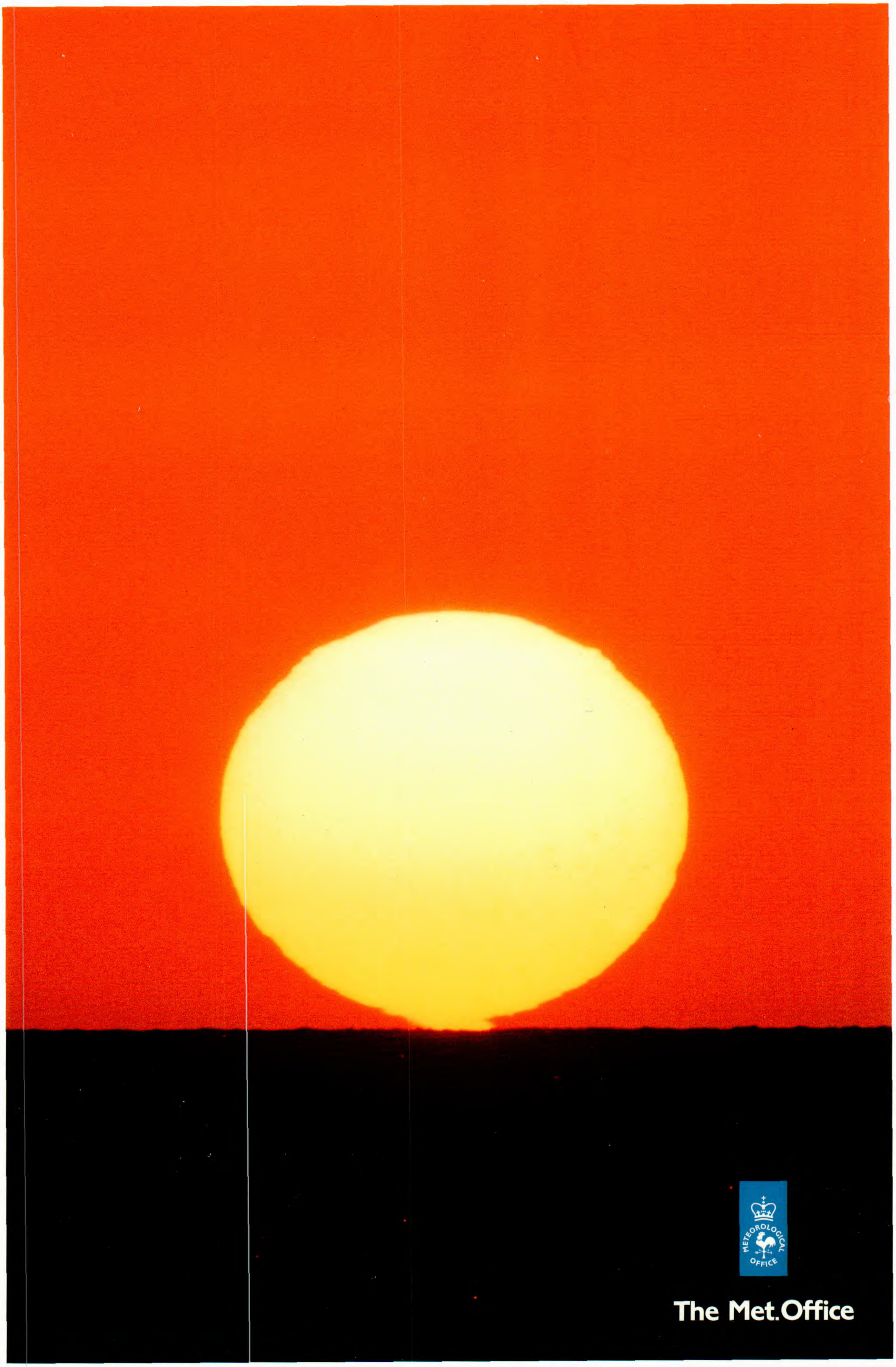
SCIENTIFIC & TECHNICAL REVIEW 1995/96



CHARTER STANDARD FOR THE PUBLIC
1996/97

We aim to serve the public by providing the following services.

Up-to-date weather information and forecasts

We will provide weather information and forecasts through radio and television, newspapers, and telephone and facsimile services. Our performance standards are based on the accuracy of the 24-hour national forecasts broadcast at 1755 on BBC Radio 4, and a satisfaction score for our general public forecasts on BBC Television and Radio 4. The targets and our achievements against them in 1995/96 were:

	Target	Achievement
Accuracy	84.0%	84.5%
Satisfaction score	80%	84%

The targets remain unchanged for 1996/97.

Weather warnings

We will issue warnings of severe weather through radio, television, and emergency organizations such as the police and fire services.

We will also provide warnings of adverse road conditions to the police, and to local and national radio.
Our performance standard for these warning services is based on the satisfaction expressed by members of emergency organizations. For the first time in three years the target score of 80% was exceeded in 1995/96 with 82% achieved. The target remains at 80% for 1996/97.

We will provide gale warnings and marine forecasts for radio.
Our performance standards for these marine services are based on targets set for the accuracy of gale warnings. For the first time in many years neither target was achieved. This was mainly due to a difficult December and highlights the problems in forecasting for extremes. The target for success rate remains the same for 1996/97, but that for false-alarm rate has been tightened further to 17%. Both success rates and false-alarm rates are monitored, and the targets and achievements for 1995/96 are given below.

	Target	Achievement
Success rate	81%	78%
False-alarm rate	18%	20%

Advice in emergencies

We will provide warnings of coastal flooding to the Environment Agency and the police.
Our performance standards are agreed each year with the Ministry of Agriculture, Fisheries and Food, the government department responsible for coastal flood protection and warning. Our targets are related to timeliness of issue, identification of major surges and the minimization of false alarms. All four targets were achieved in the eight months ending 30 April 1996 (few significant surges occur during the summer months). The most important target is to issue warnings to the Environment Agency, and police forces concerned, a minimum of 12 hours in advance of a major surge. The most significant surge occurred 19–20 February 1996 and accounted for almost half the warnings issued.

We will provide weather advice for the statutory authorities in environmental pollution emergencies.
These emergencies may arise, for example, from the accidental release of toxic chemicals into the atmosphere. Our performance standard is based on the response time in providing the emergency services with specialized weather information. The newly introduced target for 1995/96 was to provide this within 30 minutes on 85% of occasions. However, in this first year a figure of only 81% was achieved. As we are committed to improving our performance for this vital service, we have increased our target in 1996/97 to 87%.

Weather and climate information

We will maintain the National Meteorological Library and Archive at Bracknell (which you may visit free of charge).
We will develop low-cost publications containing basic weather and climate information for schools and the general public. We measure our performance by the high demand for our services. During 1995 loans to the general public and outside libraries increased by nearly 25% whilst our education section answered around 6000 enquiries.

Measuring how we are doing

Monitoring our forecasts
We continually monitor our performance. For instance we compare the forecast with what is observed and measure its accuracy. Forecasts have been steadily improving over the years and this is reflected in the performance targets set for our forecasts on radio and television and for our gale warnings.

Public surveys
We use independent consultants to make regular surveys. We welcome your comments and will react positively to them. Satisfaction scores are calculated using a scale of 1 (very dissatisfied) to 5 (very satisfied). The average value, scaled to lie between 0 and 100, is the percentage satisfaction score.

Finding out more

You can contact your nearest Weather Centre, or the Enquiries Officer at Bracknell.
We will be pleased to answer any questions you may have on our services, and you can ask for a brochure describing them and The Met. Office. You can also find out about our services from programme magazines, newspapers, and in telephone directories under 'Weather'. We want to hear your views and learn if you are satisfied with our services.

Should you have a complaint:
please telephone the Enquiries Officer or, better still, write in. We aim to respond to a complaint within five working days of its receipt, or at least provide you with an acknowledgement and an estimate of when a full reply may be expected.
The Enquiries Officer, The Met. Office, London Road, Bracknell, Berkshire RG12 2SZ
Tel: 01344 420242

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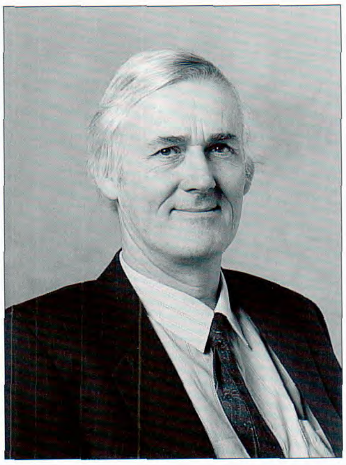
The Met. Office



Chief Executive's Foreword

(taken from the Annual Report and Accounts 1995/6)

Introduction

This is our last Report as a Vote-funded 'Next Steps' Agency; 1995/96 marked our transition to a Trading Fund on 1 April 1996. The Report is designed for a wide readership: Members of Parliament; our Ministry of Defence (MoD) owners; our customers, including the general public; and our own staff.

I very much appreciate the loyalty and commitment shown by my staff during this successful and exceptionally busy year. I am sure they realize that changes, though sometimes painful, are necessary in order for The Met. Office to flourish. Indeed we all recognize that the move to Trading Fund is no more than another stage in our 142-year history of excelling in the provision of meteorological services.

During the year, we adopted two clear aims; to deliver the year's programme as described in the Business Plan, and to focus our planning on producing new Corporate and Business Plans that clearly defined our strategies for the future. We used these documents to show the Treasury and Ministers that The Met. Office would be viable as a Trading Fund. We demonstrated once again our growing scientific and technical prowess and the commitment of our staff to the delivery of excellent services to our customers. We met the majority of our seven key targets (see page 7 of the Annual Report and Accounts) whilst making some important changes to the way we run our business.

Getting in shape for the future

As part of the review of strategy, we examined the business organization. We created a new Services & Business Directorate, to concentrate on the business needs and service provision for our principal customer groupings. We also reviewed our business and financial structures and our reporting systems, and started developing a more sophisticated management information system better to meet our needs as a Trading Fund.

The need for the improvement and measurement of performance, and their publication, has always been a notable feature of meteorological services. As far back as 1913, it was possible to compare the timing of forecasts issued to the navies of Europe! Since we became an Agency in 1990, we have reported statistics for an increasing range of our activities and services. Nevertheless, in an investigation of The Met. Office, the National Audit Office (NAO) found that there were shortcomings in the way that we targeted, measured and reported our performance; that said, they noted that it was not always possible to meet demanding targets. The Public Accounts Committee (PAC) endorsed these conclusions, while commenting favourably on the considerable international reputation of The Met. Office. After publication of their report, we introduced systems to enable us to review and track many aspects of our performance on a monthly basis, allowing us to keep right on top of service delivery. This year, for the first time, our performance against these key targets has been validated by the Comptroller and Auditor General.

Part of our strategy to create more-effective management has been to reduce the number of managers, thus increasing the focus on specific technical and service activities. This reorganization started at the top with a restructuring of the Management Board. At Board level, Peter Ryder retired from The Met. Office and we also lost Mike Nicholls, Roger Wiley and Peter White. I wish them well in their retirement or new careers. At the same time, I welcome on to the Management Board Jim Caughey (Director of Observations), Colin Flood (Director of Operational Services) and two Directors who have joined the Office from the private sector, Simon Cross (Director of Services & Business, the integrated division for the provision of all customer services) and David Roberts (Director of Corporate Development).

During this year, we acknowledged the need for more-rapid and face-to-face communication with staff by introducing Team Briefing. Senior managers also carried out a nationwide tour of our operational facilities to inform staff of the key elements of our change to a Trading Fund. Both initiatives have helped staff prepare for the new environment.

Highlights of the year

As every year, special features of the weather tested our forecasting ability. According to our historical climate records for Central England Temperature, much of the UK experienced the hottest August since the 17th century. Our numerical model provided forecasters with reliable predictions during the summer and accurately forecast the end of the hot, dry spell. At the other end of the temperature spectrum, in the winter of 1995/96, the Central Forecasting Office and our outstations dealt with many occasions of heavy snows and storms. This allowed the accurate and timely issue of severe weather warnings to the public and armed forces. The winter was particularly severe in the Balkans where the Mobile Met. Unit (MMU) was operating. MMU staff provided guidance first to the United Nations forces and latterly to the ACE Rapid Reaction Corps as part of the Implementation Force (IFOR). IFOR commended the MMU for their forecasts in difficult circumstances.

During the year, our research staff further raised the high international standing of the unified Numerical Weather Prediction model (UM) by introducing improvements that resulted in a significant increase in accuracy. The world-leading work at the Hadley Centre on the climate version of the UM was the basis for most of the recent conclusions of the Intergovernmental Panel on Climate Change about the likely effects on climate change of artificially generated greenhouse gases and aerosols. After a meeting in Berlin of the Framework Convention on Climate Change, at ministerial level, the Secretary of State for the Environment commended the work of the Hadley Centre in Parliament.

I presented the Chief Executive's excellence awards – always a pleasing task – to teams involved in this progress. These included staff focusing on forecasting research, satellite imagery, international presentations, and the application for MoD purposes of the UM for stratospheric forecasting.

After five years of gestation, the European Commission approved the Brussels-based ECOMET organization of the European national meteorological services (NMS) in August 1995. ECOMET's purpose is to enable customers in the European Economic Area to purchase meteorological services from any NMS while allowing them to share revenues arising from the sales. European NMSs also formed another meteorological network, EUMETNET, for co-ordinating improvements in the effectiveness of their larger-scale operations, for example in climate and observations programmes.

Every fourth year is always a special occasion for international collaboration when 176 countries attend the Congress of the World Meteorological Organization (WMO). On this occasion, it coincided with the 50th anniversary of the United Nations of which the WMO is a specialized agency. Congress created a new international agreement for reorganizing and increasing the exchange of meteorological data, the UK and other European countries working closely together. The agreement strengthens the role of NMSs while allowing for the growth of national and international commercial services.

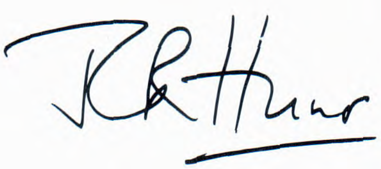
Looking ahead

In the new Corporate and Business Plans we produced this year, we emphasized that The Met. Office will concentrate on its core business of providing a world-class, science-based meteorological service that meets the needs of its customers. This is in line with the PAC conclusions and the Government's response to its findings. We have begun to monitor the accuracy of our Numerical Weather Prediction model by introducing a performance index – see page 9 of the Annual Report and Accounts. We have used a combination of internationally exchanged performance measures that allows us to compare our forecast accuracy with that of other centres and to track our relative performance year on year.

We expect that our participation in EUMETNET initiatives will help to reduce duplication of effort between European NMSs and to ensure fair cost-sharing for common facilities thus helping to increase our efficiency for the benefit of all our customers.

Income from Commercial Services will continue to be important. There is no cross subsidy of commercial activities by other areas of The Met. Office and to maintain this position we must concentrate on higher margin business. We will focus increasingly on delivering quality services to customers at an acceptable financial return. To this end, we are expanding our customer education programme to enable customers to assess the value and benefit of receiving meteorological services. On the international commercial front, we see real benefits in supporting the ECOMET organization.

With these and other strategies set out in our Plans, we expect to be able to meet the challenges of the 21st century. Improvements in forecasting accuracy, and increased collaboration and partnership with other NMSs and the private sector will put us in the best position to deliver value-for-money services to all our Trading Fund customers.



JCR Hunt
Chief Executive
10 October 1996

OBSERVATIONS

Observations of atmospheric and surface conditions are vital for three main purposes:

to provide input to Numerical Weather Prediction (NWP) and other methods of forecasting, both automated and manual;

to monitor the weather, e.g. to warn of hazardous conditions, and to verify the accuracy of forecasts;

to determine the variability of climate in space and time and to study 'climate change'.

A variety of space, surface and airborne systems have to be used to make the necessary measurements in all locations. For example, geostationary satellites provide frequent images of cloud systems and vector winds. Over the oceans, polar-orbiting satellites provide profiles of temperature and humidity; ships and buoys are used to determine surface pressure, air temperature and weather, and commercial aircraft are the main sources of upper-air wind data. Over land, the observations are provided by manned and automated surface stations and rainfall radars; radiosondes give upper-air temperature, humidity and wind data.

Surface-based observing

The supply of observations involves capturing the data, evaluating and field testing new or upgraded equipment, installation and maintenance of equipment, inspection of co-operating observing sites and recruitment of voluntary observers. There is also a test and calibration laboratory to ensure that both new and existing equipment are up to standard.

Networks

The United Kingdom operates 30 key land stations manned by professional observers reporting 24 hours each day and contributing to the World Meteorological Organization's (WMO) World Weather Watch as part of our international agreements. A further 205 secondary land stations and approximately 65 offshore sites are maintained.

Auxiliary or co-operating observers, for example coastguards, oil-rig staff and power station personnel, run approximately 93 land and 45 offshore sites. Additionally the climatological (492 sites) and rainfall (3984 sites) networks are almost entirely manned by volunteers. Considerable effort is devoted to training and encouraging these observers with network inspectors making regular visits, organizing training courses and running a system of awards for meritorious service.

This collaboration is an extremely efficient means of providing observations for the national good.

Automation

The programme of automation is bringing major improvements in cost-effectiveness. Twelve more Semi-Automatic Meteorological Observing Systems (SAMOS) have been installed, bringing the operational total to 68. So far 62 laser cloud-base recorders (LCBRs) and 59 visiometers have been installed in the UK in parallel with the SAMOS programme.

Algorithms and software have been developed to integrate both LCBRs and visiometers with SAMOS so that cloud amount, cloud base and visibility can be provided automatically. Several present-weather sensors have been evaluated and it is planned to develop an algorithm to add them to SAMOS as well. A trial of remote-controlled closed circuit television was conducted during the winter, with the camera at Eskdalemuir and control units/displays at Edinburgh and Bracknell. This development has significant potential for remote assessment of conditions by both observers and forecasters.

Enhanced Synoptic Automatic Weather Stations (ESAWS) operate at 43 of the secondary sites. They are fully automatic and, although using outdated technology, continue to give good service. The ESAWS in Scotland performed satisfactorily throughout the unusually severe winter weather; Altnaharra survived a minimum temperature of −27 °C. Twenty-four of the LCBRs and 27 of the visiometers are installed at ESAWS sites. It is planned to replace the ageing ESAWS by a development of SAMOS, thus moving to state-of-the-art equipment and standardizing design and spares. The SAMOS design has considerable potential and has led to a commercial variant, the Computer-Aided Meteorological Observing System (CAMOS), produced by AGI Limited using software supported by The Met. Office. Of the seven CAMOS purchased by the Irish Meteorological Service, three have now been installed.

Wind display

During the year, a prototype wind display, designed to meet Royal Air Force requirements to fit their standard air traffic control console, was tested and accepted. Sixty units will now be produced by a commercial manufacturer using The Met. Office specification.

Servicing

The increasing reliance upon automation, and the consequent impact of unserviceability on Met. Office services, makes the role of The Met. Office Maintenance Organization (Met OMO) ever more vital. Met OMO has reviewed its working procedures and organization and significantly increased efficiency allowing a reduction of nine staff, from 45 to 36 this year. Met OMO met the customers' requirement for service restoration times for 90% of faults during the year.

Upper-air observing

Sonde network

Eight upper-air stations continued to operate during the year making 6-hourly soundings of pressure, temperature and humidity with winds determined by Navigation Aid (NAVAID). A review of working practices led to the move of the Aughton operation to Aberporth, combining the network commitment with that of the military range with little impact on data availability. All the sites are multi-functional with commitments to ozone measurements, trials of equipment, surface observing, and services to military and civil aviation. Since they are single manned much of the time, the operation is extremely efficient. To encourage competitiveness in supply The Met. Office has engaged in a large amount of test and evaluation of commercial radiosondes and ozone sondes.

Considerable effort has been put into negotiations to retain much of the current radio-frequency spectrum for radiosonde use both in Europe and worldwide.

ASDAR

The Met. Office continued to support the WMO Aircraft to Satellite Data Relay (ASDAR) system by running the UK technical centre and the data monitoring centre. Out of 17 units supplying data to Bracknell, 10 are installed on British Airways aircraft. The accuracy of the data is good and they are a significant contribution to upper-air observations.

Ozone

Total ozone column measurements are made at Camborne and Lerwick on behalf of the DoE, and ozone-sonde ascents give vertical profiles at Lerwick. Weekly bulletins were produced during the period mid-January to March when ozone depletion usually peaks. Record low ozone amounts were recorded at Lerwick in March (with one daily total of 195 Dobson Units compared with a more usual 390), but to what extent this was due to the effect of anthropogenic factors has yet to be established. See also under **Atmospheric Processes Research**.

