably unmatched at present. The parametrization for wet deposition incorporates the results of research undertaken for the Met. Office by the University of Manchester Institute of Science and Technology. Recent additions include: the scavenging of pollutants by snow, orographic enhancements to precipitation and the turbulent deposition of cloud-borne pollutants over high ground.

Other advanced features of the model consist of automated techniques to adjust the modelled plume spread and reinterpret the source profile in the light of actual observations of radioactivity.

Areas of particular uncertainty – along the path of a fast-moving depression, for instance – can be handled by increasing the model diffusivity in line with the wind vector difference over the preceding 3 hours.

The model was used during the Gulf crisis to forecast the spread of pollutants from the oil fires, and the likely acid depositions. Extension of the model to allow global coverage was complete by March 1992. It received a 'baptism of fire' almost at once when an accident (subsequently adjudged minor) occurred at a nuclear power station near St Petersburg.

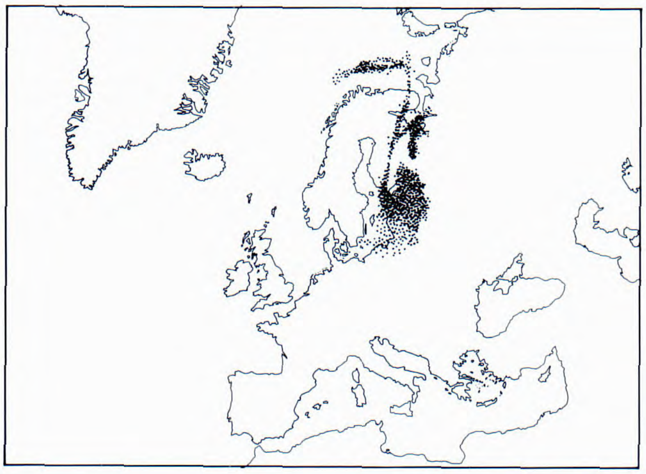

Figure 25. Five-day forecast of the threatened spread of ^{131}I from Sosnovoyy Bor: the instantaneous plume in the atmospheric boundary layer at 0600 UTC on 29 March 1992 is illustrated.

