The Met.Office

Scientific and Technical Review 1998/99

Excelling *in weather services*

The Met.Office

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The *Scientific and Technical Review* is a sister publication to the *Annual Report and Accounts 1998/99.* Here we cover in much greater depth our scientific and technical programmes, and their progress during the year. This is aimed at scientists in other national meteorological services throughout the world, in the academic community and in commercial and research organisations.

At the start of the year, The Met. Office underwent some changes in organisation and management structure. The main changes were a separation of business management and technical aspects of service delivery, and the creation of a Technical Services Division. All underpinning technical services, including observations and IT, were brought together under this one heading.

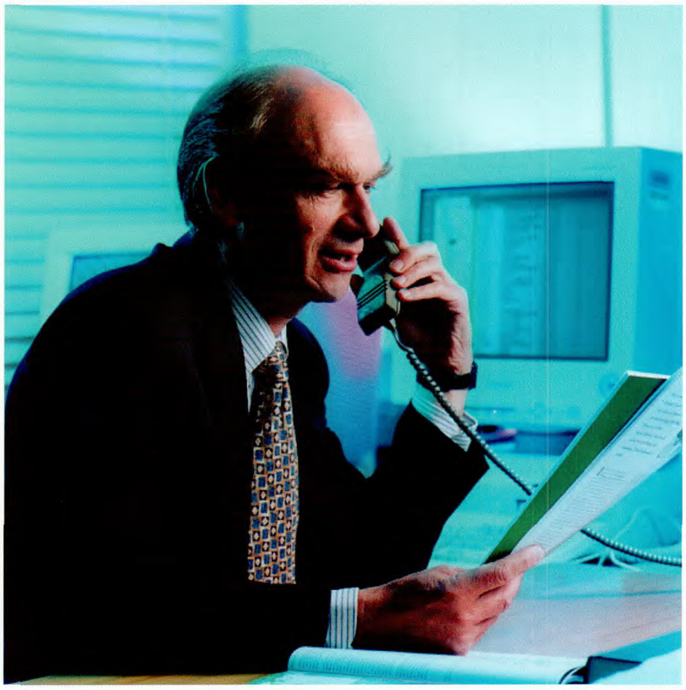
The renamed Business Division concentrates on marketing, sales and account management, while all forecast production and service delivery now comes under Forecasting Division. To emphasise the growing importance of IT, another Directorship was created within Technical Services.

Each year, a few topics are covered in more detail. This year, we look at the latest developments in IT Division, following the reorganisation, and in Numerical Weather Prediction.

The Annual Report and Accounts provides our owners in MoD, Parliament, our customers, and our staff, with a review of our performance against our key targets and our main activities in 1998/99 (see inside of the back cover for details of how to obtain a copy or more information).

An excerpt from the Chief Executive's review, taken from the *Annual Report and Accounts*, gives an introduction to the year's events, and provides an overview of some of the more relevant technical and business issues faced by The Met. Office.

Chief Scientist Paul Mason



About The Met. Office

The Met. Office was formed in 1854 as a small department within the Board of Trade to provide meteorological and sea current information to mariners. Early this century, The Met. Office started responding to new demands for weather services, most importantly in the field of aviation. This led to The Met. Office being taken under the wing of the Air Ministry just after the First World War, later moving into the Ministry of Defence.

The Met. Office became an Executive Agency in April 1990, and started operating as a trading fund on 1 April 1996.

The Met. Office employs around 2,200 people, over 70% of them scientists. Some 900 staff are spread across more than 80 locations around the UK and overseas, observing the weather and providing forecast services to our customers. The remainder work in our main offices at Bracknell, Berkshire, in a wide range of activities including forecasting, research, the development of IT and observational systems, and central support functions such as finance and human resources. We also have a small number of research facilities elsewhere in the UK.

Chief Executive's review

(Excerpt from the *Annual Report and Accounts 1998/99).*

I am pleased to report that 1998/99 has been another successful year for The Met. Office.

Customer focus

We have developed a closer and, I believe, more open relationship with our Core customers, and we have welcomed a new customer to our Core Customer Group — the Department for Media, Leisure and Sport (DMLS), through the BBC, have taken responsibility from the MoD for national media forecasts. Also, the Department for Education and Employment (DfEE) has assumed responsibility from the MoD for enquiries and services for education.