Wind profiler

Results of field studies of the performance of the wind profiler radar at Aberystwyth, operated by the Rutherford Appleton Laboratory in conjunction with the University of Wales, are being prepared for publication. Analysis of the data gives a useful insight into the variability of atmospheric wind fields at high temporal and spatial resolution, and this helps design observing systems. An operational test, in early 1997, is planned for wind profiler radars located in Spain, France, Switzerland, Netherlands, Germany, Denmark and UK. Data from most of the profilers will be made available in real time.

Marine observing

Ships

The UK Voluntary Observing Fleet of 569 ships forms part of the WMO scheme with about 7300 ships. There are also 37 oil rigs and platforms providing data. All make voluntary observations of weather in full WMO SHIP code, at specified hours. Port Meteorological Officers visit ships of all nationalities, liaising with the crews to maintain observing standards; these visits can also resolve causes of observational error, detected through data monitoring.

Weather ship

The Ocean Weather Ship *Cumulus* maintained routine operations throughout 1995, keeping station at position 52° N, 20° W, west of southern Ireland, during 5-week deployments from the base at Greenock. The ship was operated and manned by Marr Vessel Management on behalf of The Met. Office. *Cumulus* also undertook many scientific activities for various institutions, including plankton sampling, the measurement of sea temperatures and salinity at various depths and the observation of life in the sea and air.

Buoys

In 1988/89 the first two open-ocean buoys were deployed with the intention of completing a 10-buoy network over a 10-year period. In July 1995 the last was successfully deployed east of Aberdeen completing the network two years early and within budget (Fig. 1). This is a significant achievement bearing in mind the difficulties of working in open-ocean conditions.

Figure 1. An ODAS open-ocean buoy and a servicing vessel.

Data collection

The Met. Office has become one of the two Global Collecting Centres for marine climatological data established by the WMO. Common quality-control checks for ship observations have been agreed and the data are made available in a standard exchange format; some 2.7 million reports have been processed so far.

Space-based observing

The Met. Office relies increasingly on the assimilation of space-based observations into the NWP models to provide a consistent source of global data with a horizontal resolution commensurate with the model.

New satellites

EUMETSAT is the focus for operational meteorological satellites within Europe and currently operates the geostationary Meteosats. The Meteosat Second Generation (MSG) is on schedule to be introduced in 2001; all major issues are resolved and the final design and build phase has started. The Met. Office has been influential in helping industry meet the challenging performance targets for the MSG by proposing a revision to the specification. The new European Polar System will take over responsibilities for the morning component of the current US polar series at about the same time. It is slightly behind schedule but indications are that it will be affordable, with enhancements and additional instruments for monitoring climate change.

New instruments

The Met. Office has been closely involved in the testing and building of the new Infrared Atmospheric Sounding Interferometer (IASI), including field trials on The Met. Office's C-130 aircraft and reviewing its error characteristics. The instrument is the next major advance in infrared sounding from space and its dramatic improvement in height resolution should show more detail of the structure of baroclinic systems and lead to improved forecasts.

A new microwave humidity sounder (AMSU-B) was developed and built as part of a package of upgrades of the operational polar-orbiting spacecraft undertaken jointly with NOAA (who provide AMSU-A). The initial characterizations of the three flight models of AMSU-B have been completed and the proto-flight model successfully fitted to the spacecraft, ready for launch in March 1997 as NOAA-K. The upgrade of the engineering model to provide a fourth (spare) flight model is under negotiation with NASA.

As well as the provision of the instruments there has also been work on the supporting science. This has involved mounting, on the C-130 aircraft, two microwave radiometers which work in the atmospheric windows corresponding to the channels used by AMSU-A and -B. The microwave properties of the sea and various types of ice and land were measured in a series of campaigns.

Weather radar

Throughout the year the network radars continued to be the prime source of raw rainfall data for the short-period forecasting systems in The Met. Office. FRONTIERS has been replaced by the fully automated precipitation forecasting system, Nimrod, and this has allowed a more stringent and systematic comparison to be made with rain gauges. This has shown up instability problems with individual radars, the prime cause of which has been tracked down to the magnetron, which provides the radar pulse. See also **Nimrod** in the **Central Forecasting** section.

A user requirement for data and products from the weather radar network for England and Wales has been prepared with the National Rivers Authority (NRA) and a companion archive requirement document has been drafted. These will guide future decisions on the development of the radar network and its products.

Applications

The operational weather radar group has been strengthened by the addition of a small group dealing with applications of radar and precipitation data. Studies have included Probable Maximum Precipitation, for reservoir safety and dam design, and improvements to rainfall forecasting.

INFORMATION SYSTEMS

The principal business of The Met. Office is to gather information, mainly observational data, add value by generating weather forecasts and other weather-related products, and then to deliver services to customers. Speed is of the essence in the delivery of perishable weather forecasts. Information technology (IT) has a crucial role to play in the transmission of observational data, in Numerical Weather Prediction (NWP), in the organization and presentation of information, and in the delivery of customer services. These functions occupy the bulk of resources devoted to information systems.

Value for money

Industry continues to offer increasing value for money for IT systems. This has given The Met. Office the opportunity to improve the reliability and capacity of major components of the IT infrastructure at reduced cost.

Satellite data reception

During the year, The Met. Office's satellite data reception and processing system was moved from an eight-year-old mini-computer platform to a system based on a small workstation. Modern programming tools and protocols allowed the system to be built in a small fraction of the time needed to construct its predecessor. The workstations offer considerably increased performance (for example products are produced nearly ten times faster) and the monitoring facilities allow problems to be much more readily identified, located and cured.

Large-scale computers

Mainframe computing

For many years The Met. Office has operated a mainframe computer to provide a range of functions:

the maintenance of databases of weather observations and of forecast output;

the processing of forecast output into a wide range of products;

and other general-purpose computing functions.

In October 1995 the mainframe computer, a Hitachi Data Systems EX100 which had been in operation for five years, was replaced with a new machine with some 65% more capacity.

CMOS computer

The new machine, an IBM 9672 model R73 supplied by IBM (UK) Limited, uses complementary metal oxide semiconductor (CMOS) technology. Although such technology is the dominant one in use for desktop computing systems, it has only been adopted for use in mainframe computers within the last year.

The major advantages offered by CMOS arise because it is possible to put a very large number of circuit elements on a single wafer of silicon, and because of its very low power requirements. The older machine (built using bi-polar semiconductor technology) required around 100 kVA in power and 33 m^2 of floor space compared with the new, more powerful machine's 3 kVA and 2 m^2; Fig. 2.

Supercomputing

The Met. Office's supercomputer can run large numerical models. The majority of work involves running The Met. Office's Unified Model; the two dominant applications are NWP in support of routine forecasting services, and supporting the Hadley Centre's climate prediction and research. The present supercomputer is a Cray Research C916 (strictly C916/16–256) machine, which was installed in April 1994 (since then this

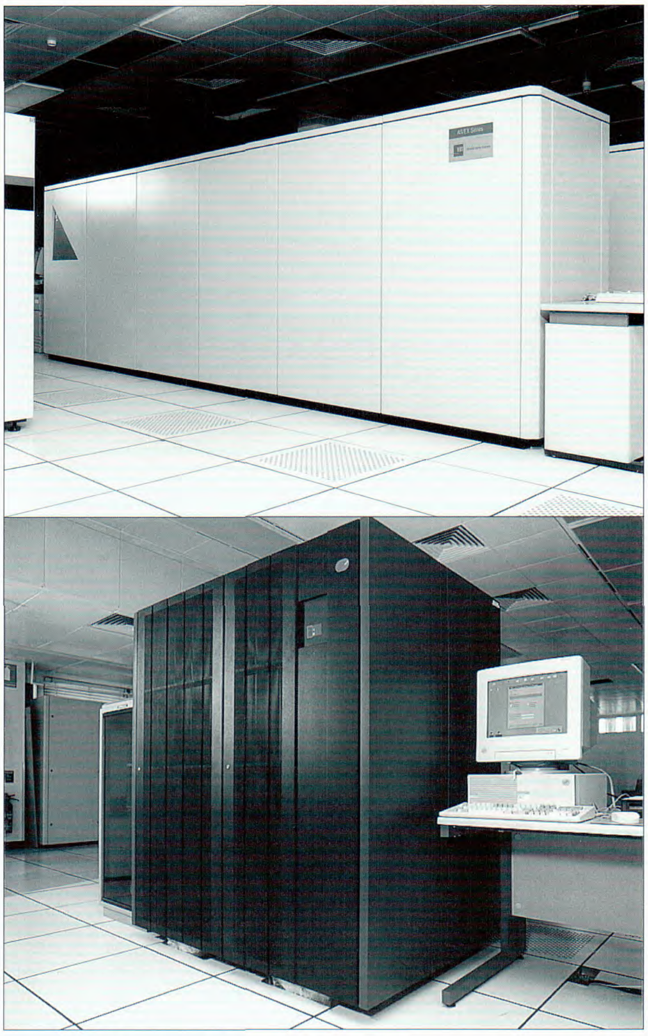


Figure 2. (a) Hitachi Data Systems EX100 mainframe computer in service 1990–95, (b) IBM 9672 model R73 mainframe computer installed in 1995.

machine has also been referred to as the C90 and C90/16256). At that time it was a top-of-the-range machine capable of a peak rate of around 16,000 million calculations per second.

Complex calculations

More computer power is required to support improved formulations of models. There is a fixed time between the receipt of observational data and the deadline for delivering NWP products to customers. This limits the amount of computation that can be carried out; a faster machine allows more-complex formulations of model to be adopted, and hence the opportunity to improve the accuracy of the output. For climate research, the need is to run the models for periods of at least 200 years of model time. It takes that long for the atmosphere/ocean combination to settle into a particular climatic regime after a change to some of the model's constraints.

New supercomputer

In May 1995 it was established that The Met. Office needed a five-fold increase in computing power for modelling purposes. A competitive procurement to select a supplier of a new machine to meet this requirement was made for a contract to be awarded in mid-April 1996. *(This resulted in a contract with Cray Research for their T3E supercomputer system.)*

Networks

Weather Information Network (WIN)

The WIN will replace a number of analogue and digital networks with a single, resilient, high-speed digital network. This network will provide the means for the collection of observations, transfer of data between Met. Office HQ, Weather Centres and forecast offices, and also plays a role in delivery to customers. The new network will use the Defence Packet Switched Network for its main bearers. In November 1995 Digital Equipment Company Ltd. (DEC) won the contract to provide the network components including the main network store-and-forward nodes, which will allow identical streams of data to be moved to many locations without overloading the network. DEC will also provide the equipment required at each network node, called the Outstation Communications Processor. Installation of the first element of WIN began in February 1996 and will continue until acceptance of the complete network about a year later. The new network will provide improved reliability, resilience and capacity, whilst the overall cost of the network and its support will be substantially reduced.

Global networks

Global observations are central to modern meteorology. One function of the World Meteorological Organization (WMO) is to maintain the framework for international exchange of observations. The Office plays a key role in both the routine exchange of information and in planning how the system will develop. Bracknell is one of several major hubs in the Global Telecommunication System (GTS) which links all the National Meteorological Centres (NMCs) around the world, and is also a critical element of the European regional network. The latter needs a major overhaul to meet evolving requirements. The Met. Office is co-operating fully with European partners to define and implement a new network, taking advantage of the emerging competitive environment for telecommunication services across the EU.

Bulletins

The GTS was established so that individual weather observations could be efficiently transmitted in the form of a small, coded bulletin, typically of about 1000 bytes. Increasingly NMCs are interested in exchanging larger units of information – for example a satellite image file may contain up to 5 Mbytes of data. The Met. Office has developed links which allow the efficient transfer of both small bulletins and large files. Such links have been established with European Centre for Medium-range Weather Forecasts, the Australian Bureau of Meteorology, NOAA/NESDIS in Washington, and the Canadian Meteorological Center. The experience gained from operating such links will be useful when WMO has to take decisions about the future form of the regional and global meteorological networks, Fig. 3.

World Wide Web

The Met. Office has established a public Web site which allows Internet users to access a selection of current weather and forecast data. The site contains the answers to the most frequently asked questions by the public. For example, the complete forecasting process is described from the collection of observations, through the various stages involved in computer prediction, to the presentation of results. The site contains links to a sister site operated by the BBC Weather Centre. The site has proved to be extremely popular with over 10,000 accesses per day. As well as the public site, The Met. Office runs a site for users interested in more-specialized and detailed information, Fig. 4 (centre pages).

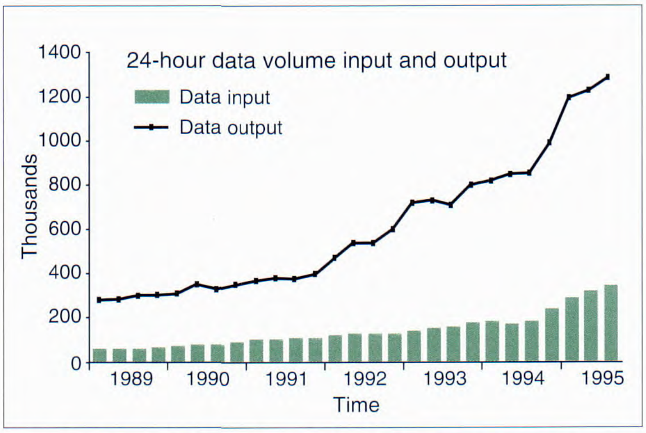


Figure 3. The volume of traffic switched by Met. Office computers as a function of time.

Probabilities

In any Numerical Weather Prediction (NWP) forecast there is uncertainty in the validity of the results which generally grows with the forecast period. In the Central Forecasting Office (CFO) there is a trend towards using more probabilistic guidance, an approach which has been used to good effect over the past year in the provision of early warnings of severe weather. When a severe weather event (capable of causing widespread disruption) is expected, the Chief Forecaster supplies a map to the BBC Weather Centre and International Weather Productions (IWP) showing the probability. This product is widely displayed, for example on national television forecasts, and effectively depicts the areas most at risk from severe weather. It also supplements the table showing regional probability of occurrence which is supplied to local authorities and emergency services. Customer feedback shows that this type of presentation is popular, although the public needs educating in its use.

At longer range

Medium-range guidance is also now being tailored to reflect uncertainty, with a greater appreciation of risk, especially for the period beyond day 5. The written guidance for days 6–10 has been redesigned to include both an assessment of alternative solutions and explicit sections on confidence – not just on the expected evolution but of individual elements such as weather, temperature and cloud. Additional products are being developed for days 4 and 5 based on site-specific probability forecasts.

Ensembles

Much of the uncertainty in predictions stems from doubts about the initial conditions, with the possibility of small perturbations in those initial conditions giving rise to appreciable differences in the ensuing forecasts. Running not one discrete forecast, but an ensemble of forecasts which vary slightly in their initial states, is gaining recognition as an effective way of predicting probable/possible atmospheric developments. Such ensemble forecasts are produced daily at the European Centre for Medium-range Weather Forecasts (ECMWF), and are now being presented routinely, albeit not operationally, to the forecasters in the CFO. The use of ensembles of forecasts in the CFO continues to grow and the presentation of 'spaghetti charts' on a workstation gives the forecaster an overall view of the areas and time when doubt about the evolution is at its greatest.

In Fig. 5 a 500 hPa geopotential height contour is used to give the forecaster a feel for the broad scale (model) atmosphere evolution. Over the UK and east Atlantic the consistency between the individual forecasts is evident six days ahead (T+168), giving the forecaster reasonable confidence in the likely evolution of the real atmosphere out to that time ahead. However, by ten days ahead (T+240) the more chaotic state of the model atmospheres in the ensemble of forecasts is very clear, emphasizing that in this case categorical forecasts at this range would be inappropriate.

Automatic text

We have identified a range of products, created in the CFO, suitable for automatic text generation. The initial focus has been on the shipping forecast and other associated forecast products such as the inshore waters forecast. Rules defining the construction of the forecast products, and the vocabulary to be used in them, are being developed. Definitions of terms

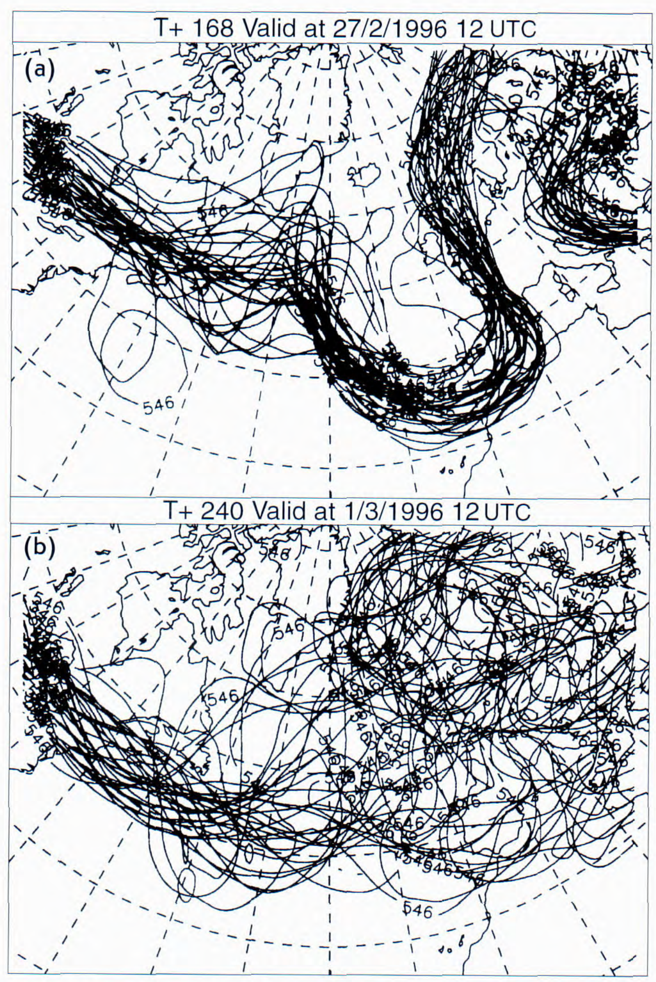


Figure 5. Examples of ensemble forecasts. Each forecast within the ensemble is represented by a single contour of predicted 500 hPa geopotential height (546 dam) in each figure. The ensemble of forecasts at (a) T+168 hours and (b) T+240 hours ahead.

used in the forecasts such as 'soon', 'later', 'perhaps', etc., have been created in terms which can be understood by an automatic text generator.

Diagnostics

More diagnostics products (showing vorticity and thermal advection at various levels, for example) are being used in the CFO to help identify errors in the model analysis. This is done through a workstation link with the Joint Centre for Mesoscale Meteorology (JCMM) at the University of Reading. It is hoped to make these products available on the operational workstation system in the next year.

Less intervention

The trend towards less pre-processing (i.e. human intervention) of NWP and more post-processing of the output has continued in the CFO; the duties of old intervention post have been amalgamated with those of Medium-Range Forecaster to form a Deputy Chief Forecaster position. This forecaster now spends more time on the production process with less emphasis on intervention. The post-processing aspect of the work should develop as methods to semi-automate the production process come on stream.

The NWP system

The majority of operational forecasting processes in The Met. Office continued to be underpinned by the operational running of the Unified Model, the development and performance of which is described in the **Numerical Weather Prediction** section.

As a measure of progress, there were 198 formal changes made to the operational output production part of the NWP suite in 1995, an increase of 19% over the previous year, which itself had been a record year for changes. This was achieved without increase in staff, thanks in part to better technical facilities now available.

Nimrod

The first trial of Nimrod, a fully automated precipitation-forecasting system, took place in February 1995 showing its basic capabilities but also insufficient accuracy. Before the second trial several improvements were made; the two most effective were extending the analysis beyond radar range (using NWP model and satellite data) and biasing the forecast towards the NWP model with increasing forecast lead time. The first two weeks of September provided a good test of the upgraded system, which was found to be superior to its semi-automated predecessor, FRONTIERS. After final preparations, operational production was switched to Nimrod in November. A further upgrade was made in January to adjust observed radar intensities using hourly rain-gauge reports. The scheme uses all reports in a week to determine whether the radar has changed its calibration and, if so, it computes a revised adjustment factor; now all radars are subject to rain-gauge adjustment for the first time.

Rain or snow?