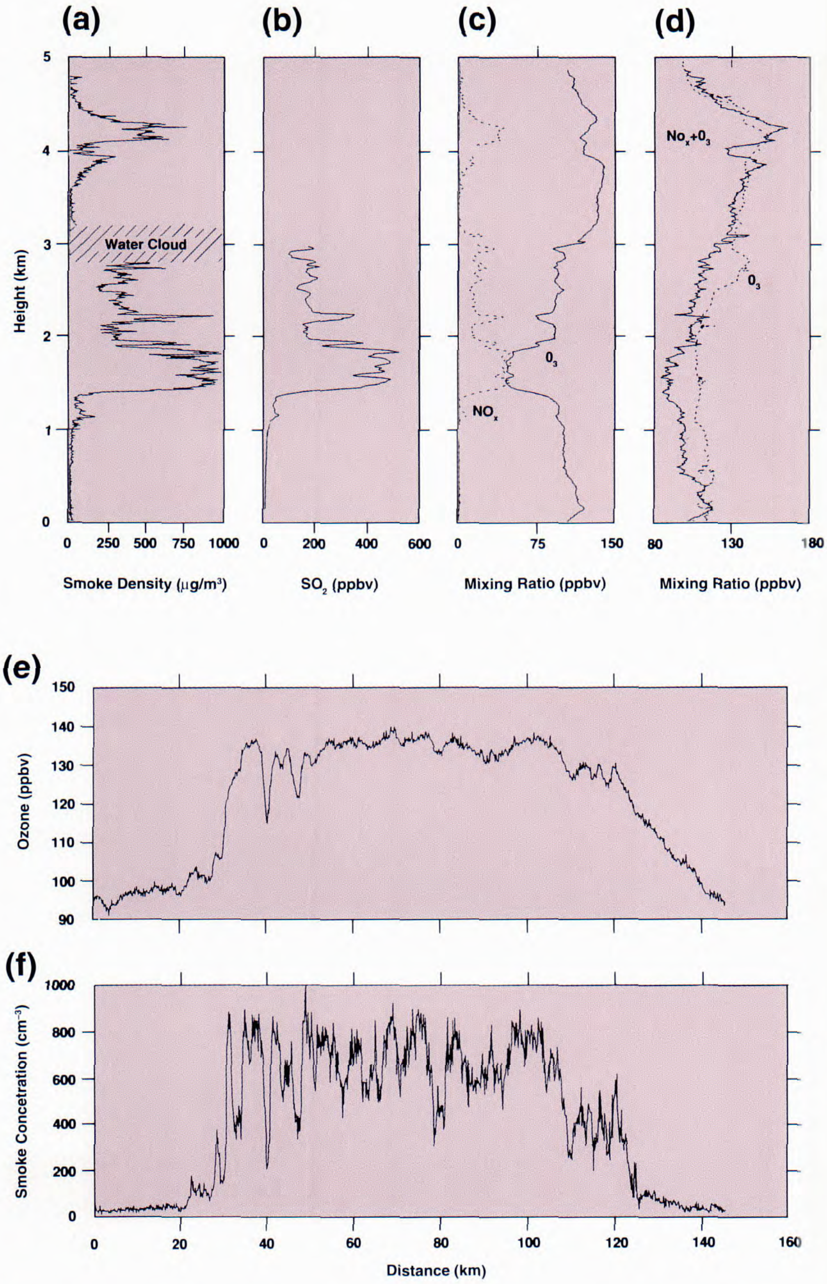

Figure 26. Examples of profiles found by the MRF C 130 on passes through Kuwait oil-smoke plumes. Vertical profiles are shown in (a) to (d) and horizontal ones in (e) and (f).

Characteristics of the smoke plume from Kuwait measured by the Met. Research Flight

In order to assess the environmental impact of the burning Kuwaiti oil wells (reported in the 1991 Annual Report) some assumptions about the physical and chemical characteristics of the smoke had to be made. To check many of these assumptions, and to provide observations of the plume to compare with model calculations, the MRF C-130 was detached to Bahrain in March 1991, soon after the wells had been set alight.

During the detachment over 50 hours of measurements were made in and around the plume, involving straight and level runs and rapid ascents and descents through the smoke at different distances from Kuwait.

Detailed measurements of wind vectors and two-dimensional structure of the plume were carried out by making multiple passes through the plume 100-200 km from the fires, allowing the sulphur flux in the plume to be estimated. From the known sulphur content of the fuel, the oil burning rate was estimated to be 4 million barrels a day (±40%); about twice the rate of the pre-war production of the oilfields. Emissions of nitrogen and particulate carbon were also estimated.

Measurements were also made in the plume over central Saudi Arabia, about a thousand kilometres from Kuwait, several days after it had been emitted. In contrast to the earlier flights, the concentration of O_3 in the smoke was enhanced throughout the whole depth of the plume due to production in sunlight from NO_x, and hydrocarbons collected in this area of smoke showed that the more reactive species had been severely depleted during the formation of the O_3 whilst the slower reacting species were much less reduced (see 'Tropospheric Chemistry' page 40)

Particles collected on filters deployed from the aircraft were examined under an electron microscope; they are built up from spherules of about 0.15 μm in diameter. Nearer the fires, these spherules are aggregated into chains a few microns long made up of several hundred spherules. At a distance of a thousand kilometres from the fires the bunches are more spherical, due to aging in air of high humidity.

Although the burn rate of the oil was greater than that taken in the modelling study (see below), the net effect of the smoke on solar radiation was similar to that assumed. The model prediction that the smoke would not get into the stratosphere (where it could cause global effects) was borne out by aircraft observations that the top of the plume never reached 5 km. Total CO_2 emissions were about 1% of other human-made sources during 1991; they would not have had a major effect on global warming. The larger sulphur emissions, on the other hand, mean that the acid-rain effects could have extended over a wider area than those predicted, although the dearth of monitoring in the region does not enable this to be confirmed.

The MRF airborne observations thus support modelling conclusions that, although effects of the smoke plume in the Gulf region could have been significant, those on a wider scale, such as the Asian monsoon and global warming, will have been insignificant.