We are also particularly conscious of the increased financial stringency imposed on our Core customers over several years, with no respite in prospect. We share their concern about the potential loss in quality of service on behalf of the public they serve — a concern also voiced throughout the developed and developing world, and one which has attracted the attention of the World Meteorological Organization at its Congress in May this year. While we have been able to reduce the cost of the Core programme in real terms in each of the three years as a trading fund, efficiency gains cannot be sustained indefinitely. Without some stability in Core programme funding, especially to meet the UK's international obligations, it will not be possible to sustain the current programme. More importantly, future potential improvements in weather forecasting accuracy and service delivery may not be realised, and the UK will be in danger of losing its world-class position in meteorology and climatology. We are currently working with our Core customers to find a solution to this apparently intractable problem.

With regard to our direct services to the public sector, we have been busy meeting increased demands for our services. Internationally, these range from increased support to our Armed Services in the various trouble spots around the world to advice to our government in their discussions and negotiations on global warming. Nationally, they include developing relationships with the Environment Agency, particularly in the areas of heavy rain and flood warnings in the light of the flooding at Easter 1998, and working closely with National Air Traffic Services (NATS) — the UK meteorological authority for aviation — as they move from public status to that of a private/ public partnership.

Commercial emphasis

In July 1998, following a major internal review of our business management and service delivery, we decided to create a financially separate Commercial Division which would be able to concentrate on our

Peter Ewins, Chief Executive, briefing visitors to a UK Simulation Advisory Group meeting services to commerce, industry and the private sector generally. This will help us to focus on the special needs of the sector while building on the strong position of The Met. Office as market leader in weather services. It will also enable us to demonstrate publicly that we are competing in this important market on equal terms with private service providers, without cross-subsidy from our public sector business. At the same time, it will help sharpen our internal services and drive further efficiency improvements, to the benefit of both public and private sector customers alike. The new Commercial Division came into being on 1 April this year.

Investing for growth

Over many decades The Met. Office has won an enviable international reputation for excellence in meteorology and, more recently, for the quality of service and value for money it provides to its customers. But such a reputation must not be taken for granted, and needs to be continuously reinforced through a strong research and development (R&D) programme, the application of new technology and, above all, the training and development of our staff. The past year has seen substantial investment in all three areas. We have, for example, increased our R&D in automation and NWP, and have supported this work with the introduction of our new Cray T3E supercomputer. By the end of the current year we expect to have commissioned a second T3E, greatly expanding both our NWP and climate research and prediction capability. We have also begun a new investment programme of £5 million over five years aimed at expanding our product range and improving our services to customers.

Looking ahead

Turning briefly to the future, the most immediate task for The Met. Office is to address the year 2000 problem — the 'millennium bug' — and to ensure continuity of services to our customers, many of whom, like The Met. Office itself, are part of the National Infrastructure Forum. I am delighted to report that, with six months to go, our year 2000 project is in very good shape, and our confidence has been reinforced by the independent assessment carried out by the National Audit Office. Clearly, there is no room for complacency and we still have important work to complete, but I am confident of our ability to meet all the essential needs of our customers, in both the public and private sectors, over the New Year and during the other critical dates in September 1999 and February 2000.