While detailed forecasts of rain rate and accumulation are important, the action required in response to a forecast depends critically on whether it is rain or snow. An algorithm for distinguishing precipitation types was developed using NWP model variables as input, and has been assessed through the past winter. Between 10 January and 26 February the processed observations included nearly 9000 of snow with a hit rate of 91% (percentage of snow observations for which snow or mixed precipitation was forecast) and a false-alarm rate of 22% (percentage of snow forecasts for which rain was observed). The inclusion of mixed precipitation in the hit rate is appropriate since the results refer to a 15 km square in which, on some occasions, an observation on higher ground could be of snow while a simultaneous observation on lower ground could be of rain. In such situations, the diagnosed precipitation is classified as mixed. There was also a rare opportunity to assess skill at detecting freezing rain. Fig. 6 (centre pages) shows an example of the diagnosed precipitation type distribution (left), compared with observations (right) during this event. The area of diagnosed freezing rain (red) over southern England, agrees well with the observations, and the rain/snow boundary is close to that observed, though a little too far south over Ireland.

Very low cloud

Techniques for very short-range forecasting of low cloud and fog has also progressed. The cloud scheme has been run routinely since January and shows a significant improvement over both persistence and the NWP model. An accurate analysis has been the focus of effort on the fog scheme. Results from experiments conducted in January indicate that this should be achieved during the coming year.

Emergency response

On 28 June there was a successful international test of the Environmental Emergency Response procedures to be followed in the event of a nuclear incident. As an RSMC (Regional Specialized Meteorological Centre), Bracknell has certain obligations to fulfil – chiefly to predict the movement of pollutants and to pass this advice to contact points in national meteorological services (NMSs) within its area of responsibility. The Met. Office's dissemination reached 90% of the 49 NMSs targeted.

Severe weather

The exchange and use of severe weather warnings and advisories need to be co-ordinated internationally and The Met. Office contributes to that process. During the year tropical cyclone forecasts were particularly successful. Measures of skill for such events show The Met. Office's global model to be amongst the best in the world at this, partly due to the initialization technique developed for NWP around such storms.

Horace

The aim of the Horace project is to develop a workstation-based computer system to support the forecast offices at HQSTC, CFO and at the Royal Navy's Fleet Weather Oceanographic Centre. There has been good progress this year, all three sites now have an operational capability, and are upgraded every four months.

SADIS

SADIS, the satellite distribution system went operational in June 1995; it is a part of the ICAO global Aeronautical Fixed Service (AFS) to disseminate World Area Forecast System (WAFS) products. A report of the operational trial is awaited, but 25 users are now routinely receiving WAFS output from the World Area Forecast Centre (WAFC) London, via the Intelsat 604 satellite. Due mainly to economic constraints the SADIS take up has been disappointingly slow, especially within Africa. It is hoped that its use will increase when cheaper processing and display systems appear in the near future.

Forecast performance

Following a recommendation of the National Audit Office, the operational NWP system now has a single composite measure of performance which complements other routinely produced objective measures of forecast accuracy. It combines into a single measure several individual measures of accuracy made for regions of the globe, for selected forecast quantities (for example wind and pressure) and for selected prediction periods of 1–5 days ahead. Expressed relative to a baseline score of 100 for the year 1991, the score for the 12 months to March 1996, is 120.9. This is a very encouraging rate of progress, reflecting the fact that the most recent in-year improvement in NWP accuracy was extremely good – substantially more than the 2% or so which was aspired to before the start of the year. A new verification system, incorporating a more flexible, and maintainable suite of programmes and facilities, has been used since 1 January 1996. See also under **Numerical Weather Prediction**.

Timeliness of forecast production

Timeliness and reliability, as well as accuracy, are critical in forecast production, and the Office seeks to achieve a high standard of service. For example, the delivery of the Limited Area Model NWP forecast products are scheduled to be issued within 2 hours and 40 minutes of the observation time. This delivery, performed twice daily throughout the year, was achieved on approximately 97.5 % of occasions.

SERVICES AND BUSINESS

The Services and Business (S&B) Division of The Met. Office was set up in April 1995 to bring together, in the one management area, all those groups providing services to external customers. There are four main customer groupings: the Ministry of Defence (MoD), the Civil Aviation Authority, commercial customers and the Public Met. Service. Science and technology have a significant impact on the services that can be provided to these customers.

Defence

The Defence Provision (DP) branch of S&B is responsible for the production and delivery of operational meteorological services on RAF and Army airfields and to various Army and Defence Test and Evaluation Organization (DTEO) training and testing ranges. (The Royal Navy has its own uniformed meteorology staff although The Met. Office provides basic data and numerical forecasts.) Staff are based at over 40 military locations in the UK, Germany, Mediterranean and the South Atlantic. However, meteorological advice is also provided 'in theatre' to commands such as the Allied Command Europe Rapid Reaction Corps or in support of UN/NATO operations and exercises. This support is provided by the Mobile Meteorological Unit (MMU), which is based at RAF Benson and is an MoD asset within Headquarters 1 Group of RAF HQ Strike Command (HQSTC). The MMU is currently providing meteorological support for operations in the Former Republic of Yugoslavia (FRY) and northern Iraq, with meteorologists based in Italy, FRY and Turkey. In addition, DP manages The Met. Office's response in the event of nuclear and chemical accidents, develops specialized techniques and products for Defence and new Information Technology (IT) facilities to improve the production and delivery of services.

Service delivery

The defence customers at, for example, RAF and Army Aviation stations are served principally by locally based Met. Office staff. Using computer-based information systems known as Outstation Display Systems (ODS) the local outstation meteorologists receive guidance from the Principal Forecast Office at HQSTC and routine data and centrally generated products from Bracknell. Work has continued on extending IT-based distribution to meteorologists of the MMU (supporting the military away from fixed bases) and on the direct delivery of services to the military.

MMU

In 1994 the MMU tested a toughened prototype of the ODS. The lessons learned were used to specify the production system and five were ordered and delivered by the end of 1995. Satellite communication facilities have been used to give great flexibility in deployment; two complete systems are currently in operation with the MMU supporting Implementation Force (IFOR) operations in the FRY. Also for the MMU, toughened portable satellite receivers were purchased to provide a worldwide source of imagery independent of fixed communication links.

Remote forecasting

During the year, an MoD-sponsored trial was started to see if meteorological support to an RAF base could be provided from a remote location. The met. office at RAF Coningsby was chosen to provide all support for RAF Marham, as well as their own normal services. To ease the workload, IT-based information distribution systems were introduced. These were based on a Meteorological Information Self-briefing Terminal (MIST) developed in collaboration with Matra Marconi Space.

Defence applications

The Acoustic Prediction Package (APP) which was developed with the Department of Applied Acoustics, University of Salford, was originally released in spring 1994; this has now been made easier to use. It is hoped that the effects of topography on sound propagation will be included in the APP within a year.

Tactical meteorology

Tactical Decision Aids (TDAs) are tools that enable the forecaster to predict the impact of weather on military systems and equipment. Meteorological conditions influence the refractive index of the atmosphere. Changes in refractive index affect the performance of radar, 'ducting' conditions giving extended ranges and sub-refraction reduced ranges. Parabolic Equation (PE) models can give accurate predictions of radar performance, but the reliability of the predictions is usually limited by the vertical and horizontal coverage, and accuracy, of the meteorological data. A study carried out in the summer of 1994 in collaboration with the Royal Navy's Fleet Weather and Oceanographic Centre showed that the Mesoscale Unified Model (MUM) profiles could be used with the PE model to give useful propagation predictions. Further work has been carried out with the RN to develop a method of using multiple MUM profiles, along the radar coverage, to predict radar propagation. It is planned that this will be incorporated in the Electromagnetic Environment Modelling System (EEMS). The Royal Navy (and, it is hoped, The Met. Office) will replace the current TDA Integrated Refractive Effects Prediction System (IREPS) with EEMS. This will improve predictions when the environment is not homogeneous, in coastal areas for example.

Ballistic messages

Various Army training ranges around the UK require ballistic meteorological messages to support gun firing. The Standard Ballistic Met. Message (SBMM) contains ballistic (i.e. weighted) winds and temperatures, and the Standard Computer Met. Message (SCMM) contains winds and temperatures for specified 'zones' up to a height of 20 km. Previous studies have shown that MUM profiles can be used to produce the SBMM and SCMM. A dial-in facility, using the MIST host, was developed to enable outstations to receive site-specific MUM profiles. This facility has now been included in the Artillery Meteorology software package and delivered to the range stations and Main Met. Offices throughout the UK and to a site in Germany. In Germany the Limited Area Model (LAM) output is used in place of the MUM profiles, and its use in the production of ballistic met. messages is currently being tested.

Low light

Predictions and measurements of clear-sky night illumination have been compared. It was found that some modifications to the algorithm were required, and these have been implemented in a new version of the TDA. Further data are currently being recorded at Aberporth, where there is little light pollution, and the modified version of the model will be verified against these data.

Contrails

Operational Decision Aids (ODAs) are tools that enable the forecaster to predict the implications of the meteorological conditions on military operations. Under certain conditions, condensation trails (or contrails) will form in the wake of an aircraft. For decades contrails have been forecast from the MINTRA line, which is printed on tephigrams. The MINTRA indicates temperatures below which contrails will form, but it has been found that their formation depends not only on the dew point but on the efficiency of the aircraft engine as well. A technique which takes these parameters into account has been developed and tests are being planned.

Commercial

S&B's commercial customers are many and varied, ranging from individual members of the general public to the utilities and multinational companies. They take a diverse range of services, using climatological, current or forecast data, and receive their service via a wide range of communication technologies. A limited number of the science or technology-based services, developed over the past year, are highlighted in the following sections.

Data analysis services

A number of specialist groups provide services using the information stored in The Met. Office's data archives. These archives are extensive and include observational data, imagery and past forecast data.

Insurance

In response to requests from insurance companies, observational data representative of postal districts are now available. This helps settle weather-related insurance claims efficiently.

To assess the risk of coastal flooding for the insurance industry, the Marine Consultancy Group collaborated with Sir W. Halcrow & Partners to undertake a detailed study of storms likely to have caused maximum flooding around the coasts of England and Wales. A few storms were identified as being characterized by the critical combination of tide, surge and waves to produce overtopping or erosion of sea defences.

Waves

The Marine Consultancy Service extended work on quantifying forecast uncertainty and produced a report for the Offshore Division of the Health & Safety Executive (HSE). A study, also for the HSE, was carried out using The Met. Office's wave-model hindcast archive. This detailed notable storms which have affected UK offshore areas over the last decade. Fig. 7 shows the analysed wind and wave data for one such storm.

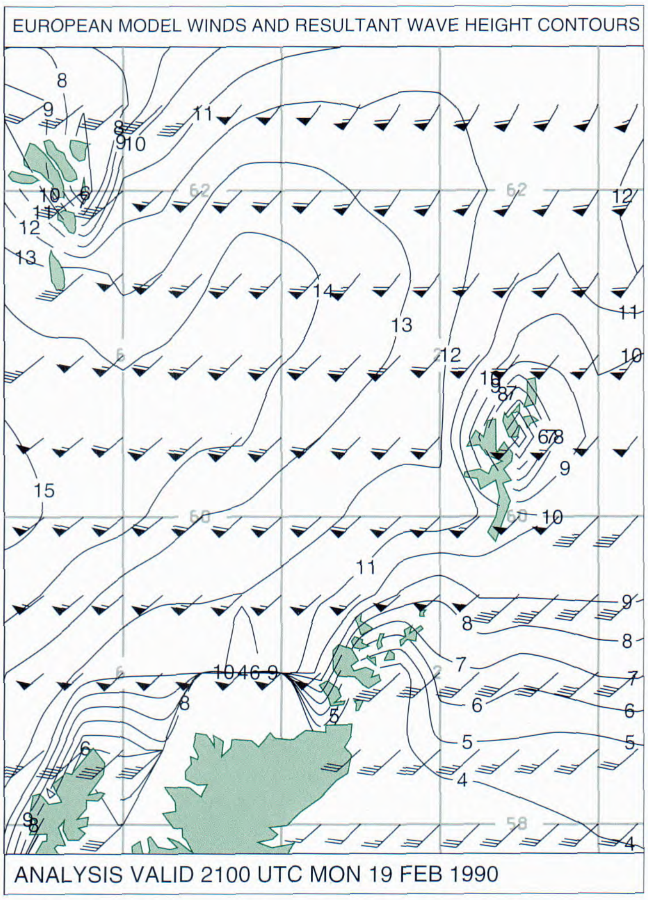


Figure 7 shows the analysed wind and wave data for a notable storm.

Following international concern over the safety standards applied to passenger ferries, the Marine Safety Agency sought analyses of wave data which could be used to characterize wave climates along ferry routes operated from UK ports. A similar type of advice was given to a company developing a new design of 'FASTSHIP', planned to cross the Atlantic at much higher speeds than conventional vessels.

Extremes

The British nuclear power industry has to ensure that its equipment is designed to withstand climatological extremes that have a 1:10,000 chance of occurring in a given year. Existing guidance on temperature extremes is based on linear extrapolation techniques that fail to acknowledge the existence of a physical limit. This has now been remedied and a statistical model has been developed which will estimate return values of maximum and minimum temperatures for any location in the UK. Although the model does not take into account the density of urban development or proximity to water, and the effect of cold air drainage is only crudely represented by an average height parameter, it estimates 1:50-year maxima and minima with standard errors of about 1 °C and 2 °C respectively.

Dispersion

The atmospheric dispersion model is being increasingly used to estimate dispersion and deposition from a potential or actual source of pollution, e.g. a power station or smelter. Three such studies have been undertaken during the past year.

Wind climatologies

A two-year project to evaluate the use and limitations of the *European Wind Atlas* in estimating site-specific wind climatologies has been completed. This type of information is of particular use in siting wind farms. The modelling techniques, used in the *Wind Atlas*, have been compared with methods of estimating wind climatology derived from short-duration on-site measurements. In general the *Wind Atlas*-derived climatologies were not as accurate, but were better than those obtained by just using the nearest, or most appropriate, site with a long-period wind record.

Agriculture

The National Agrometeorological Unit is attached to the Agricultural Development and Advisory Service (ADAS), Wolverhampton. Much of its work deals with the emission of odours and dusts into the atmosphere. Reports are submitted to local authority planners, often as part of an environmental assessment, and used in the evaluation of the overall impact of an industry on the local community. Some of the more interesting studies included:

odour concentrations and emission rates from sewage treatment abatement plants;

the effect of different stack heights on ground-level odour concentrations and flow rates were assessed for a company making dog biscuits;

at a broiler rearing farm, odour emission rates were measured and downwind dispersion modelled, to help a Department of the Environment inspector determine a planning appeal for expansion of the farm;

hourly wind speeds and directions were measured over a six-week period at two sites in the north-east, the data were used in a marine and tidal flow model to determine the direction and concentration of discharges from a sewage works.

More-obvious work for an Agrometeorological Unit is crop protection. Disease infection probability models for brown and yellow rust were evaluated against actual disease records. The models take account of leaf-wetness duration and concurrent temperature during the growing season. It is intended to incorporate the models into a decision-support system designed to optimize the use of fungicides on UK wheat crops. The Unit also provided support to ADAS regarding the consequences of the UK switching to the same time as adjacent continental Europe.

New services

FleetMet Marine

An increasing number of vessels equipped with INMARSAT-C satellite terminals operate in waters north of Scotland. These vessels can now routinely receive enhanced weather forecasts by using the new FleetMet Marine service.

Sparks

A rather unusual fire-risk forecast service was set up for steam train operators. As well as forecast weather, the service also makes allowance for the soil moisture deficit; the drier the soil and the vegetation the more likely a flying spark is to cause a fire.

Trajectories

The Met. Office trajectory model, which can be linked to output produced by the Numerical Weather Prediction (NWP) models, has been used as the basis for a number of services. Perhaps the most novel of these is in support of Richard Branson's hot-air balloon exploits.

Precipitation

A short-period lightning-risk forecast has been introduced in response to customer requests. An example of a forecast is given in Fig. 8. Output from The Met. Office's nowcast model, Nimrod, is becoming available and is finding a number of uses. Fig. 9 (centre pages), taken off the MIST system, is an example of a forecast of precipitation type.

Cloud or precipitation forecasts generated direct from NWP model data look very unreal when compared to observed imagery. This is because the models have limited spatial resolution. The past year has seen fractal techniques used to add 'structure' to the NWP output. Products based on this technique are now regularly used by the television companies.

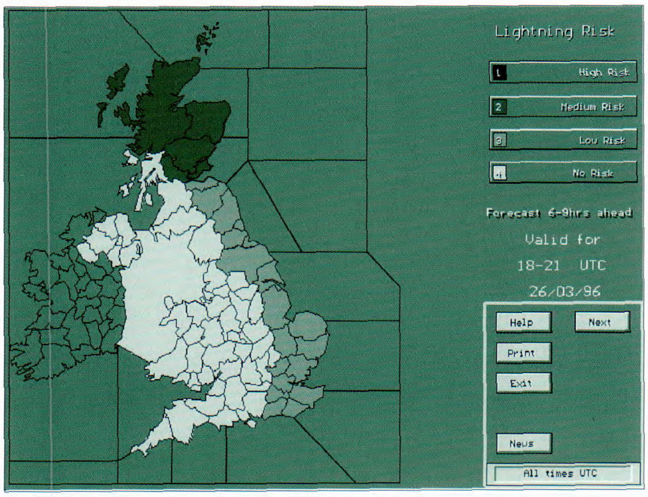


Figure 8. An example of a lightning forecast.

Fig. 10 (centre pages), again taken from a MIST display, is an example of a forecast rainfall field enhanced using this technique.

Efficiency

At the beginning of the year The Met. Office had 74 production units attached to S&B (the year closed with 73). Most of these are scattered throughout the UK, having the very real benefit of being close to the customer (for some customers this is essential). This can also cause problems; distribution of production without co-ordination can result in inefficiencies. This section also discusses the developments in systems that underpin S&B's ability to deliver products and services.

OPUS/WIN

The interconnection of all the distributed commercial production units and Bracknell was completed during the year. This wide-area network, when coupled to the local-area network of computers at each commercial production site, forms the basis of a versatile production system called the Outstation Production Unified System (OPUS). Products can be generated at one location and distributed efficiently and automatically to any other site that needs them. It is possible to generate a single output by combining input from a number of sites. Products generated automatically direct from NWP output can be distributed to production sites (for local adjustment if necessary) for onward transmission to customers. Examples of all these ways of working have been developed, demonstrated and implemented over the past year. Defence sites will be given similar facilities, as part of the Weather Information Network (WIN) project, over the next year.

Generic efficiencies

A Geographic Information System (GIS) was purchased and evaluated. Among its uses are, interactive quality control of climatological data, generation of certain types of product (particularly in the environmental area) and help in the production of truly site-specific forecasts.

Production units put significant effort into the generation of text. After a couple of years of development the automatic text-generator software has now been used in real time to create text forecasts for various commercial markets. See also **Automatic text** in the **Central Forecasting** section.

Internet

The Met. Office's public World Wide Web site on the Internet was launched in September 1995. It offers information about The Met. Office and its weather services, educational and research material, the UK 24-hour forecast, severe-weather warnings, satellite images and a UK current-weather round-up. In its first six months it has supplied over 750,000 pages of information and received favourable coverage from the UK press. On one day alone, during the bad weather in February 1996, there were over 20,000 accesses. See also **World Wide Web** in the **Information Systems** section.

Mobiles

Because of the growing use of mobile communications, S&B are looking at service distribution via mobile messaging, including the GSM Short Message Service. A pager-based weather service was tested in the Solent area, and the results are now being assessed.

Fax

The Met. Office continues to operate and enhance the MetFAX range of dial-up fax products for a wide range of users (the master index is on 0336 400400).

Collaboration

BT

The past year has seen increased collaboration with British Telecom plc. Of particular technical interest are the investigations of text-to-speech synthesis and voice recognition. Both could be very useful in product generation and distribution.

Video conferencing is interesting because it has applications both within the organization and as a means of interacting with customers.

MIST

We continue to collaborate with Matra Marconi Space on MIST, the PC-to-PC delivery system. Additional resilience, and more products, are being added as the customers become more numerous and sophisticated.

Atmospheric Prediction Development

The Atmospheric Prediction Development Programme is designed to improve the capability of The Met. Office's computer modelling system in operational Numerical Weather Prediction (NWP). The models are also designed to be suitable for use in climate prediction and other environmental research, and are made available for use by UK universities. This wider use of The Met. Office's forecast models results in feedback on its performance and hence substantial benefit to forecast customers. The model is used for operational predictions in global, regional and mesoscale configurations, for short-range forecasts, for monthly probabilistic forecasts which are made on behalf of specific customer groups, and for experimental seasonal forecasts. It has also been used experimentally in medium-range ensemble forecasts in a joint experiment with the European Centre for Medium-range Weather Forecasts (ECMWF).