Numerical modelling of the Kuwait oil smoke

As part of the environmental impact study of the burning Kuwaiti oil wells, the nonhydrostatic mesoscale model (15 km resolution) was adapted to run over the Gulf region and modified to allow prediction of the transport and diffusion of smoke away from specified source locations. Estimates had to be made of the source strengths and locations based on prior knowledge of oil production and, once the wells had been lit, on the basis of Meteosat satellite imagery. The resolution of the model was insufficient to allow studies of the initial plume rise, and of details of the flow and of the interactions between individual well fires, so sources of smoke were modelled assuming uniform injection rates in vertical columns up to specified tops. The tops were estimated from expected heat sources and a range of atmospheric boundary-layer stabilities, and also by comparing the forecast vertical wind profile with the direction of transport of the bulk of the observed smoke. In special runs of the model it was also possible to study the interaction of the smoke with solar radiation, and hence its effect on surface and boundary-layer temperatures, as well as the horizontal and vertical distribution of the smoke in the atmosphere within about 500 km of the oil fields.

The model was run twice daily throughout the year to provide guidance on the near-surface wind field and on the weather in the Gulf region. Predictions of the horizontal coverage of the smoke 30 hours ahead were also provided until the fires were finally extinguished in November 1991. During the year the model domain was enlarged (with a compensating reduction in vertical resolution) to allow coverage of Northern Iraq and Southern Turkey, and boundary conditions were obtained from the new global version of the Unified Model. By monitoring the predicted locations of the smoke during the spring and summer of 1991 it was found that they agreed well with satellite imagery and with the predictions from the Lagrangian NAME model. On many occasions the plume was correctly forecast to bifurcate as a consequence of vertical wind shear.

The model, in agreement with satellite imagery, sometimes generated cloud in regions of elevated smoke. Similar features were observed by the MRF aircraft during its detachment to the Gulf in March. Detailed comparisons with MRF data for 28 March 1991 showed that the model gave, (a) a good 30-hour prediction 120 km downwind of the presence of a layer of water cloud at 3 km, (b) a lower layer of smoke with peak concentrations at an elevation of 1-2 km being advected southeastwards down the Gulf, and (c) an upper layer between 3.5 - 5 km being advected eastwards. Discrepancies in the prediction of ice cloud and smoke concentrations were probably the result of limitations in the treatment of the combined interaction of smoke and cloud with solar radiation, in the specification of the source locations and relative strengths, and in the finite-difference methods used in the mesoscale model.

COMMERCIAL AND BUSINESS ENTERPRISE

The past year has seen substantial growth in revenue and contribution to core costs from commercial activities. It has been a period of very rapid development. In this brief Review we have selected a number of examples of new service concepts and initiatives which have contributed to the growth in our business during 91/92. We have also highlighted several organizational initiatives which have been targeted at improving the way in which we aim to meet customer needs.

Television services

The Met. Office provides services to the TV industry through two Business Units: International Weather Productions (IWP) and the BBC Unit.

Both have been involved recently in major studio development. In March '91 IWP moved its HQ to the INTERCHANGE, Camden, whilst the BBC designed and built its new Weather Centre. IWP offers a wide range of services and produces the ITV National Weather Forecast using Spaceward Weather-In-Vision graphics systems. The BBC Unit supplies forecasts for BBC national radio and, with the support of the BBC graphics workshop using a Quantel Paintbox, produces the BBC TV National Weather Service. Both services have expanded during the year. The BBC Unit now supplies forecasts for the new BBC World Service TV for Europe and Asia, whilst IWP supports the B-Sky-B weather service.

Much regional work is done from the Weather Centres and contracts have been won to supply forecasts to BBC North and BBC North West using Spaceward graphics systems installed at Leeds WC who already supply YTV.

IWP is supplying weather services to Granada TV through 'IMAGINET', a commercial co-development specializing in AppleMac technology. Internationally, services to Europe (particularly Norway) and the USA are also expanding.

These Business Units are supported by the Media Services Cell, based at Bracknell, which develops new TV products and maintains the weather graphics software running on the Office mainframes. Products are delivered to the front-end systems via BT dial-up lines and/or 9.6 k baud Kilostream links. Communications upgrades, using the Met. Office Phase 4E communications computers and 64 k baud ISDN and Kilostream lines, are under way and a new weather graphics system (GETMET), based on PC technology, is being developed. This system will be used at the INTERCHANGE and other selected Weather Centres in the UK in support of regional TV services.

New services for the press

Technical developments in the Press industry are such that most of our customers have moved, or are about to move, to computerized layout and typesetting, and many of these are also converting to colour printing or have already done so.