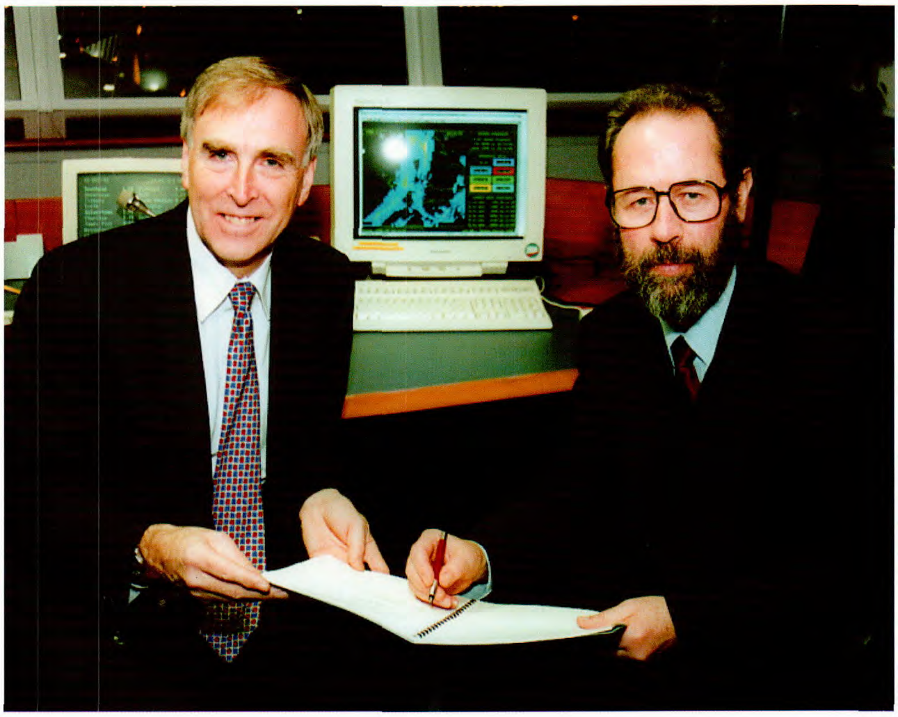
While the impact of year 2000 issues will be over within the next nine months, we have started to tackle another issue that will be with us for some time and affect our future over several decades — the need for new accommodation. We came to Bracknell in 1961 and our main building is now coming to the end of its useful life. It is inefficient, with high maintenance costs, and is ill-suited to a business so dependent on information technology. To take The Met. Office successfully forward, we must harness the benefits that go with a modern building and its associated infrastructure. We have therefore started our relocation project, with a view to moving to new premises in 2003/2004.

Finally, in my brief forward look, we need to be ready for — indeed, to lead in — the development of European meteorology and to take advantage of the new opportunities presented by the increasing concern about changes to our natural and man-made environments. Our scenario-planning project, aptly named *Odyssey*, has provided a valuable insight into the issues we face over the next 10 years as well as the opportunities, and we shall be using these extensively in the formulation of our strategic and business plans.