Forecast performance

The overall performance of the global forecast model is illustrated in Figs 11 and 12. Fig. 11 shows a time-series of the root-mean-square (r.m.s.) errors over the North Atlantic and Europe from 1970 to the present. This illustrates that 72-hour forecasts are now as accurate as 24-hour forecasts were in the early 1970s. The current model was introduced in 1991, and improvements to it since have resulted in 72-hour forecasts today being close to the standard of 48-hour forecasts in 1990, the last year of the previous model. Fig. 12 illustrates a composite measure of the global model performance based on individual measures of accuracy at the surface and in the upper air for all parts of the world. The index is weighted according to the relative importance of aspects of global model performance to Met. Office customers. Thus greatest weight is given to 24-hour forecasts of northern hemisphere sea-level pressure and 250 hPa wind. The latter is the most important product for civil aviation. The index is calculated from ratios of the r.m.s. errors at the time to the values of the errors in April 1991. It shows a 20% improvement since the introduction of the current model.

Weather parameters

The model is also used to forecast weather parameters, such as cloud and precipitation, primarily for the UK. Precipitation forecasts up to 36 hours ahead are obtained from a regional version of the model covering the North Atlantic and Europe with a 50 km grid. Over the UK, extra guidance up to 24 hours ahead is obtained from a mesoscale version of the model with a 16 km grid. This gives more-detailed precipitation forecasts, together with predictions of other weather parameters such as cloud and fog.

The usefulness of these predictions to the forecasters in the Central Forecasting Office is illustrated in Figs 13 to 15 in which a positive value indicates that the mesoscale model gives useful guidance. A value of 1.0 indicates that this was true in every forecast. Fig. 13 shows that in most months the extra precipitation detail provided by the mesoscale version of the model is useful. The exception in recent months has been the very dry August of 1995 when there were only a few scattered showers. Fig. 14 shows that, during 1995, the cloud forecasts were found useful in most months. This is a result of several model and analysis upgrades made in Autumn 1994. There is large variability from month to month which reflects the seasonal variability of the frequency of low cloud and the different predictive skill of the model in different synoptic situations. Stratocumulus, for instance, is much harder to predict than frontal cloud. Fig. 15 illustrates that the fog predictions were considered useful in autumn 1995 but not Summer 1995. This is encouraging, as fog is much more significant in the autumn. In summer, the transient nature of the fog is always likely to result in relatively worse forecast performance.

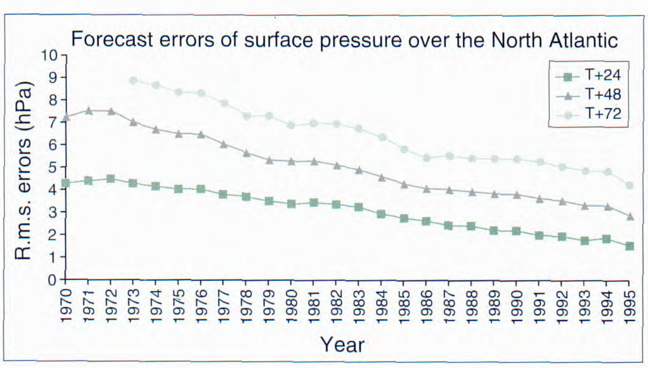


Figure 11. Time-series of annual mean sea-level pressure errors for the North Atlantic and Europe from 1970–95. Separate curves show errors in 24-, 48- and 72-hour forecasts.

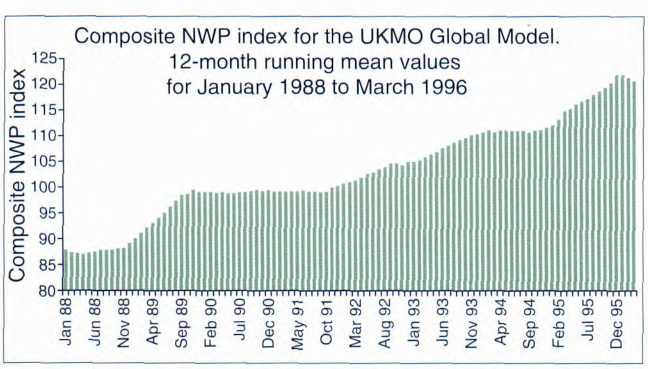


Figure 12. Composite index of errors in global forecasts from 1988–1996.

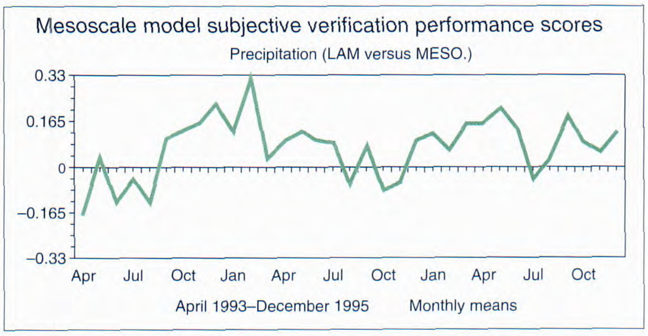


Figure 13. Time-series of subjective assessments of precipitation forecasts from the mesoscale model as compared with the regional model from April 1993 to December 1995. A positive value indicates that the mesoscale model adds useful value. A full-scale value of 1.0 indicates that this was true in every forecast.

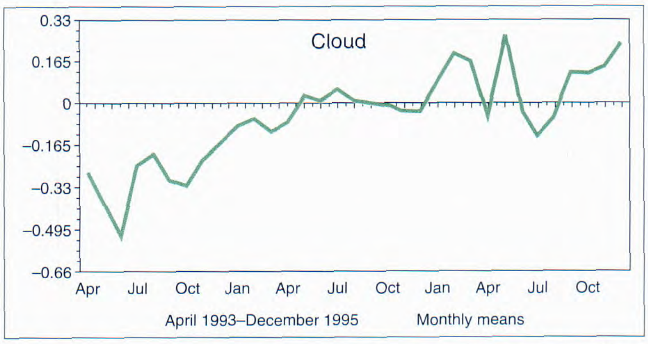


Figure 14. Time-series of subjective assessments of cloud forecasts from the mesoscale model from April 1993 to December 1995. A positive value indicates that the mesoscale model gives useful guidance. A full-scale value value of 1.0 indicates that this was true in every forecast.

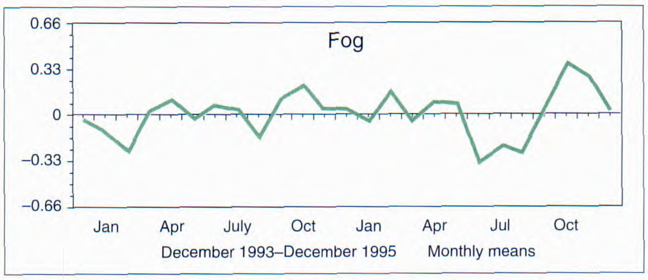


Figure 15 illustrates that the fog predictions were considered useful in Autumn 1995 but not Summer 1995.

Observation processing

Use of satellite sounding data

In its analysis the forecast model uses measurements, or 'soundings', of the radiance emitted by the earth's surface and the atmosphere at infrared and microwave wavelengths. Wavelengths are observed where atmospheric gases absorb the emitted radiation. If the absorption is very strong the atmosphere becomes optically thick and only radiation from the upper atmosphere is received by the satellite. As the absorption becomes weaker, radiation is received from lower altitudes. A careful choice of channels with different absorption characteristics can enable radiation originating from a range of heights to be measured. If the absorber is a well mixed gas, such as carbon dioxide, then the temperature of the air can be

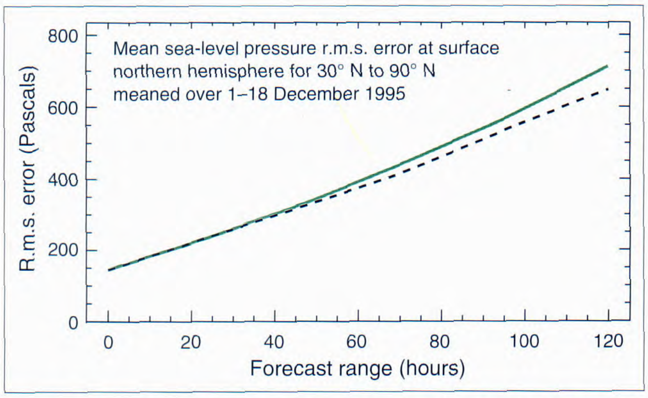


Figure 16. R.m.s. errors for the extra-tropical northern hemisphere for forecasts using GLOSS data (dashed) and the operational forecasts (solid line).

calculated from the measured radiation. If the absorber is more variable, such as water vapour, then it is the amount of absorber which can be deduced.

TOVS

The sounding data are collected by polar orbiting satellites, currently NOAA-12 and NOAA-14. These satellites carry instruments known as TIROS Operational Vertical Sounders (TOVS). Primarily, TOVS measures radiation between 0.7 and 15 µm but there is also a microwave instrument observing between 50 and 58 GHz. The infrared channels provide temperature and humidity information in clear air. The microwave channels provide temperature information in cloudy skies, as cloud absorption is small because of the long wavelength. TOVS is shortly to be replaced by the Advanced TOVS, which will have a significantly enhanced microwave instrument with more channels measuring temperature, especially in the stratosphere, and a new instrument for measuring humidity.

GLOSS

Satellite radiance measurements for assimilation into the Unified Model (UM) are processed by the Global Soundings System (GLOSS) package developed by the Satellite Sounding Group. GLOSS uses a radiative transfer model to predict clear-air radiances from a background UM forecast field. These are compared with the satellite measurements, for both infrared and microwave channels. The differences in radiance are then used to improve the original background field. So although the product is referred to as a satellite sounding, the procedure is a one-dimensional variational analysis (1DVAR). The impact of GLOSS has been repeatedly measured by using both the UM parallel and rerun suites, most recently in December 1995. The GLOSS soundings were found to give very substantial benefits in forecasts compared to the soundings previously provided by NOAA/NESDIS, especially in surface fields of pressure, wind and temperature but also for vertical profiles of height and wind. The impact on r.m.s. mean sea-level pressure error for 30° N to 90° N is given in Fig. 16, where a 10% reduction in error at T+120 can be seen. GLOSS will be used in the operational assimilation suite from April 1996.

Data assimilation

Moisture

The assimilation of moisture data into the forecast model is important when the emphasis is on prediction of weather elements as opposed to the large-scale flow pattern. The last year has seen improvements in the ability of both the mesoscale and regional configurations of the model to assimilate remotely sensed rainfall and cloud information.

Rainfall

A scheme has been developed to 'nudge' the mesoscale model's rain-rate distribution towards that observed by the weather radar network. The scheme operates by applying increments (derived from the radar observations and a knowledge of the model's latent heating distribution) to the model temperature field. These increments in turn help generate the necessary vertical motion to produce the observed rain rate. Most of the benefits are seen in frontal situations, as in Fig. 17. Objective measures of rainfall forecast accuracy show a systematic benefit from the new scheme over the first 6–9 hours of the forecast.

'Spanish plume'

In the summer months, the UK weather can sometimes be influenced by thundery systems which have their origins in warm moist air brought north from the Bay of Biscay. The mesoscale model has shown some skill in forecasting these thunderstorms at short forecast ranges, once they enter its restricted domain. Investigations revealed that the benefit was due largely to the assimilation of humidity data derived from Meteosat imagery. A project was started to prepare similar humidity data for the regional model over a larger area

Figure 17. Note the forward band of rain in the operational forecast which is correctly removed in the test forecast with radar assimilation.

of the east Atlantic and Europe, which includes the otherwise sparsely observed Biscay region. With this extended data coverage, it proves possible to predict the movement of thunderstorms into the UK at forecast ranges of 15–24 hours ahead in situations when the mesoscale model might have given only 6–9 hours warning; see Fig. 18. The inclusion of visible imagery into the cloud analysis alongside the existing infrared data is expected to bring additional benefits. One of these is the analysis, and prediction of its subsequent movement over UK land areas, of low cloud in coastal waters.

Four-dimensional variational analysis (4DVAR)

In the longer term, we plan to develop methods of data assimilation which make explicit use of our knowledge of the model equations for predicting observed quantities. Variational methods (known as 4DVAR) can be used to find the sequence of model states, obeying the given predictive equations, which best fit available observations. 4DVAR should be better at using observations of derived quantities, such as rainfall, and should give more-realistic evolving dynamical structures. The 4DVAR algorithm requires the integration of the forecast model, and its adjoint, for many iterations. The full model for this would be prohibitively expensive, so the scheme is being designed to use a cheaper 'Perturbation Forecast' model, as shown in Fig. 19. The initial run of the full model calculates the deviations of its predictions from the observations (shown as $\mathbf{y}$ in the figure). The perturbation forecast model, and its adjoint, is then iterated to find the perturbation which minimizes these deviations, plus the deviation from the background model state.

Penalty function

A major milestone towards the development of 4DVAR was achieved this year, by completing variational code for the combination of the background model state with observations at one time (3DVAR). The background state used is a forecast from the assimilation system, containing all information from previous observations. It is important to allow for the accuracy, balance and smoothness of the background state when adjusting it to fit the new observations. This is done using a total penalty function,

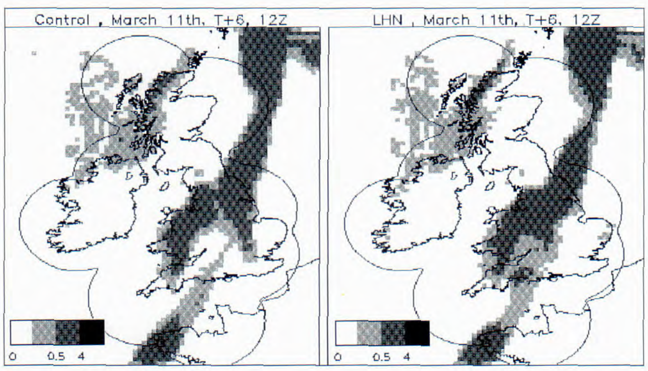


Figure 18. The example shows a band of rain in East Anglia, as observed by radar, which is absent in the operational forecast where the cloud analysis based on satellite imagery has been assimilated, but clearly present in the test forecast.

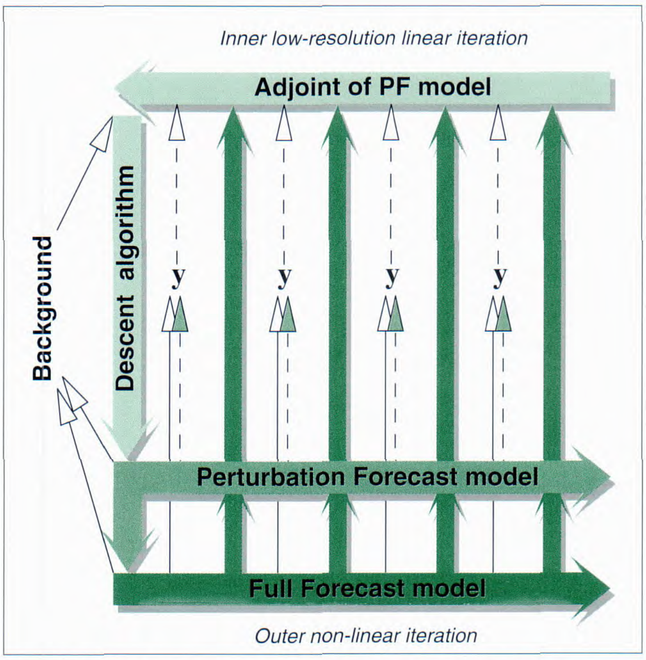


Figure 19. The scheme is being designed to use a cheaper 'Perturbation Forecast' model.

which is the sum of a background penalty measuring the size, imbalance, and roughness of deviations from the background state, and an observational penalty, measuring the poor fit to the observations. An iterative descent algorithm is used to find the model state which minimizes the total penalty.

This year it is planned to demonstrate that by careful definition of the penalty function the effectiveness of the current assimilation scheme, which spreads the information from each observation in a smooth and balanced way, can be replicated or improved. Then, by inclusion of the prognostic equations, which are currently being coded in the perturbation forecast model, the system should be able to be extended to a full 4DVAR.

Model formulation

Parametrization

The predictive part of the model contains representations of the equations of motion and of the thermodynamics that govern atmospheric behaviour. However, because of the restrictions imposed by computer limitations, many processes can only be represented statistically. The Atmospheric Processes Research (APR) programme measures and studies many of the processes which have to be represented. The development programme then has to draw on this knowledge to incorporate the results into the prediction model.

Radiation

A major development in this area in the past year has been the development of a more realistic representation of the effects of radiation. The new method is extremely flexible and includes

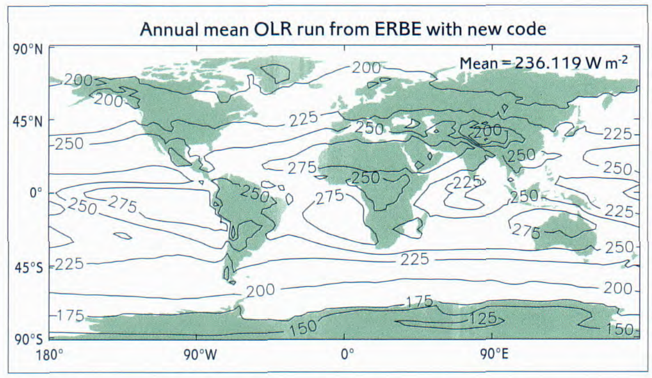


Figure 20. The simulation of the outgoing long-wave radiation compared with data from the Earth Radiation Budget Experiment (ERBE).

state-of-the-art formulations for the effects of gases and clouds. Results from the code compare favourably with reference calculations and with observations made from the MRF C-130 aircraft. The code was included in the latest version of the model and has improved several aspects of its performance. For example, the cold bias in the upper troposphere was reduced by 1–2 K and the radiation budget at the surface in both the solar and thermal regions of the spectrum was improved. Interestingly, there were also improvements in the winter surface pressure pattern over the North Atlantic. Recent work has focused on improving the computational speed of the code while retaining the accuracy and improvements to the model. It is planned to bring the code into operational use during 1996 and to use it for the next transient simulation of global warming with the coupled model. Fig. 20 shows that the simulation of the outgoing long-wave radiation compares favourably with data from the Earth Radiation Budget Experiment (ERBE).

Aerosol

Satellite programmes such as ERBE provide an important source of data for evaluating the model. Comparisons have also been made with the products created by the International Satellite Cloud Climatology Project (ISCCP). These show that there is scope for further improvements to cloud amounts and optical properties in some regions. Improved simulation of these quantities is important both for forecasting and for climate change experiments. ISCCP data were also used to evaluate simulations in which the mean size of cloud drops is predicted. Sulphate aerosol created as a by-product of industrial emissions has a significant impact on the drop size, and hence also on the radiative properties of clouds, and climate. Recent experiments have shown a strong sensitivity of the results to the manner in which these relationships are represented, indicating the need for more comprehensive modelling of the aerosols which grow to become cloud drops. See also under **Climate Research** and **Atmospheric Processes Research**.

Re-analysis Project

Comparisons with satellite data inevitably provide a one-sided view of the model's performance and it is important to check

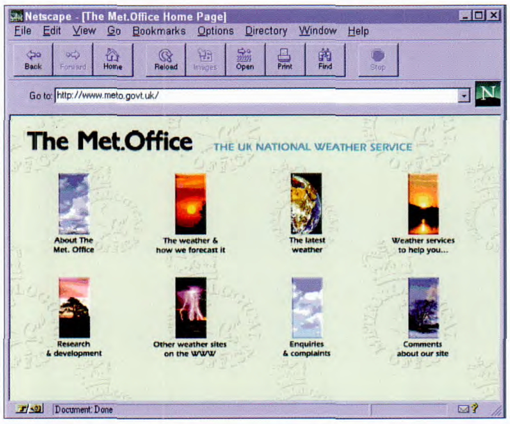


Figure 4. The Met. Office's Public Web Home Page (http://www.meto.gov.uk). Links from the home page allow Internet users to access current satellite and weather radar images as well as textual information such as the shipping forecast.