The difficulty in interfacing with the sophisticated and varied technology of our press customers has been solved by the signing of a commercial joint venture contract with Computer Newspaper Services (CNS) in Humberside. The main business of CNS is to prepare camera-ready listings of information (sport, financial, TV, etc.) for most major newspapers. This agreement now means that CNS take responsibility for the technological link with papers, all layout design, and sales and marketing of specialized weather graphics. The Met. Office concentrates on the daily provision of tabular and graphical information to CNS in a single package which will serve all customers.

Development of telephone services

Telephone forecasts continue to be managed by Telephone Information Services (TIS) in London, business partners since 1986. As with CNS, TIS take care of all the technology and marketing of our telephone products, whilst we provide a daily input of scripts from weather centres for recording. Development work is done jointly, an example being a current project to provide an hourly service of actual weather reports from around the UK using computerized speech. Further innovations may involve the use of speech recognition to select the information required, and the development of new services based on nowcasting techniques. Market research is to be undertaken to establish priorities for new services.

Development of Weatherfax for Farmers

Market research in the mid 1980s showed clearly that large farming businesses were not being adequately served by the Met. Office. Weather windows for planning crop spraying, harvesting and adverse weather were not being identified clearly. By obtaining such guidance farmers could manage their men, machines and chemicals more efficiently. In parallel with this need for greater detail came the development of modestly priced facsimile machines and computer-based faxing technology.

With the need and communication medium identified, the Weatherfax service was developed. At 6 a.m. each day it gives farmers an easily assimilated, but detailed, table of forecast weather conditions, tailored to their individual need. The computer automatically decides which weather elements, in up to 77 areas of Britain, need to be forecast, keeping production costs to a minimum. The computer then sends out the areas and elements requested by each of 100 or more customers.

The Weatherfax technique and system is now to be applied in other market sectors.

Services to the offshore, oil and gas industry

The North Sea is perhaps the most hostile environment in the world for the exploration and production of oil and gas for offshore locations. The Met. Office provides services for all stages of the process, mainly through two specialist units.

The Marine Products Group (MPG) at Bracknell quality control and store observations from vessels and installations at sea. Services for design and operational planning are produced from analyses of these data, along with post-operational performance. The North European storm study (NESS), a hindcasting design study sponsored by the major North Sea operators, is archived by the MPG, who also analyse the data for the users.

For operational forecasting services, the Offshore Forecasting Unit (OFU) was moved to Aberdeen Weather Centre in 1990. It provides day-to-day forecasting, aimed specifically at the needs of the industry. This may include sending a forecaster to an installation, and providing direct input into the client's decision-making process. All forecasting services depend critically on output from the modelling suite, particularly the wave models.

A range of new services is being developed, for example the use of probability forecasts, and to PC-to-PC communication of forecasts based on the 'MIST' concept.

Weather Consultancy to manufacturers and retailers

Weather affects business and now The Weather Initiative (TWI), a business Division of the Met. Office, has applied and developed its scientific understanding of meteorology and business practice to allow businesses to alter their decision-making processes. By use of multi-variate analyses, TWI has been able to demonstrate quantitatively how weather influences the purchasing decisions across a wide range of consumer items, particularly those related to food and beverages. The technique can be used either to isolate weather influences or can be extended to incorporate non-meteorological variables such as demographic and/or economic factors. The results from using this technique have already been used, for example, by a major soft drinks manufacturer to alter production and distribution schedules and by a retailer to adjust purchasing and promotional decisions. The technique is sensitive enough to cover variations between regional characteristics as well as coping with National coverage.

Selling expertise in organization and systems

Research and development have always been at the forefront of work in the Met. Office. The high reputation of Met. Office scientists is known throughout the world, but until recently their expertise was not available to others except on an informal basis or through very occasional collaborative scientific studies. In recognition of this gap in the services offered to industry and other scientific and technical organizations, a new consultancy service was established on 1 October 1991. The service, known as METSTAR (METeorological Scientific and Technical Advice and Research) Consultants, draws upon experts throughout the Met. Office, who agree to contract some of their time to particular projects within an agreed overall plan.

The new consultancy will seek commissioned R&D primarily in the fields of hydrometeorology, nowcasting, remote sensing, the environment (atmospheric dispersion and climate change) and meteorological systems, including the licensing of software. So far contracts have been won from EUMETSAT, the States of Jersey Public Services Department and several companies including Thomson-CSF (France), Logica and SD-Sicon. A small involvement in a CEC project studying polarization diversity radar is also to be undertaken. Many other bids are at various stages of preparation or evaluation, and METSTAR resources will be augmented as a function of the level of business it wins.