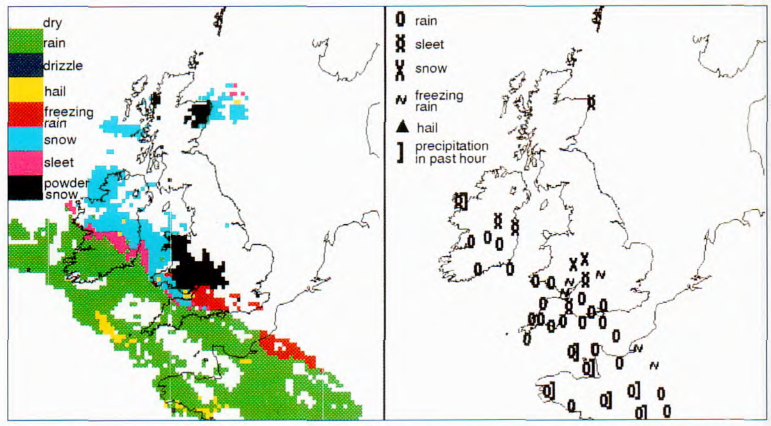


Figure 6. Diagnosed and observed precipitation types at 1200 UTC 30 December 1995.

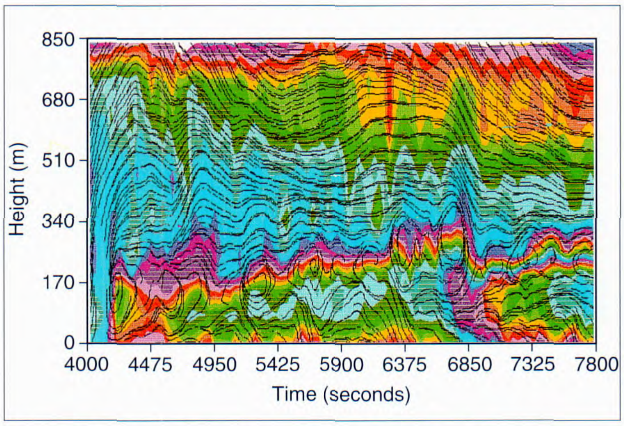


Figure 27. Time–height section of the temperature structure in an advancing sea-breeze density current (in colour) with black lines denoting 'streamlines' of the flow.

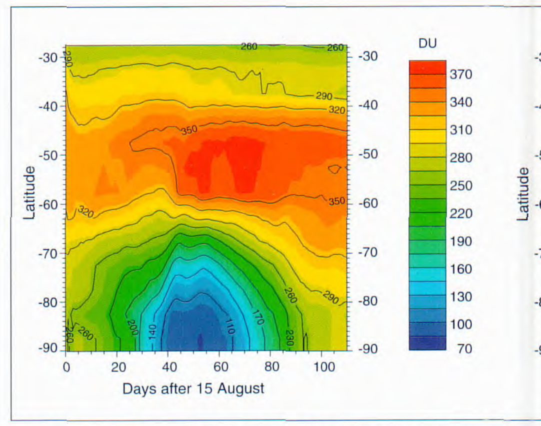


Figure 33. Model simulation of the Antarctic ozone hole with bac decrease in ozone for a post-Pinatubo aerosol loading (right-hand

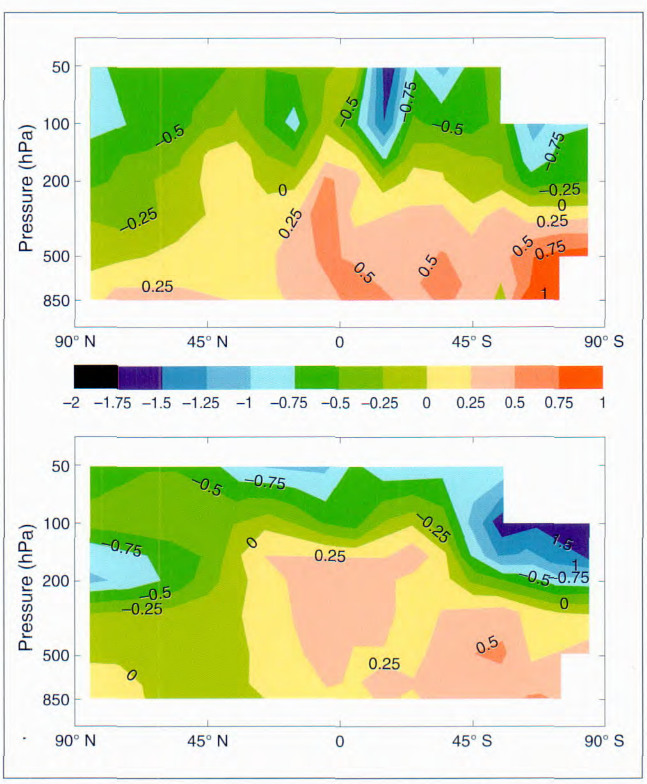


Figure 35. Observed zonal-mean cross-section of temperature changes between 1958–72 and 1979–93 (top); simulated changes with changing carbon dioxide, aerosols (mm day^{-1}) and ozone (bottom).

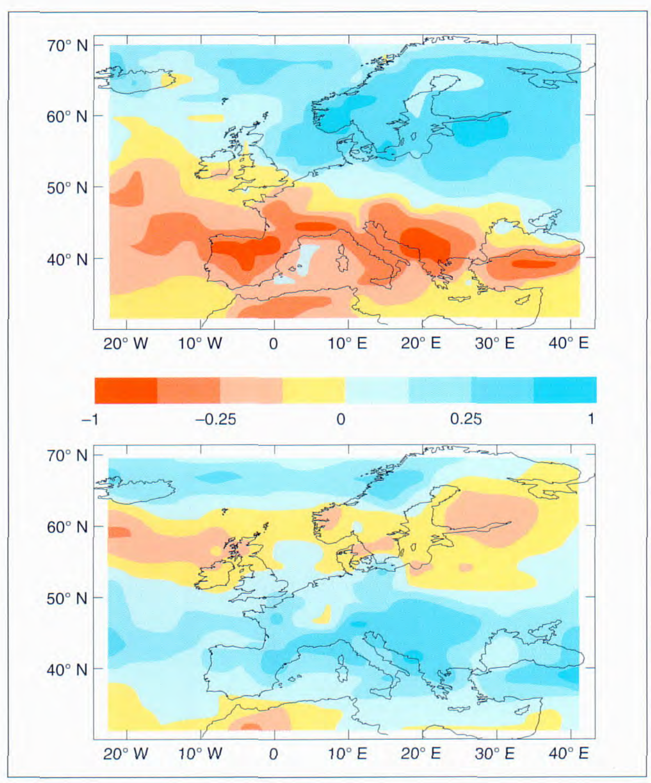


Figure 36. Simulated change in June to August precipitation over Europe due to the effect of increases in greenhouse gases alone (top); greenhouse gases and sulphate aerosols (bottom), (mm/day^{-1}, areas of decreases are shaded blue). The change is over the period 1860–2040, made assuming a 'best-estimate' emissions scenario.

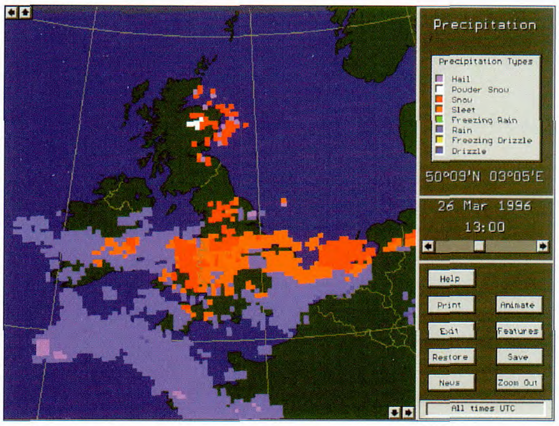


Figure 9. An example of a forecast of precipitation type now obtainable over the MIST system.

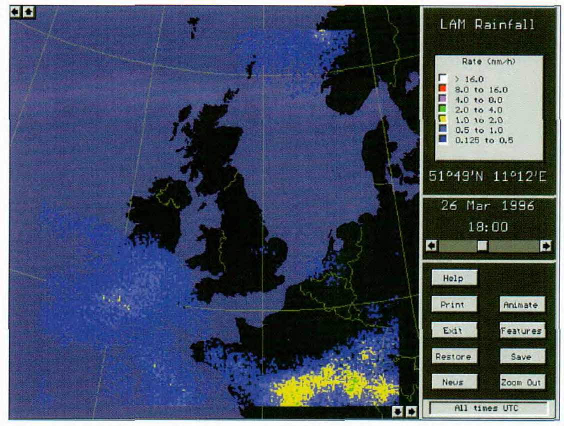
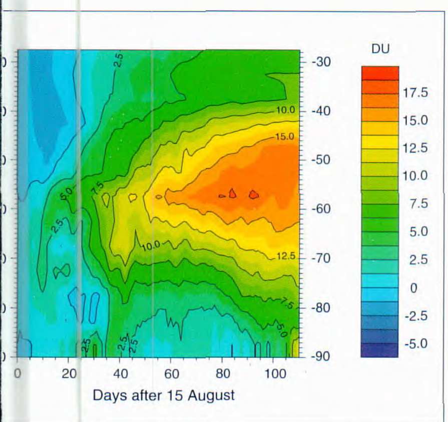


Figure 10. An example of a forecast rainfall field taken from a MIST display.



ground aerosol levels (left-hand panel) and the panel).

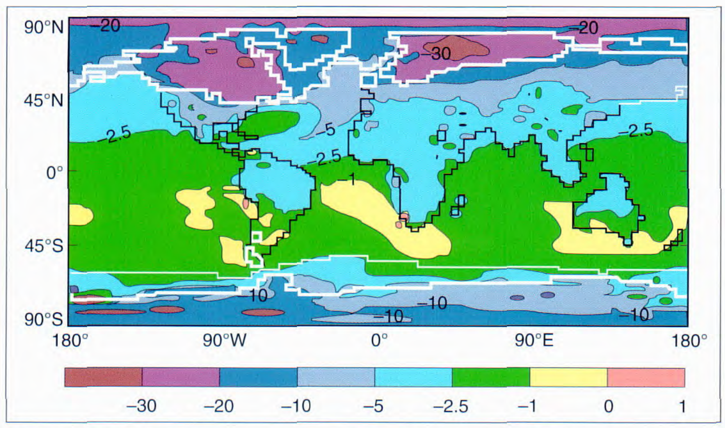


Figure 39. Change in annual mean temperature between the last glacial maximum (21,000 years Before the Present (BP)) and today using an atmospheric model coupled to a simple ocean. Contours at −30, −20, −10, −5, −1 and 0 K. Average cooling is 4.4 K. Thick white lines show the ice sheets, thin white lines show the sea extents at 21,000 BP.

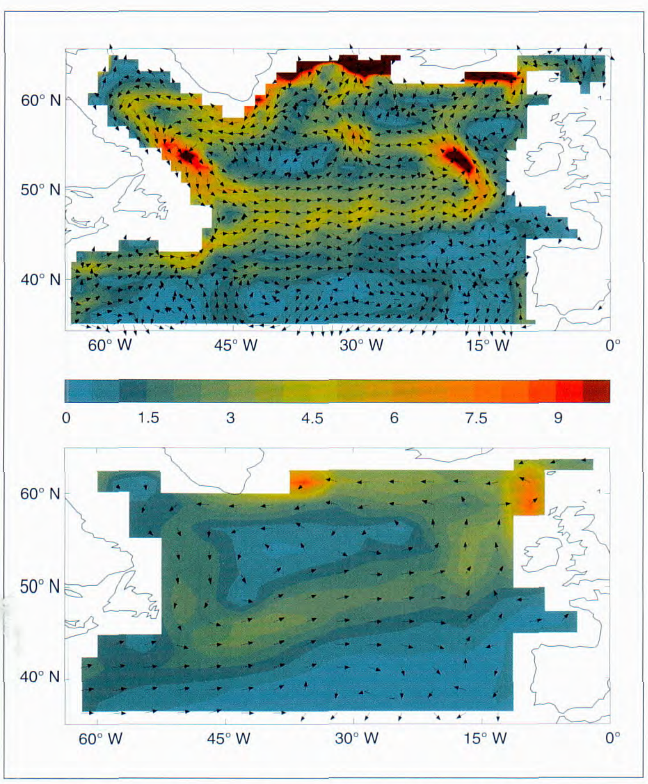


Figure 44. The simulation of the North Atlantic ocean gyre at 666 m using the 1.25 x 1.25 degree model (top); and the 2.5 x 3.75 degree model (bottom). In the higher resolution case the gyre is considerably more realistic. The representation of this northern gyre is particulaly important in simulating the uptake of heat by the oceans at high latitudes.

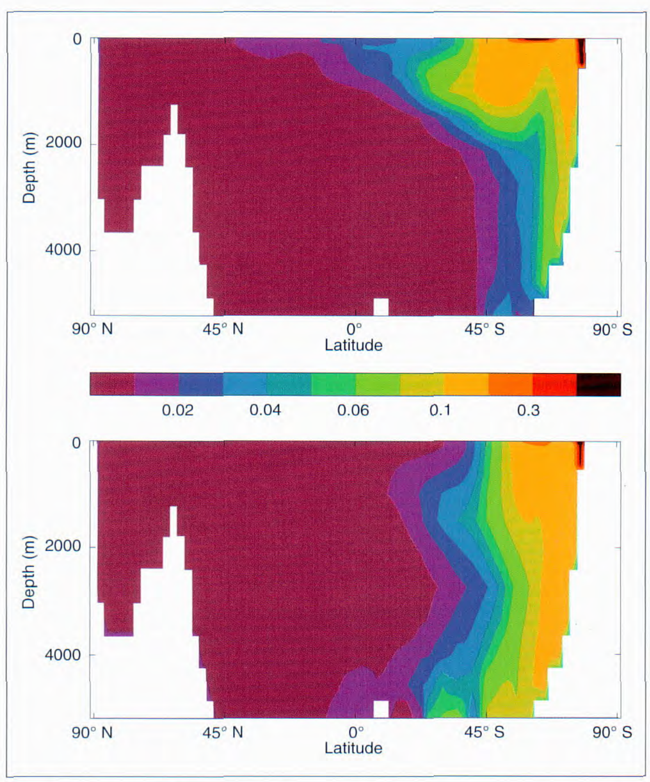


Figure 45. Modelled concentrations of a tracer which has been introduced at the surface of the ocean south of 60° S, at a constant rate, for 100 years. The figure shows the strikingly different ventilation patterns in the cases of weak (top); and strong ocean vertical mixing (bottom).

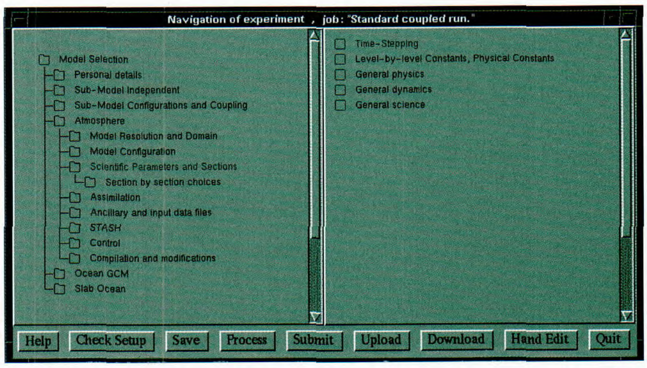


Figure 21. The main navigation window of the UMUI. Nodes in the tree (left) may be expanded and collapsed. In this example, the atmospheric model node is expanded. Selected nodes are opened up to display windows (right).

the simulations at all levels. For the radiation fields, this is being achieved through involvement in the ECMWF Re-analysis Project, which is providing a much improved three-dimensional climatology of the atmosphere for the period 1979–93. Using the new radiation code, simulations are being performed of the thermal radiation fields at the top of the atmosphere and also at the surface, as well as the vertical profiles of atmospheric heating rates. These simulations provide tools for a deeper evaluation of the UM performance than has hitherto been possible, as well as a wealth of information for understanding the factors which control the greenhouse effect.

Computer implementation

UM User Interface

The UM supports a wide range of options and is designed to be as flexible as possible. This often means that a large number of parameters have to be set to specify and control a particular model configuration. This can be a time consuming and error-prone operation. To reduce the scope for error, and help the user be as productive as possible, a graphical user interface has now been developed. The new software, known as the UM User Interface (UMUI), is X-Windows based and is designed to be portable and user friendly.

The UMUI runs in the familiar environment of the user's own local workstation and is designed to give access to all the functions of the UM and speed the learning process. By use of interactive windows, a user may control parameters such as model resolution, the date and time of the initial data, the length of forecast, the choice of output diagnostics and so on. The user may also control the scientific content of the model by selecting from a library of alternative representations of the physical processes, see Fig. 21.

Jobs

Using a central database that works in a distributed environment, the UMUI provides an efficient method of defining model runs and for managing those definitions. A run definition is known as a job. Users can search for, and copy, jobs belonging to colleagues, and definitions can even be sent by e-mail from one site to another. This allows colleagues and collaborators at remote sites to increase their efficiency by pooling their effort and knowledge. The job management system also provides help for users wanting to upgrade from one version of the UM to another.

The UMUI also contains a comprehensive job definition system. This is an intelligent editor that allows modifications to be made to existing jobs. It is made up of a large number of windows, each with visual clues to ensure that users can quickly see when options have been disabled due to other responses. Each window has a help button that displays information relating to the options available.

Once a job has been defined, the responses are translated into control files that can be read by the UM. On request, the UMUI will then copy these to the target machine and submit the job. The control files are text based so a user can easily override the UMUI by editing the control files. This makes it easier to develop new facilities.

Use of massively parallel computers

Recent history

For the last three decades The Met. Office has used some of the world's most powerful computers to produce numerical weather forecasts and, more recently, predictions of global climate. The enormous increase in computer power over this time, combined with advances in numerical methods and the understanding of atmospheric processes, has enabled constant improvement of the accuracy of forecasts and the speed of their production. The architecture of supercomputers used by The Met. Office has evolved significantly over this period. From the scalar IBM 360/195, through the vector Cyber 205, to the current machine, a parallel vector CRAY C90, The Met. Office has utilized the most-effective architectures for achieving maximum performance from its numerical models. See also under **Information Systems**.

Parallel Processing

The next stage in supercomputer design appears to be Massively Parallel Processor (MPP) computers. Unlike the CRAY C90 where a modest number (16) of specialized and expensive processors address a single memory space, MPP computers consist of many hundreds of commodity processors, with each processor usually owning its own distinct memory space. MPP computers offer a scalable increase in computer power with the number of processors. To transform traditional shared memory codes written in FORTRAN, so that they use the distributed memory architecture of MPP computers efficiently, requires compiler technology that is not yet available. This means that the current UM code must be modified to take explicit account of distributed memory if the model is to be run on MPP computers. See also **Mainframe computing** in **Information Systems** section.

Domains

The method used for exploiting distributed memory computers is called 'domain decomposition'. The geographical area covered by a UM integration is split up into rectangular sub-domains, and each sub-domain is assigned its own processor. For much of the time, calculations within each sub-domain are independent of their neighbours. However, at certain points through the computation it becomes necessary for the sub-domains to exchange data. This exchange of data is achieved using 'message passing', Fig. 22.

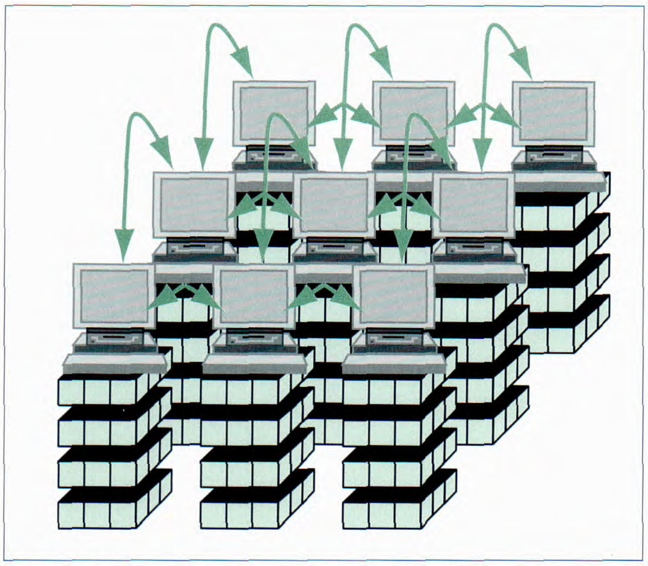


Figure 22. A schematic diagram of domain decomposition.

Message passing

One potential problem with message passing is that a variety of message passing libraries exist and most manufacturers also have their own high-performance machine-specific libraries. These systems have many basic functions in common but have different interfaces. For this reason, The Met. Office has chosen to use a 'portable' interface to message passing, called the General Communication (GCOM) library. This allows the basic functions of many different message passing systems (including manufacturer-specific systems) to be accessed via a consistent interface without changing the code when different message passing libraries are used.

During the past two years, the atmospheric component of the UM has been converted to use message passing. Tests using key sections of the code have has been run on a number of MPP computers which have shown the model to be scalable over many hundreds of processors.

Treatment of atmospheric flow as that of a compressible fluid, obeying classical physical laws, has led to successful weather forecasting by computer. However, many important processes are poorly understood, or occur at too fine a scale to be resolved on a forecast model grid (e.g. cumulus clouds). These processes need to be represented (or parametrized) in terms of other Unified Model (UM) variables to improve the accuracy of the forecasts. The level of complexity involved in some phenomena (e.g. radiative transfer in a field of convection clouds) is often formidable and requires a deep understanding of the underlying physics. The role of Atmospheric Processes Research (APR) is to combine observational, numerical-modelling and theoretical studies to improve the representation of these processes through greater understanding.

Data gathering

Observational research in The Met. Office centres around the instrumented C-130 aircraft of the Meteorological Research Flight (MRF) (Fig. 23) and a tethered kite balloon system based at the Meteorological Research Unit, Cardington. In addition to its research function, the tethered balloon has also been used to make routine ascents for the Central Forecasting Office providing detailed profile data up to heights of 1–1.5 km. Because of the high cost of observational campaigns it is often necessary to participate in major international collaborative projects to obtain the required data sets.

Models

A number of very-high-resolution numerical models are used to study convection, the boundary layer and mountain flows. These often provide highly realistic descriptions of atmospheric flow phenomena, and their output data sets may be regarded as a substitute for real observations. They have the advantage of far better spatial and temporal resolution, but they have the potential to be misleading if the model is deficient in any respect.

In addition to the core research function, APR supports some Public Met. Service activities such as the development of the Nuclear Accident Model (NAME) and an air-chemistry model.

The Visiting Scientist scheme and university training programmes strengthen collaboration.

Meteorological Research Flight

Campaigns

The C-130 research aircraft was involved in a number of experiments abroad, notably in Ascension Island and Namibia. These two detachments were undertaken to study the radiative properties of stratocumulus cloud (Sc) over the Southern Atlantic. Some of the flights were arranged to coincide with overpasses of the Along-Track Scanning Radiometer (ATSR-2) orbiting aboard ERS-2. These coincident data will be used to validate methods of retrieving sea-surface temperature and cloud properties. Shorter visits were made to Europe for a variety of international remote-sensing experiments.

NERC

There has been a great deal of success in bringing in funds to support the aircraft's activities over the next few years. Four EC contracts have been initiated and a contract with Natural Environment Research Council (NERC) has now formalized the growing university interest in using the aircraft. Much of this contract work requires new instrumentation to be fitted to the aircraft to meet new requirements in atmospheric chemistry and aerosol physics. Progress with these installations is well advanced and the flying programme for the next few years is extremely full and exciting. One of the new aspects of the work with NERC was a flight with the NERC remote-sensing aircraft to study sediment-laden water. Another was a flight in which air samples were subsequently analysed to determine the ratio of various stable isotopes within methane (which provides evidence for its origin).

Figure 23. The MRF C-130 being prepared for a flight from Ascension Island in May 1996.

Absorption of solar radiation in clouds

Some recent papers have claimed that clouds absorb four to five times more solar radiation than can be accounted for by current understanding. Such an increase in cloud absorption, if correct, would have a significant effect on our forecast and climate models. Data collected from the C-130 aircraft over the last ten years, from a number of different locations worldwide, have been analysed to see if this 'enhanced' absorption was present in any of the cloud fields which were sampled. One analysis studied the transmission through Sc and is shown in Fig. 24. The black lines were calculated from the radiation code recently developed at the Hadley Centre, using values of solar zenith angle corresponding to the maximum and minimum values observed. Both the dashed and solid green lines are attempts at introducing the 'enhanced' absorption into the model. The former assumes that the enhancement is in the near-infrared region of the solar spectrum (where almost all absorption by liquid water is thought to take place) whereas the latter also enhances the absorption in the visible region. It can be seen that the existing model, without any 'enhanced' absorption, gives the closest agreement to the observations. The conclusion of this study was therefore that the claim could be ignored.

Cloud and aerosol

The indirect effect of aerosols has been identified as one of the largest uncertainties in the radiative balance of the earth's atmosphere, and it needs to be determined for climate-change prediction. The aircraft has now been involved in several measurement campaigns to study the effects of aerosols on warm clouds (clouds with tops warmer than 0 °C). For instance, during June 1994 the aircraft participated in a multinational experiment to investigate the effect of the emissions of aerosols from ship funnels on the microphysics of stratus and Sc layers. This experiment provided an opportunity to study anthropogenic aerosol in a very controlled manner. It was found that diesel-powered ships emit significant quantities of aerosol that are good cloud condensation nuclei (CCN). The ships can cause local increases in the concentration of CCN in the marine boundary layer by about an order of magnitude. This increases droplet concentrations and decreases droplet sizes, which changes the radiative transfer characteristics of the clouds; this in turn allows a ship's track to be observed in the cloud from satellites. (See page 31 of last year's S & T Review for a satellite image.) One of the more surprising results of this investigation, which may have wider implications, was how rapidly the aerosol from the ships was being processed by the clouds; this resulted in a significant change in the aerosol size spectrum with time. Fig. 25 shows a contour map of the time-series of the aerosol-size spectrum during a flight leg below cloud. The aircraft was zigzagging in and out of a ship plume as it moved away from the ship. Directly above the ship the particle sizes emitted are relatively small, no larger than 0.2 µm. However, 70 km away from the ship the largest particle sizes in the plume are greater than 0.4 µm. This change in aerosol size distribution is likely to be radiatively significant. The concentrations of this size of particle cannot be accounted for by the entrainment of background air into the plume. Efforts are being made to determine the importance of coalescence and aqueous-phase reactions in cloud in modifying the aerosol spectrum.

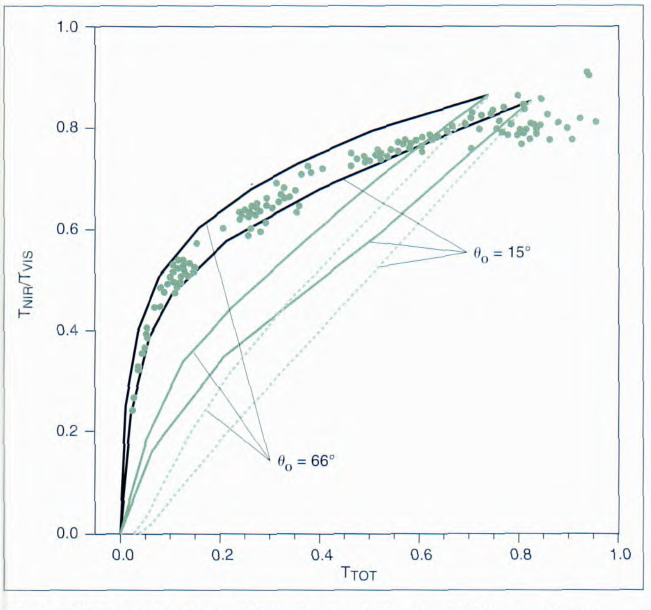


Figure 24. The ratio of near-infrared transmission to visible transmission (T_{NIR}/T_{VIS}) plotted as a function of total solar transmission (T_{TOT}) during a series of low-level runs beneath Sc. The dots represent the aircraft measurements. The solid and dashed lines are calculated values based on various assumptions, see text. The angles θ_o refer to solar zenith angle used in the set of calculations.

Clouds and the ice phase

The radiative transfer characteristics of clouds and their potential for producing precipitation is very dependent on whether they are composed of liquid or ice. There remains a great deal of uncertainty about how clouds glaciate. To help

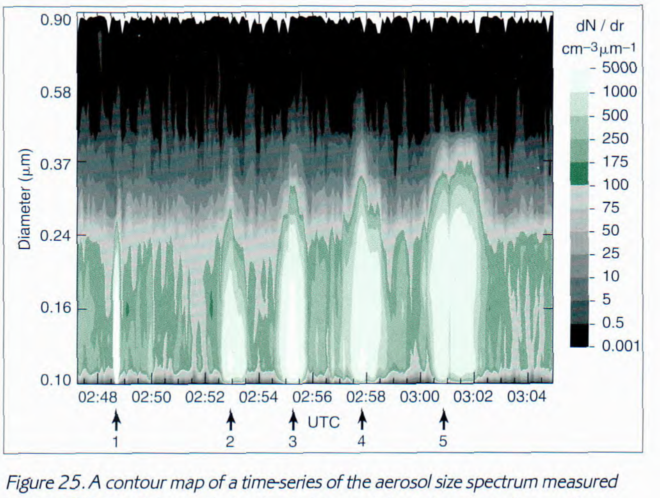


Figure 25. A contour map of a time-series of the aerosol size spectrum measured by the MRF aircraft beneath cloud as it zigzagged through a plume from a diesel-powered ship showing the evolution of the aerosol as it moves away from the ship. Penetration number 1 of the plume is almost overhead the ship. Penetrations 2, 3, 4 and 5 are progressively further away from the ship ending at a distance of approximately 70 km where the aerosol in the plume has reached its largest size.

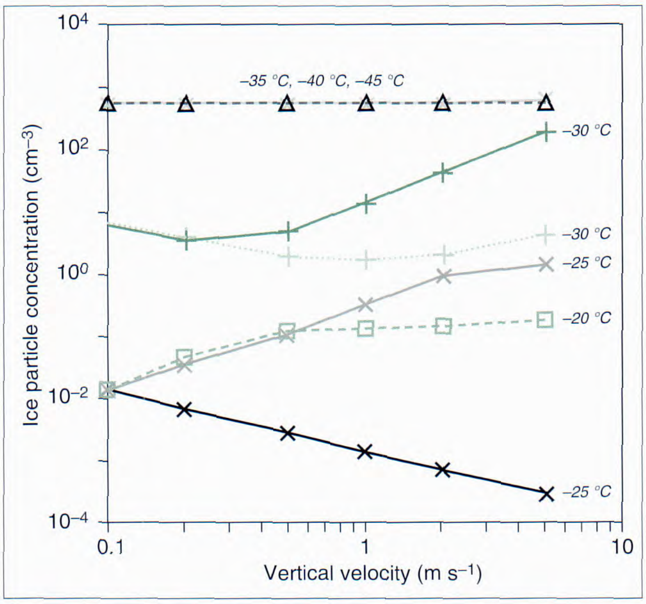


Figure 26. Model-predicted ice particle concentrations in a parcel of air that has ascended 1000 m above the condensation level as a function of vertical velocity. Solid lines represent runs where homogeneous freezing has been allowed, dashed lines where homogeneous and heterogeneous nucleation is occurring. The different symbols indicate clouds with different, noted, cloud-base temperatures.

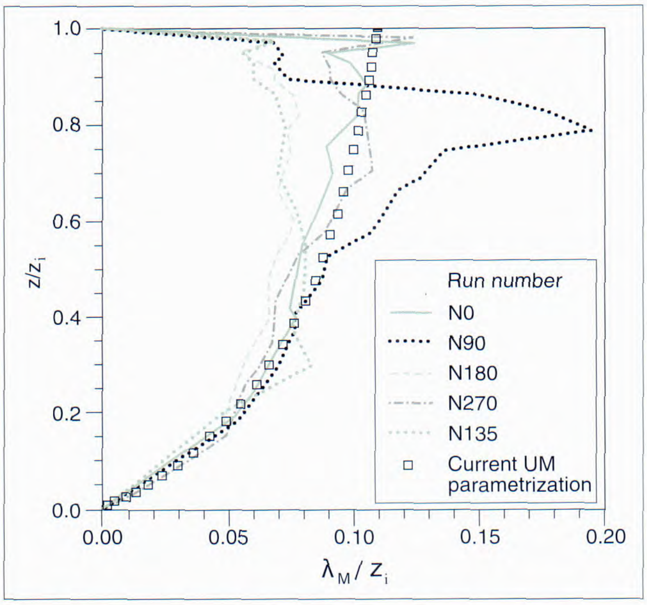


Figure 28. Profiles of mixing length (λ) normalized by the boundary layer depth (z_i), from five large-eddy simulations with shear in the geostrophic wind. Also shown is the current UM parametrization (squares).

understand the processes involved in this, the C-130 has been used to make measurements in orographic clouds where the nucleation of new ice particles can be observed in isolation. The results are being compared with simulations from a simple parcel model which allows both the homogeneous freezing of supercooled water drops and heterogeneous processes – such as sublimation of water vapour directly on to ice nuclei (IN). The IN concentrations have been parametrized in a variety of ways to establish the sensitivity of the model to heterogeneous processes. Fig. 26 shows a comparison of the ice-particle concentrations predicted by the model for different vertical velocities and cloud-base temperatures, first, when only homogeneous freezing is allowed, and second, when a combination of homogeneous freezing and heterogeneous processes occur. In this case the heterogeneous processes have been parametrized as a function of supersaturation with respect to ice. It is generally found that homogeneous freezing dominates the glaciation processes at temperatures below −35 °C. However, at higher temperatures concentrations of IN become increasingly important in determining the formation of ice particles in clouds.

Boundary layer

Sea breeze

In 1995 the Met. Research Unit studied the structure of sea breezes on the North Humberside coast. Three sea breezes passed through the instrument array (including tethered balloon) and a uniquely detailed data set was obtained. The balloon-mounted turbulence probes rapidly sample temperature, humidity and three wind components and were equivalent to flying nine instrumented aircraft simultaneously through the fronts at different levels. No such data have previously been obtained for any frontal circulation. The study has been focused on entrainment at the inversion above the sea breeze; this affects the dispersion of coastal pollution.

Analysis of the data shows that one of the sea-breeze fronts penetrating into a convective boundary layer has a structure similar to that deduced from previous studies – with a pre-frontal updraught, a frontal 'head' and entraining Kelvin–Helmholtz instabilities running along the interface. Details of the 'head' from the measurements are shown in Fig. 27 (centre pages). Other cases being analysed show a more complex structure with gravity waves above the density current.

Mixing length and shear

It has recently been suggested that the presence of vertical shear in the geostrophic wind leads to the failure of simple mixing-length closures like the one used in the boundary-layer scheme of the UM. However, Fig. 28 shows the mixing length diagnosed from five, neutral, large-eddy simulation runs with varying geostrophic shear, and this suggests that it is only a weak function of that shear. Furthermore, the simulated mixing-length profile is well reproduced by the current UM parametrization.

Cloud-top entrainment

Forecasting Sc formation and dispersion remains a high priority, and the controlling physical processes are subtle – particularly entrainment at the cloud top. As a first step towards parametrizing cloud-top entrainment in all types of convective boundary layers, high-resolution three-dimensional large-eddy simulations were run with convection generated only by combinations of surface-heating and cloud-top radiative cooling

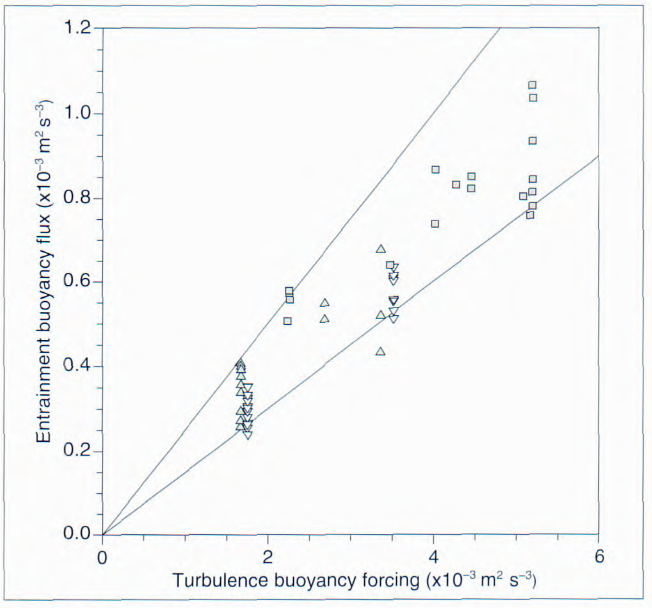


Figure 29. Modulus of the entrainment buoyancy flux (averaged over various hours of the simulations) plotted against a parametrization of the turbulence buoyancy forcing (a linear combination of the surface buoyancy flux and the cloud-top radiative cooling). Downward-pointing triangles denote simulations with radiative cooling only, upward-pointing triangles surface-heating only, and squares combined forcing. The lines represent constants of proportionality equivalent to 15 and 25%.

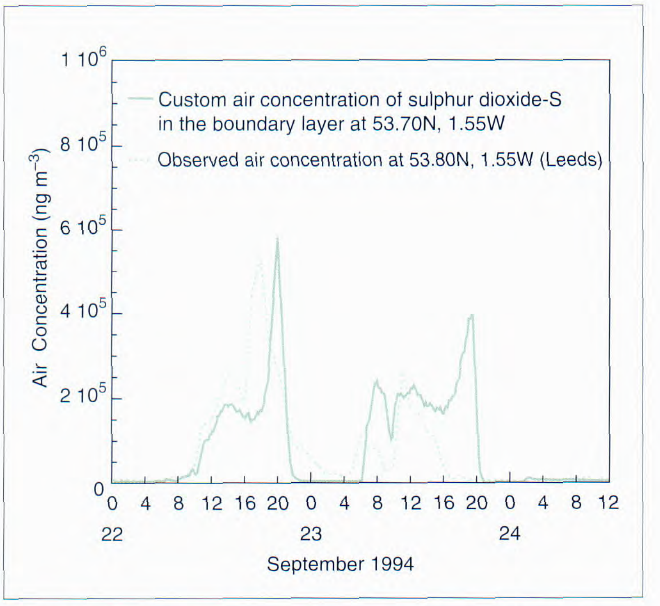


Figure 30. A time-series of air concentrations of sulphur dioxide during a severe episode at Leeds, 22–23 September 1994, as modelled and observed using a customized high-resolution grid with the NAME 2.1 dispersion model.

(with the latter driven by a 'dust' cloud to remove the complicating effects of liquid water). The results were analysed to determine whether there is a difference between the entrainment characteristics of surface-heated and top-cooled boundary layers.

The results shown in Fig. 29 suggest that about 20% of the energy supplied to the boundary-layer turbulence (through buoyancy forcing) is available to drive entrainment, whether the forcing is remote from the entraining interface or adjacent to it. This would appear to be the case despite the very different length scales for the entrainment process associated with each forcing mechanism.

Short-range dispersion

Over short ranges, dispersion is dominated by turbulence in the atmospheric boundary layer. The main Met. Office tool for predicting dispersion over short ranges is the Atmospheric Dispersion Modelling System (ADMS), a practical PC-based system developed in collaboration with Cambridge Environmental Research Consultants and the University of Surrey. Version 2, released during the year, extends the model to include treatment of multiple sources and pollutant species, area and line sources; it has improved treatment of concentration fluctuations, buildings effects and plume-rise modules, there is also a new user interface and graphical output. These improvements will enable it to be used for an increasing fraction of Met. Office short-range dispersion modelling.

Current models are not good at treating fluctuations in concentration, which are of great importance for toxic, flammable or odorous releases. Although a basic scheme has been incorporated in ADMS, further research has been conducted to improve our current understanding of fluctuations, particularly in the inertial-meander sub-range. This has explained the failings of some previous models.

Urban pollution

An improved box model, BOXURB, has been used for the national daily forecasts of urban pollutants. The model takes urban heating effects into account, and now separates NO_2 from the forecast of NO_x. Comparisons with observations from the Department of the Environment (DoE) urban monitoring network during the summer showed that the model performed better for large conurbations than for smaller towns. Trials with an associated street canyon model showed a fall-off of performance in summer – this is likely to be due to the effects of strong insolation. PM10, particulate matter below 10 μm size, is now considered a significant health hazard, and the statistics of its occurrence in combination with other pollutants were investigated with a view to producing forecasts.