Working in Europe

The Office has been taking a leading role in opening up opportunities for the commercial provision of products and services by collaboration between National Met. Services (NMSs) in Europe. Considerable preparatory work was conducted through bilateral discussions and working-group meetings.

A major result of this initiative was an in-principle agreement in December 1991 by 17 countries to create an Economic Interest Grouping (EIG). The purpose of the EIG will be to: "enforce the WMO principle of free exchange between NMSs, ensure the ability of the NMSs to maintain their basic infrastructure according to their institutional goals, create the basis for fair competition in the field of meteorological services and give the necessary impulses in the fields of technological development and scientific research in order to improve both production and distribution of meteorological data sets and products". It is planned to reach final agreement by the end of 1992. Meanwhile, first commercial agreements with European NMSs have been negotiated, including the provision of substantial marketing consultancy and commercial training to other National Meteorological Services.

Monitoring skill and customer satisfaction

Objective assessments of accuracy and skill are being extended to several commercial services. For example, predictions of road surface temperatures, part of the OpenRoad Service provided by all Weather Centres, are automatically checked against observations to determine bias; predictions of frost on the surface are checked to find the percent correct, false alarm rate, probability of detection and the Heidke skill score. Also included is a comparison of the number of correct forecasts with those expected by chance. More complex measures (Brier scores) are made of accuracy and skill of probability forecasts. In all cases information is fed back to the forecasters enabling them to improve the quality of the forecasts.

Accuracy, presentation and timeliness of services are subject to routine assessment by almost 50 customers. They cover all market sectors and complete returns containing a six point marking system for services they receive over a 7-day period every 3 months.

Creating the Right Sales Environment

At the time of the Agency launch in April 1990, there were few dedicated sales staff. Since that time, the Sales Branch has been enlarged significantly, recognizing the need to commit specialized and technical sales effort in order to achieve ambitious growth targets. By April 1991, the Sales team consisted of a National Sales Manager and dedicated Commercial Manager located at each Weather Centre.

During the past year we have concluded that the sales force needs more structure. In the last quarter of 91/92 we have divided the United Kingdom into four sales regions each the responsibility of a senior Regional Commercial Manager who will manage three or four Commercial Managers and take personal control of some of the key accounts – for example in the sale of consultancy in the Retail and Manufacturing Sector. Key account management techniques are being developed, particularly with relation to the targeting of potential new clients of commercial or strategic importance to the Office. Significant efforts have been devoted to sales training, and a four-monthly sales conference is held to ensure maximum two-way flow of market intelligence and to brief the sales team on new products and services.

Corporate Communications

Corporate Communication serves the media, our marketing and commercial managers, professional meteorologists, and Met. Office staff more generally.

The Press Office and its Press Agency obtained a high level of favourable coverage in the national and trade media during the year. It dealt with some 5000 enquiries, and continues to maintain the Met. Office as an authoritative source of weather information, respected by national press, radio and TV journalists. Strong links are now established with educational programme makers, particularly BBC TV.

The new *Meteorological Glossary* was published, and amendments were produced to a range of meteorological publications and reports, including *Marine Observer's Handbook* and *Handbook of Aviation Procedures.* Annual rainfall and snow surveys were printed, as were monthly weather reports, *Meteorological Magazine* and the commended *Annual Review, Report and Accounts 1990-91.*

The internal staff magazine, *Mercury,* has been upgraded and a new digest of scientific and technical presentations and publications successfully piloted. Our high quality, colour, news magazine, *Outlook,* promotes the Office's interests to our customers, while providing valuable marketing information.

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This article by G. Holpin and R. Bosworth is reproduced from *The Meteorological Magazine* of July 1991. It illustrates an aspect of our work on the Gulf oil smoke plumes mentioned earlier in this Review.

Meteorological satellite imagery of the Persian Gulf area continues to show the effects of the many oil fires that are still burning in Kuwait. The smoke plumes have been seen to extend many hundreds of kilometres and one example of this can be seen in the images shown here.

The two reprojected visible Meteosat (Overleaf) are products from the Meteorological Office's dedicated satellite-image processing system, Autosat-2. They show the type of imagery used within the Nowcasting Section of the Short-range Forecasting Research Division to monitor routinely the extent of the smoke over the Gulf Region. This task was initiated in January this year, when smoke was first apparent in satellite imagery.