Medium- and long-range dispersion

The NAME mesoscale and long-range multiple-particle dispersion model is the national operational model for emergency response in the event of a nuclear accident. In March 1996 version 1.0 was replaced by the latest version, 2.1. This work was under contract to the DoE Radioactive Substances Division. Changes to the model during the year included improved scavenging coefficients for washout from mixed-phase (ice and water) cloud, and the inclusion of a representation of plume-rise at source. Although the resolution of the input winds and meteorology for Lagrangian models of this type are necessarily fixed, the output diagnostics can be analysed on any scale for which the statistics of particle distribution are effectively stationary. Accordingly the model has

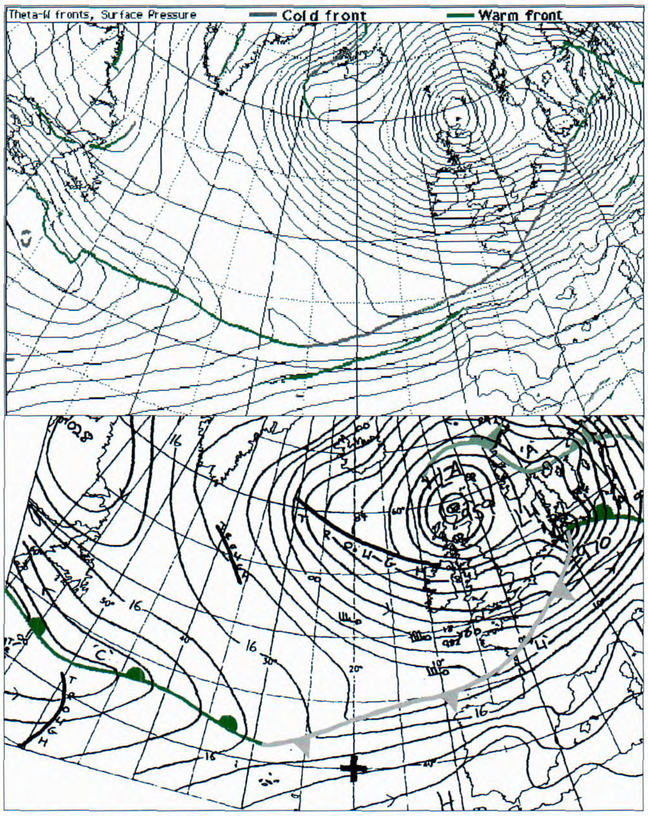


Figure 31. Each panel depicts surface pressure and surface fronts for 0000 UTC on 23 January 1995, with isobars at 4 hPa intervals. The objective fronts on the top panel are derived from a 900 hPa θ_w field; the lower panel shows the operational surface analysis.

been given a user-definable, high-resolution, near-source analysis grid, which has already proved its worth in an investigation of a sulphur pollution episode at Leeds in September 1994. This enabled the salient features of the meteorology and atmospheric stability controlling the incident to be clarified for HM Inspectorate of Pollution (Fig. 30).

The European Tracer Experiment, ETEX, the international validation study (described on page 36 of last year's S&T Review), has so far yielded only a provisional account of the spread of the perfluorocarbon tracer over Europe. This suggests that NAME performed well in terms of the correlation between observed spread and model predictions, and did particularly well in comparison with other models during the later stages of the spread.

Objective frontal analysis

A new method has been devised which will plot atmospheric fronts objectively. Input data comprise values of a thermodynamic variable (such as the wet-bulb potential temperature) at grid points on a near-horizontal atmospheric level (such as a pressure surface). Diagnostic quantities are derived from the input data, and then standard graphical facilities, such as contouring and masking, are used to depict these quantities. The resulting plot shows the fronts as (coloured) lines, which can then be overlaid on any other field (such as surface pressure or imagery).

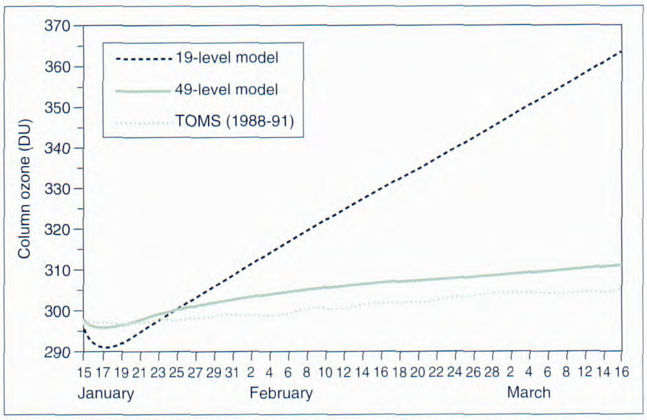


Figure 32. Globally averaged ozone versus time for two different vertical resolutions in the UM compared to the observed values (TOMS data).

The example in Fig. 31 compares objectively and subjectively drawn surface charts; there is generally good agreement between the two. Note also that the objective fronts coincide with troughs in surface pressure, implying that a thermodynamic definition is sufficient.

On the figure, cold fronts are grey, warm are green; this distinguishes between cold and warm fronts according to the sign of the thermal advection. Other front-related variables – such as vorticity, humidity and vertical motion – can be used as 'colouring variables' to highlight different aspects of frontal structure. Fronts can be plotted at several atmospheric levels to find quantities like frontal slope. When these extensions to the general methodology are animated the objective front-plotting process becomes an extremely powerful tool to use in both forecasting and research.

Stratospheric chemistry – ozone

A full stratospheric chemistry scheme has been run for the seasonal timescale in the UM, with the model-computed chemistry interacting with the radiation scheme of the model. Fig. 32 shows the globally averaged ozone as a function of time for two different versions of the UM with differing numbers of levels. The poor ozone simulation in the 19-level model was largely due to the poorly simulated meridional circulation. This shows the need to have a reasonable number of levels in the stratosphere in coupled chemistry–climate simulations.

In a study of the effects of the Mt Pinatubo eruption, an aerosol chemistry scheme has been included in the stratosphere–mesosphere model. Two sets of calculations were performed corresponding to background aerosols and volcanic (post-Pinatubo) loadings (see Fig. 33, centre pages). In this model simulation the ozone decrease reached 18 Dobson Units at the edge of the polar vortex and the vertical range of ozone depletion is extended above the ozone hole. The results support previous suggestions that the eruption of Mt Pinatubo resulted in a temporary increase in ozone depletion over Antarctica and elsewhere. See also **Ozone** in **Observations** section.

Climate research in The Met. Office is undertaken at the Hadley Centre:

to understand the processes which control climate and develop climate models which represent them;

to use the models to predict climate change over the next decades;

to monitor climate variability and trends; and

to use observations and model simulations to detect climate change and find its causes.

The work is supported jointly by The Met. Office and the Department of the Environment (DoE); DoE place specific requirements on the programme to support the formation of policy on controls to greenhouse-gas emissions.

The climate model used for simulations and predictions is based on the Unified Model (UM) of the atmosphere, coupled to models of the ocean, sea-ice and the land surface. The long-term programme sees a progressive integration of the sulphur cycle, land and ocean carbon cycles, and atmospheric chemistry, so that the main potentially important feedbacks can be included in climate predictions. Long runs of the model use the Cray C90 supercomputer, but the results are displayed and analysed on a workstation system, which was comprehensively upgraded during the year.

Detecting and attributing climate change

To claim detection of climate change, the observed change has to be shown to be larger than the internal variations which occur naturally when there are no external influences (like detecting a 'signal' above 'noise'). A recent 1000-year coupled ocean–atmosphere simulation (with no change in external forcing) shows variations in global-mean temperatures of one or two tenths of a degree Celsius on timescales of a decade or longer (Fig. 34). Assuming the model adequately simulates real internal variability, then the 0.5 °C increase in global-mean

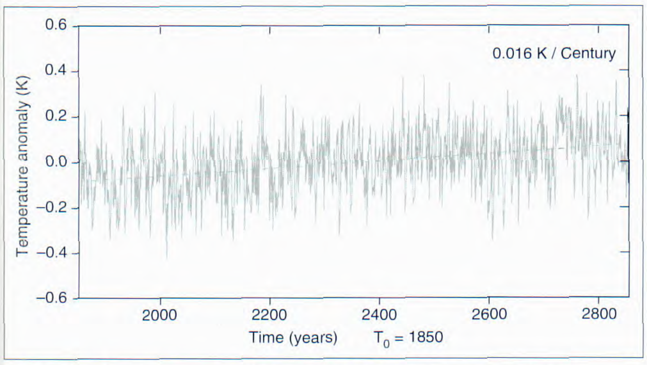


Figure 34. Anomalies in globally averaged surface temperature from a 1000-year control simulation with a coupled ocean–atmosphere model. The small trend of 0.016 K/century is shown by a dashed line

temperature over the last 100 years is very unlikely to have occurred by chance; in other words, a change in climate outside the range of natural variability is detected.

Causes

The observed warming could be due to human activity, or it could arise from natural external causes such as changes in solar output or the concentrations of volcanic dust.

The attribution of the change to a particular cause is more difficult than its detection.

Aerosol

Last year we reported that the inclusion of cooling due to increases in man-made sulphate aerosol brings simulations of global mean climate change in the coupled ocean–atmosphere model into better agreement with observations made over the last few decades. Comparison of the patterns of temperature change with the variations in the 1000-year control simulation indicate that the modelled (and the observed) changes are unlikely to have occurred by chance. Furthermore, statistical tests indicate that the spatial patterns of simulated change, both in the horizontal and in the vertical, are more like those observed when the aerosol effect is included. These results had a strong influence on the 1995 IPCC report which concluded for the first time, with proper caution, that: 'The balance of evidence suggests a discernible influence of human activity on global climate.' Including stratospheric ozone reductions further improves agreement between modelled and observed vertical patterns of change.

Further experiments are planned to test the effects of changes in solar output and volcanic activity. If these effects do not explain recent observations then we will be more confident that recent warming is due to human activities.

Sea temperature

A complementary technique for the detection and attribution of climate change relies on the atmospheric model linked to sea-surface temperatures (SST) varying as observed over the last few decades. In this way, much of the natural variability of the climate will be included, giving a lower 'noise'. However, the 'signal' can now only be searched for in the atmosphere over land areas and at higher levels over the oceans. The atmospheric climate model was forced in this way with historical SST and sea-ice data for 1949–94. Several ensembles of four members were made, each member having different initial weather conditions to estimate natural climatic variability. Each ensemble was driven by different changing atmospheric factors. These were: the observed increasing concentrations of greenhouse gases; a representation of increasing tropospheric aerosols; observed reductions in stratospheric ozone, and fixed forcing. In the lower stratosphere, best agreement with observations occurred when CO_2 was increased and stratospheric ozone decreased. Best agreement with observed tropospheric temperature changes occurred when changes in CO_2, tropospheric aerosols and stratospheric ozone were all included. Fig. 35 (centre pages) compares observed zonally averaged temperature changes between 1958–72 and 1979–93 with the simulated changes from the latter experiment. These results are consistent with those found using the ocean–atmosphere Global Coupled Model (GCM).

Predictions of climate change

Assumptions

Changes in climate to the end of the next century have been predicted using the coupled model with expected increases in greenhouse gases and aerosols. The results are sensitive at the regional level to the assumptions made. For example, continued growth in aerosol and greenhouse gases leads to increased summer rainfall over southern Europe, whereas increase in greenhouse gases alone leads to reductions in rainfall (Fig. 36, centre pages).

Extremes

Although much emphasis has been put on mean changes in climate, changes in extreme events are also as important for climate impact studies. Extreme events are often associated with small-scale phenomena which are not well represented in the coarse-resolution models. For example, a high-resolution model of daily precipitation intensity over Europe produces more heavy events and fewer moderate events than the global model (Fig. 37(a)), in better agreement with observations. Both models produce an increase in the number of days with heavy rainfall when CO_2 is doubled (Fig. 37(b)).

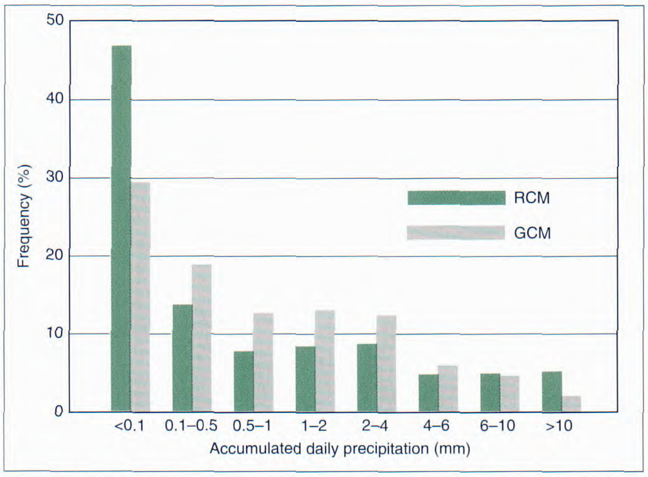


Figure 37(a). Frequency of daily precipitation rates over western Europe as simulated in the global and regional models.

Model validation

Validation of climate models has focused on two simulations, both over the Atmospheric Model Intercomparison Project (AMIP) period of 1979–88, with different model resolutions: 2.5° latitude x 3.75° longitude, as used in climate predictions, and 0.833° x 1.25° as used for Numerical Weather Prediction. The higher resolution gives a better representation of the flow over the winter North Atlantic, but in summer reduced cloud cover over Europe leads to excessive warmth and drought.

Other studies have included modelled tropical moisture using a trajectory approach, the model's tropical cyclones, and the near-surface behaviour over the ocean using the Ocean Weather Ship record. This last shows excessive model air–sea temperature differences. The new European Centre for Medium-range Weather Forecasts re-analysis data for the AMIP period are among the data added to the archive for use in model validation.

Blocking

Sustained periods of high pressure over western Europe ('blocking') lead to cold extremes in winter and warm extremes in summer, as well as marked precipitation anomalies. The current coupled model produces a much more realistic blocking over western Europe than its predecessor, though the amplitude is still too low (Fig. 38).

Glaciations

Past climates provide an opportunity for independent validation of climate models. The last glacial maximum (21,000 years ago) is one of the best documented periods in recent palaeoclimate. When changes in atmospheric composition and the terrestrial ice sheets are prescribed in a climate model with a simple ocean, the global-mean temperature change is in good agreement with 'palaeo' estimates. The cooling extends into the tropics (Fig. 39, centre pages); this is in agreement with palaeoclimatic reconstructions from terrestrial data, but not with marine data.

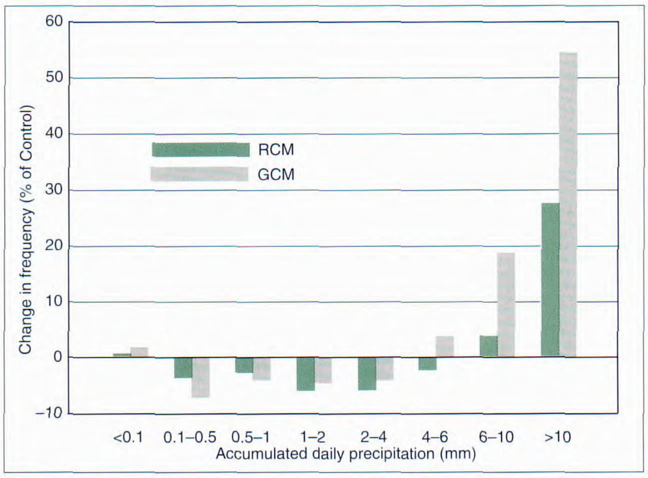


Figure 37(b). Changes in the frequency distribution of precipitation in the global and regional models with doubled CO_2 expressed as a percentage of frequency in the control simulation.

Model development

A new version of the atmospheric model, incorporating the Edwards–Slingo radiation scheme and an improved surface-exchange scheme, has recently been developed; it is now being tested ready for coupling to the 1.25° x 1.25° ocean model. It will then be used for the next series of transient climate experiments in 1997 after the model has been spun up.

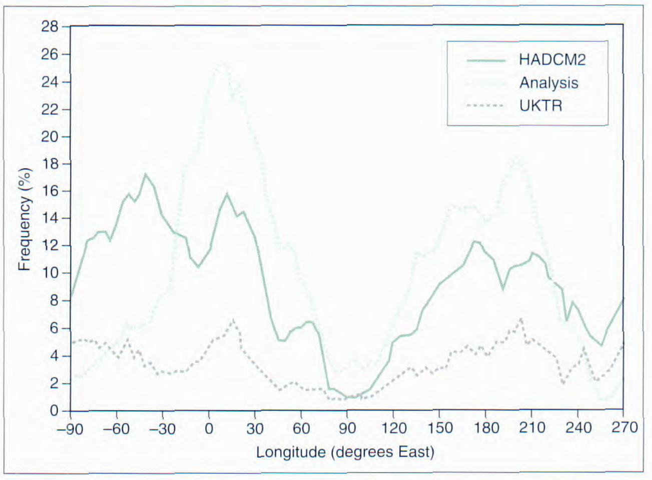


Figure 38. Frequency of blocking over northern mid-latitudes in winter. Solid line: new coupled model (HadCM2); dashed line: previous coupled model (UKTR); dotted line: analyses, 1983–93.

Hydrology and the carbon cycle

Soil moisture

A new Met. Office Surface Exchanges Scheme (MOSES) has been introduced into the UM. The soil component responds more realistically to the seasonal cycle by allowing for effects of soil moisture on temperature. These are caused by the large moisture dependence of thermal characteristics, and by the freezing and melting of soil water.

Evaporation

There is a new representation of evaporation. Models of photosynthesis and stomatal conductance have been developed for four plant functional types – broadleaf and coniferous tree, and two types of grass. These include dependences on solar radiation, temperature, vapour-pressure deficit, soil moisture and CO_2. Increasing CO_2 reduces transpiration from moist land surfaces, an effect previously neglected. The photosynthesis model provides simulations of the net atmospheric CO_2 input from land biota. These are being combined with the oceanic contribution to model the atmospheric CO_2 budget and its changes due to human activities (through fossil fuel burning and deforestation).

Atmospheric chemistry

Anthropogenic emissions of many pollutants influence concentrations of radiatively active gases such as methane and ozone. This influence is being simulated with a Lagrangian chemistry model, STOCHEM, driven by archived meteorology from UM simulations. Trace-gas fields from STOCHEM (Fig. 40) can then be used as boundary conditions for UM experiments.

Aerosols

Work on modelling sulphate aerosol using the UM has progressed substantially, as illustrated by the simulated anthropogenic aerosol loading in summer and winter (Fig. 41). The seasonal cycle is mainly due to higher summer concentrations of oxidizing chemicals (computed by STOCHEM) such as hydroxyl and hydrogen peroxide. We plan to include the sulphur-cycle model in the next version of the climate prediction model so that the links between aerosol and climate can be treated fully. See also **Cloud and aerosol** in the **Atmospheric Processes Research** section.

Observed climate variability and change

The maintenance, improvement and extension of properly quality-controlled databases of climate quantities is crucial to the improvement to our understanding of climate processes, climate variability and our ability to detect and attribute climate change.

Sea-temperature database

The new Global sea-Ice and Sea-Surface Temperature (GISST) database is being used by the National Prediction Center (USA) as part of their Atmospheric Data Re-analysis Project to provide a unique set of atmospheric data suitable for climate studies over the last 40 years. Major improvements have been made to GISST in the data-sparse period before 1950 using new analytical techniques. Major tropical Pacific El Niño warm events and La Niña cool events are now much better represented in the late nineteenth century (Fig. 42) and have typically the same size as late twentieth century events. This has important implications for studies of climate variability over the last century.

Sonde data

High priority is being given to improving radiosonde-based temperature analyses of the troposphere and lower stratosphere, which are proving invaluable for climate change detection projects.

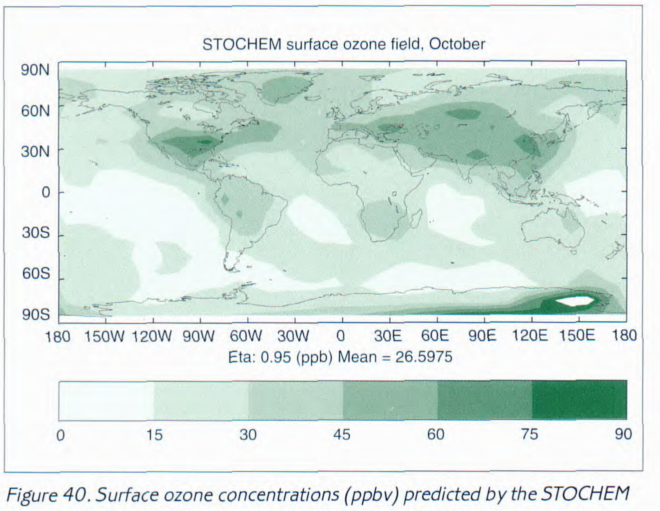


Figure 40. Surface ozone concentrations (ppbv) predicted by the STOCHEM chemistry model for October, in present-day conditions.

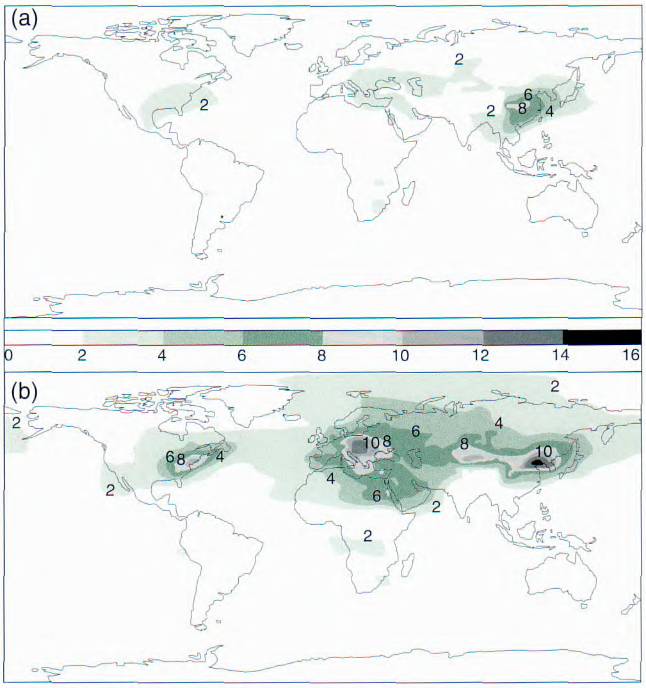


Figure 41. Column-integrated anthropogenic sulphate aerosol loadings in mg (SO_4) m^{-2}, simulated by the UM (a) June–August mean, (b) December–February mean.

Recent past

Marine temperature data analysed at the Hadley Centre have been combined with land-surface data analysed by the University of East Anglia to show that the global-mean near-surface temperature in 1995 was 0.4 °C above the 1961–90 average, the highest since the record started in 1861.

Middle atmosphere

The data

The UM data assimilation system has been adapted for use in the stratosphere and is now being run as part of the operational suite. Stratospheric analyses and forecast data have been used in the Second European Stratospheric Arctic and Mid-latitude Experiment (SESAME) campaign to study northern hemisphere ozone depletion, and for the Upper Atmosphere Research Satellite (UARS) project.

Analyses

Analyses from the assimilation system and from the Stratospheric Sounder Unit analysis system form an invaluable record for the study of the stratosphere. Fig. 43 is a time-series of the winds over the equator for the past four years, showing that the quasi-biennial and semi-annual oscillations have been successfully analysed. The analyses have also been used in a number of published studies to help interpret measurements from the UARS instruments.

Upgrades

During the past year, significant improvements have also been made to the stratosphere/troposphere configuration of the UM.

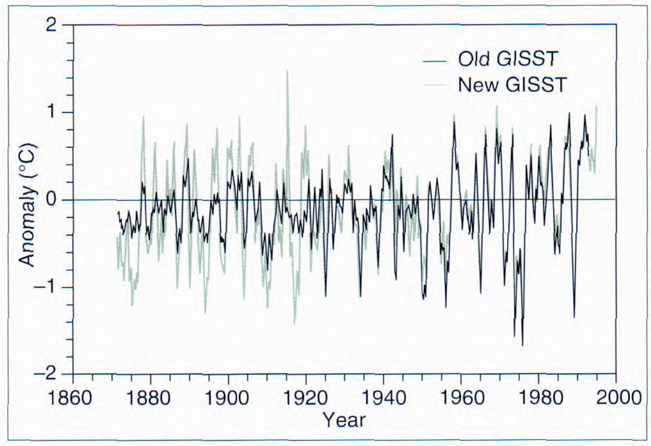


Figure 42. Five-month running mean sea-surface temperature differences (°C) from a 1961–1990 average for the area 5° N to 5° S, 90° to 150° W. Black lines are the original form of GISST; green lines are the new form of GISST.

This model now uses a set of physical parametrization schemes close to the 'third climate version' of the climate model, except that gravity-wave breaking in the lower mesosphere is parametrized by a simple Rayleigh friction scheme.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC, established in 1988, provides regular formal assessments to the UN Framework Convention on Climate Change (FCCC) to support negotiations on the control of greenhouse-gas emissions. Written and reviewed by leading experts in their field, IPCC reports are accepted as authoritative statements on climate change and its impacts.

The focus of the IPCC's Working Group I (WGI), co-ordinated by a Technical Support Unit based at the Hadley Centre, is the physical climate system. In 1995 WGI published two reports, *Climate Change 1994: Radiative Forcing of Climate Change*, and *IPCC Guidelines for National Greenhouse Gas Inventories*. The Support Unit organized a large number of workshops to draft the second major assessment report, the final version of which was agreed at a meeting of scientists and government representatives in Madrid in November 1995, and was published in Spring 1996.

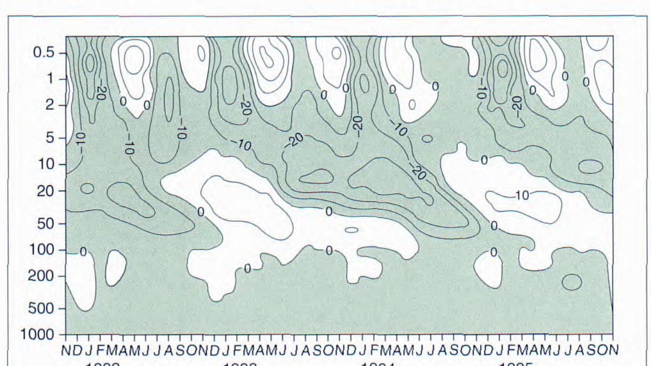


Figure 43. Time-series of zonal-mean westerly component of wind speed ($m\ s^{-1}$) over the equator from Met. Office stratospheric analyses for November 1992 to November 1995.

The Ocean Applications branch was formed during the year to draw together The Met. Office's work in ocean modelling for both climate research and operations. It encompasses: the development of ocean models for climate prediction (including ocean carbon-cycle and sea-ice models); the development of a real-time ocean analysis and forecasting system for the Royal Navy; operational wave-modelling, and tropical models and seasonal prediction. Work also started to establish the scope of the customer base for operational shelf-model products.

Ocean climate model development

Resolution and model systematic errors

To be confident of the results of coupled models it is important to represent accurately the physical mechanisms of heat transport in both atmosphere and ocean components. Compared to the version with a 2.5° x 3.75° resolution, a new version of the coupled model, with a horizontal resolution in the ocean of 1.25°, has led to a considerably more-realistic simulation of the major ocean currents, the sub-polar gyres and the equatorial current systems (Fig. 44, centre pages).

However, such models exhibit a number of systematic errors which require attention. For example, coupled models from various centres around the world have difficulty in simulating the sea-surface temperatures (SSTs) around the Antarctic continent. The temperatures tend to be too high, leading to a marked reduction in the Antarctic sea-ice extents unless appropriate corrections are applied. The warming was significantly reduced when an improved parametrization of horizontal eddy transports was added to the Hadley Centre ocean model, reducing the implied eddy heat transport across the Antarctic Circumpolar Current.

Correct simulation within the model of the position of the North Atlantic Drift (NAD), is important for the simulation of the SST pattern in the North Atlantic. In the model this has been found to be too zonal with adverse implications for its use for simulation of climate and climate change over Europe. Investigations of the model have shown the direction of flow of this current is related to the strength of formation of bottom water associated with the flow of dense water over the Greenland–Iceland ridge. Improvements to the representation of these processes are leading to better simulation of the NAD system.

Small-scale mixing

Small-scale mixing in the deep ocean has a profound effect on the global model circulation, but the strengths of the mixing processes are not well known. Tracer studies are being used in the ocean General Circulation Model (GCM) to assess the link between mixing rate and the 'ventilation rate' of the ocean (Fig. 45, centre pages). It is through the ventilation process that heat would be drawn down into the ocean in a warming climate. Initial experiments suggest an uncertainty of the order of 15% in the globally averaged ventilation rate.

Co-ordinate systems

The present ocean model employs a vertical co-ordinate system with levels at fixed depths. Isopycnic models, which use density as a vertical co-ordinate provide an alternative approach. These two approaches are being compared in a collaboration with the Southampton Oceanography Centre (SOC). Experiments carried out for the North Atlantic have helped to clarify the role of topography in the two model formulations. An initial comparison of quasi-global level and isopycnic models has highlighted differences in many areas of interest, including the tropical Pacific and Southern Ocean as well as the North Atlantic.

Eddies

Results from a variety of model-sensitivity studies are being used to examine the role of eddies in ocean circulation in collaboration with the Department of Meteorology at the University of Reading. Models with a simple rectangular domain have been run at 0.25° and 0.125° resolution, with a view to using the output both to validate currently proposed eddy parametrizations and indicate where developments may be needed.

Sea ice

Work on sea ice has concentrated on incorporation of a simple ice dynamics scheme into a version of the Hadley Centre's model which is used for climate sensitivity tests. There has also been some optimization of the handling of sea ice in the 1.25° resolution ocean model.

Carbon cycle

The SOC biological model, including phytoplankton, zooplankton, detritus and a single nutrient has now been added to the global ocean model. When combined with the inorganic model developed at the Hadley Centre, the full ocean carbon-cycle model reproduces annual plankton cycles quite well. A long spin-up of the global ocean carbon model,

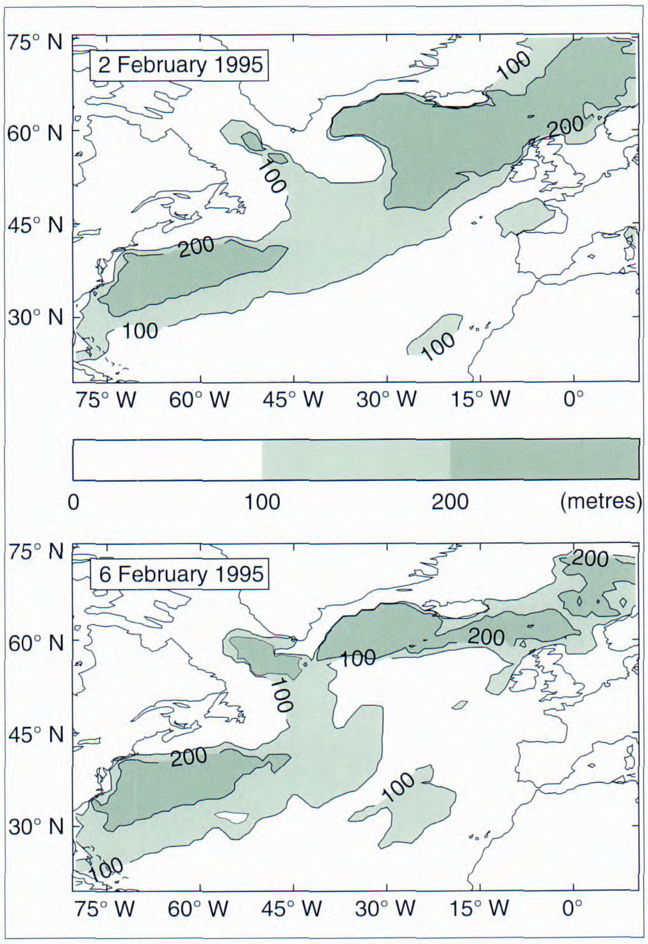


Figure 46. Mixed-layer depth from the FOAM analyses on 2 and 6 February 1995. The marked changes in the north-east Atlantic are typical of the synoptic changes represented by the FOAM system.

embedded in the ocean GCM, has now been used to produce a carbon budget for the current climate. Model runs with and without ocean biology have been carried out; they demonstrate enhanced uptake of carbon dioxide where biological production is high.

Ocean forecasting

Ocean–atmosphere model

The Forecasting Ocean Atmosphere Model (FOAM) is being developed to forecast the temperature and salinity of the upper ocean. This system is built around the ocean component of the Unified Model, running with 1° resolution in latitude and longitude for the whole globe. A data assimilation scheme has been added to the model using the same method as the atmosphere models.

The FOAM system takes observations of the ocean that reach The Met. Office in real time and uses the data assimilation scheme to produce a best estimate of the ocean temperature at the analysis time. A prototype of the system has run routinely since August 1994, so that more than a year of analyses are available. These have been used to assess the accuracy of the system and to clarify some of the systematic errors in the ocean model, many of which are shared with the versions of the model used for climate simulations (Fig. 46). Ocean observations are sparse, especially below the surface. Satellites can measure SSTs accurately over many areas of the globe, but cannot observe what is happening below the surface. However, one instrument, the radar altimeter, measures the departure of the surface elevation of the ocean from a reference state. Using an analogy with surface pressure for the atmosphere, the surface elevation of the ocean can be used to deduce information about the deep circulation of the oceans. Preliminary steps have been taken to do this in the FOAM system.

Wave modelling

New approach

Operational wave forecasts are central to many of the marine services of The Met. Office. For many years The Met. Office has used its own second-generation wave model to forecast sea state on both global and regional scales. This approach has proved to be both computationally affordable and upgradable (Fig. 47), but the limitations of this technique are becoming apparent. Future improvements to the accuracy of wave forecasts will be made by using the international third-generation wave model ('WAM'), which is being converted for use within the Unified Model.

Data assimilation

The assimilation of data into operational wave models was made feasible by the global European Remote-sensing Satellite measurements of wave height. The benefits of this are mainly felt in the global wave model, because the orbit of the satellite means that there are very few observations over the area of the regional wave model on any one day. Within the North Sea there is a dense network of stations observing waves, mostly based on visual estimates, but some are measured. Experimental analyses have been run assimilating these observations into the regional wave model. The main conclusion of this work was that without elaborate quality control of the observations, data assimilation may cause the analyses to be worse than hindcasts that do not use wave observations at all.

Shallow waters

As part of the Storm Tide Warning Service, The Met. Office runs a numerical model of the north-west European continental shelf. This model was developed at the Natural Environment Research Council's Proudman Oceanographic Laboratory (POL) and forecasts not only the sea-surface elevation that is of interest for coastal protection, but it also estimates the vertically averaged current. A later version of the model, known as UKOPMOD, extends the calculations to include the vertical profiles of currents. In a joint project with POL, this model is being prepared for running on workstations at The Met. Office. It will form a prototype system to be assessed for its usefulness in forecasting currents. Such forecasts will be useful for many surface and sub-surface activities.

Tropical modelling and seasonal prediction

Range

Skilful prediction of the day-to-day changes of individual weather systems is limited by chaotic events to a range of several days. However, for some regions and seasons there is substantial evidence that the average over two or three months can be predicted at a range of a season or more.

ENSO

On seasonal to inter-annual timescales, the largest climate variability occurs in the tropical Pacific region. The El Niño Southern Oscillation (ENSO) events which occur there are associated with major changes in the ocean and atmosphere, have a global impact, and have been demonstrated to be predictable at a range of several months. There is increasing evidence of a teleconnection between some European seasonal climate biases and ENSO.

Models

The group has developed dynamical atmosphere–ocean models to predict ENSO and its associated global climate effects. In one version, a tropical Pacific Ocean GCM with enhanced resolution near the equator, is combined with a statistical atmosphere. The latter allows the wind forcing on the ocean to be deduced from the ocean model's SST field as it evolves. This model has useful predictive skill at a range of several months. In another version, the ocean model is coupled to a version of the Hadley Centre's global atmospheric model. This coupled model is able to simulate inter-annual variability well.

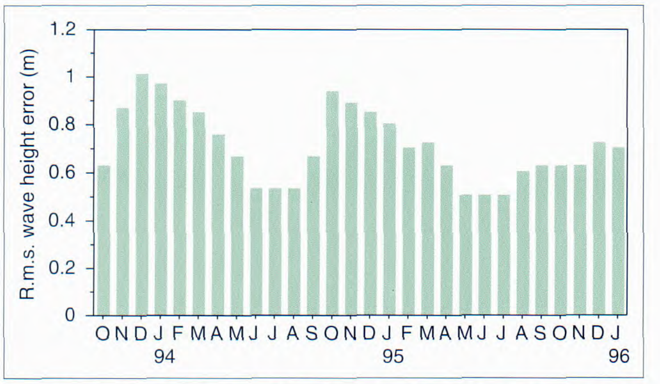


Figure 47. Global Wave Model (analysis minus observations). Monthly mean significant wave height r.m.s error, October 1993 to January 1996.

Start up

For most forecasts, the initial ocean conditions have been obtained by forcing the ocean model with observed winds only. Better initial conditions can be produced by making use of ocean observations. This is being done in collaboration with FOAM.

Statistical forecasts

Statistical models are also used to relate seasonal rainfall anomalies to observed pre-season SST anomalies. In this way shorter-range forecasts are made and issued for North-East Brazil and regions in tropical West and East Africa.

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Note: Met. Office authors are indicated by the use of capital letters.

ACRONYMS

1DVAR	One-dimensional variational analysis
ADAS	Agricultural Development and Advisory Service
ADMS	Atmospheric Dispersion Modelling System
AFS	Aeronautical Fixed Service
AMIP	Atmospheric Model Intercomparison Project
APP	Acoustic Prediction Package
APR	Atmospheric Processes Research
ASDAR	Aircraft to Satellite Data Relay
ATSR	Along-Track Scanning Radiometer
CCN	Cloud condensation nuclei
CFO	Central Forecasting Office
CMOS	Complementary Metal Oxide Semiconductor
DEC	Digital Equipment Company Ltd
DoE	Department of the Environment
DP	Defence Provision (a branch of S&B division)
DPSN	Defence Packet Switched Network
DTEO	Defence Test and Evaluation Organization
ECMWF	European Centre for Medium-range Weather Forecasts
EEMS	Electromagnetic Environment Modelling System
ERBE	Earth Radiation Budget Experiment
ERS	European Remote-sensing Satellite
EU	European Union
FCCC	UN Framework Convention on Climate Change
FLIR	Forward-looking infrared
FOAM	Forecasting Ocean–Atmosphere Model
FRY	Former Republic of Yugoslavia
FWOC	Royal Navy's Fleet Weather Oceanographic Centre
GCC	Global Collecting Centre
GCM	General Circulation Model
GCOM	General Communication
GIS	Geographic Information System
GISST	Global sea-Ice and Sea-Surface Temperature
GLOSS	Global Soundings System
GMS	Geostationary Meteorological Satellite (Japan)
GTS	Global Telecommunication System
HQSTC	Headquarters Strike Command
HSE	Health & Safety Executive
IASI	Infrared Atmospheric Sounding Interferometer
ICAO	International Civil Aviation Organization
IFOR	Implementation Force
IN	Ice nuclei
IPCC	Intergovernmental Panel on Climate Change
IREPS	Integrated Refractive Effects Prediction System
ISCCP	International Satellite Cloud Climatology Project
IT	Information Technology
IWP	International Weather Productions (a Met. Office business group)
JCMM	Joint Centre for Mesoscale Meteorology
kVA	Kilovolt amps
LAM	Limited Area Model
MIST	Meteorological Information Self-briefing Terminal
MMU	Mobile Meteorological Unit
MOSES	Met. Office Surface Exchanges Scheme
MPP	Massively parallel processor
MSG	Meteosat Second Generation
MUM	Mesoscale Unified Model
NAD	North Atlantic Drift
NAME	Nuclear Accident Model
NAVAID	Navigation Aid
NERC	Natural Environment Research Council
NESDIS	National Environmental Satellite Data and Information Service
NMCs	National Meteorological Centres
NMSs	National meteorological services
NOAA	National Oceanic and Atmospheric Administration
NRA	National Rivers Authority
NVGs	Night-vision goggles
NWP	Numerical Weather Prediction
OCP	Outstation Communications Processor
ODAs	Operational Decision Aids
ODS	Outstation Display Systems
OLR	Outgoing long-wave radiation
OPUS	Outstation Production Unified System
PE	Parabolic equation
POL	Proudman Oceanographic Laboratory
r.m.s.	Root-mean-square
RSMC	Regional Specialized Meteorological Centre
S&B	Services and Business
SADIS	Satellite Distribution System
SBMM	Standard Ballistic Met. Message
SCMM	Standard Computer Met. Message
SESAME	Second European Stratospheric Arctic and Mid-latitude Experiment
SST	Sea-surface temperatures
SSU	Stratospheric Sounder Unit
STOCHEM	A Lagrangian chemistry model
TDAs	Tactical Decision Aids
TOVS	TIROS Operational Vertical Sounder
UARS	Upper Atmosphere Research Satellite
UM	Unified Model
UMUI	UM User Interface
WAFC	World Area Forecast Centre
WAFS	World Area Forecast System
WAM	Wave Model
WGI	IPCC's Working Group One
WIN	Weather Information Network
WMO	World Meteorological Organization
WWW	World Weather Watch or World Wide Web

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