The plume shown (formed by the smoke from the 500 oil fires reported to be still burning in the area), extended southwards at a rate of 15 kn, consistent with the winds below 850mb (5000 ft), as shown on the tephigram (fig. 27).

In the 1300 UTC image (Overleaf (b)), cumulus clouds can be seen within the smoke area. These have been termed "pyrocumulus" and form typically during the day in this type of situation. One possible explanation for the formation of these clouds is that the upper layers of the smoke plume (having an albedo of 5-8%, as measured in recent field studies by the Meteorological Research Flight) absorb solar radiation, causing local heating of the surrounding air and hence strong ascent. In this situation, the unstable atmosphere allowed the developing clouds to penetrate high into the atmosphere, perhaps as high as 300mb (30 000 ft), as illustrated on the tephigram and as suggested by their low brightness temperatures on the infra-red imagery (not shown here).

These clouds are unlikely to provide a mechanism for the transport of significant quantities of particles (typically between 0.1 and 10 μm) to the surface; secondly, the tropopause is very much higher than 300mb.

The images show a light grey region covering a large area to the west of Kuwait. Its appearance and movement, combined with the 0600 UTC observations, (Fig. 28) indicate that it was a sandstorm, and was moving at a speed consistent with the observed near-surface winds.

The observations at 0600 UTC within the region covered by the image, reported generally very low visibility, even down to zero at some stations, indicating the extent and severity of the airborne sand and smoke.

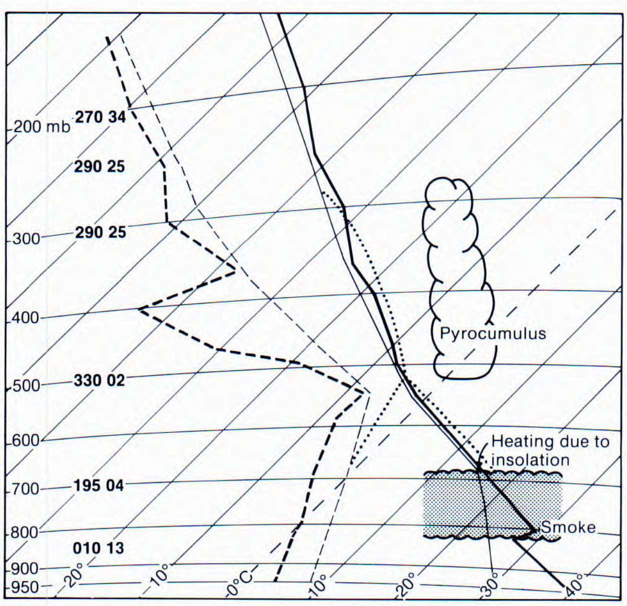


Figure 27. Tephigram for 17 May 1991 at 1200 UTC for King Khaled International Airport (location marked "K" in Fig. 28), Riyadh, Saudi Arabia (thick lines) (not through plume). Also shown is a schematic showing typical plume depth, and a postulated ascent (thin lines) through the plume (using Kuwait surface data), constructed on the assumption that insolation causes the upper layers of the smoke to behave as if they were a surface, resulting in ascent (dotted line) and cloud formation.

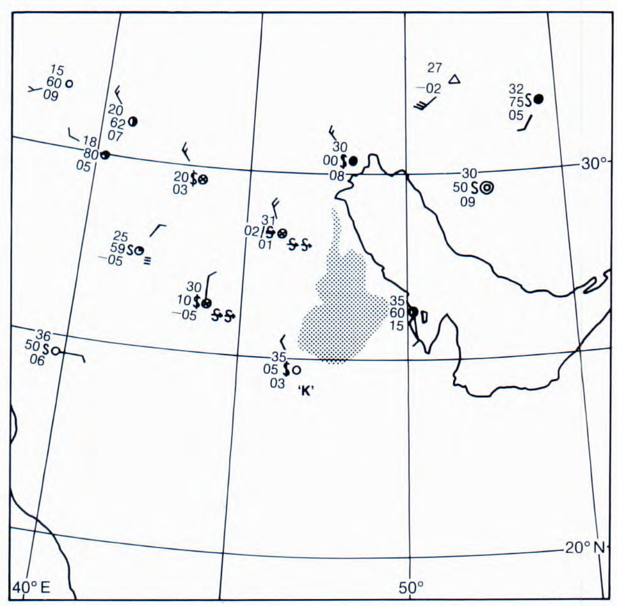
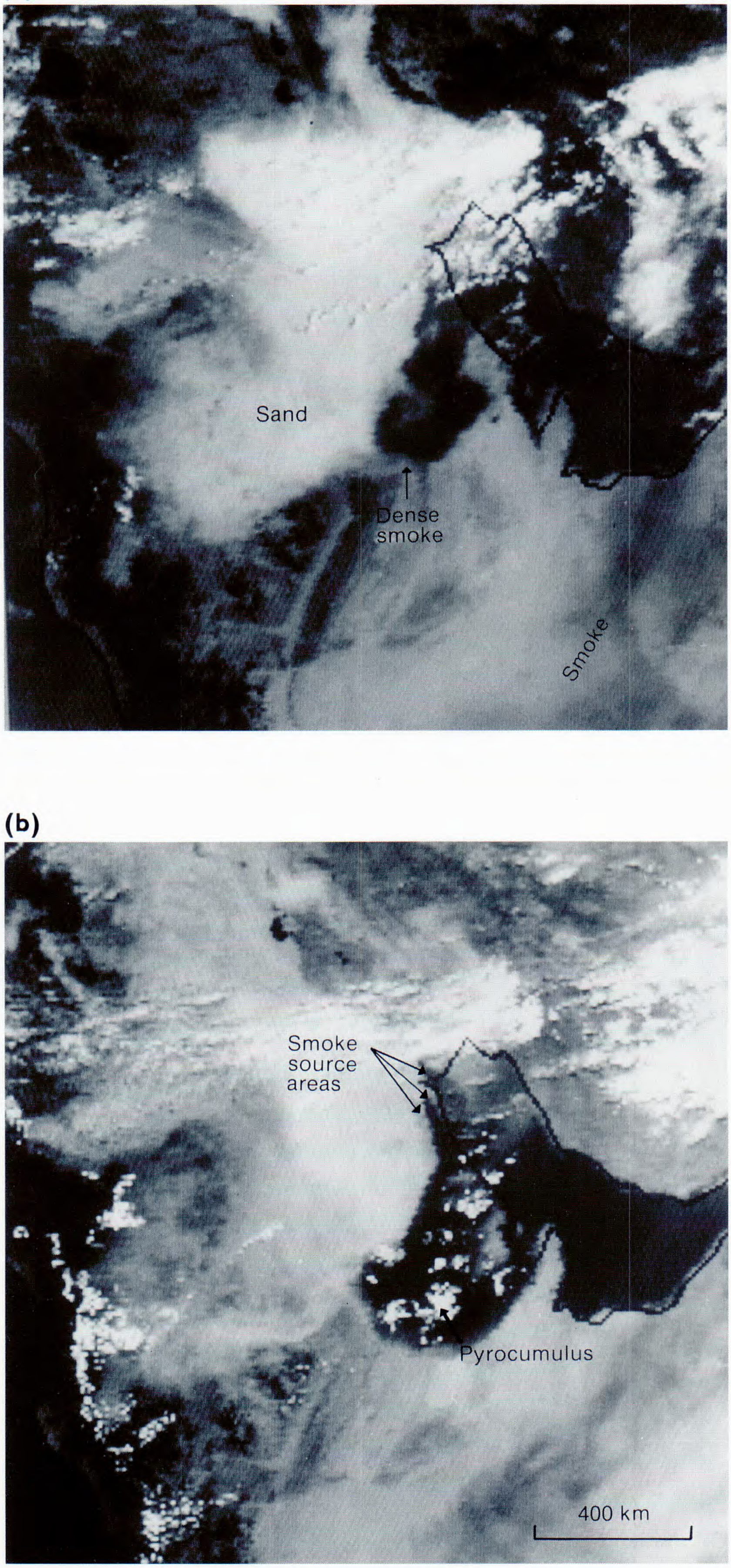


Figure 28. Middle East plotted surface observations on May 17 1991 at 0600 UTC, with plume area shown stippled.

(a)

(b)



Meteosat visible images of the Persian Gulf area on 17 May 1991 at (a) 0600 UTC and (b) 1300 UTC.

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