Building on our success

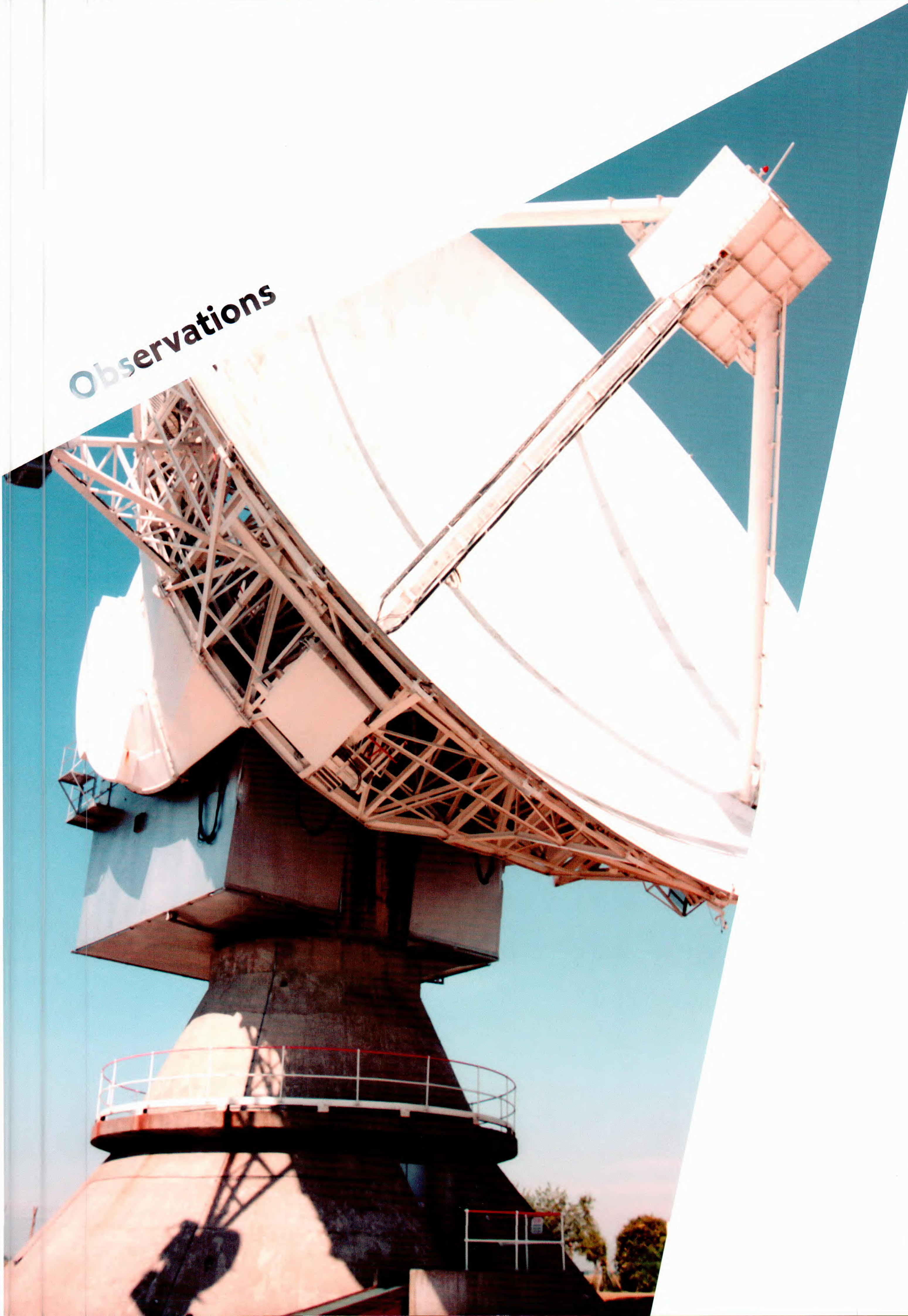
The Met. Office has enjoyed a successful year in 1998/99, a success shared by our customers, our staff and our owner. I hope, too, that the public is proud of The Met. Office as the UK's national meteorological service. The challenge now, and one which I believe we are well placed to meet, is to build on that success to ensure we go on meeting our customers' needs, to the very highest standards and at a price they can afford. In so doing, we shall continue to enjoy the support of our customers, our staff, our owner and the public alike.

P. D. Ewins



Ed Gallagher, Chief Executive of the Environment Agency, and Peter Ewins sign a memorandum of understanding

Observations



Observations

Observations of atmospheric and surface conditions are vital for four main purposes. These are to:

- provide input to numerical weather prediction (NWP) and other forecasting methods;
- monitor the accuracy of forecasts;
- monitor the weather and provide warning of hazardous conditions;
- determine the variability of climate in space and time.

Observing networks

Network planning

We completed reviews of the UK surface synoptic networks (land and marine) and the UK climatological network. The resulting policy documents each contain the agreed user requirement for these observations for the next five to ten years, and proposals for cost-effective station network designs. We also began a review of the requirements for upper-air observations and ways of satisfying them. The final overall solution will involve radiosondes, civil aircraft observations as well as innovative remote-sensing tools.

European Composite Observing System

Forecast errors in Europe are in part due to weaknesses of the current ground-based observing system, particularly in data-sparse areas such as the North Atlantic Ocean. The western European national meteorological services, forming the membership of EUMETNET, have collaborated in the establishment of a programme to design and implement a EUMETNET Composite Observing System (EUCOS). This will improve and make more cost-effective numerical weather prediction and general forecasting at the European scale (i.e. weather systems with a geographical scale of 100 kilometres and temporal evolution of 12 to 48 hours).

Initially we will use impact studies to test the hypothesis that savings can be achieved by partially replacing the upper-air network with automated aircraft data over land. Aircraft Meteorological Data and Reporting data are being provided under a jointly funded project managed by The Met. Office (see **UK AMDAR system**). This should lead to a EUCOS design with an enhanced network in data-sparse areas and further jointly funded observing systems.

Additional upper-air observations

On an experimental basis, midnight upper-air ascents at eight Supplementary Sonde Stations began in November (supplementing the network of nine main radiosonde stations). These are 'on demand' when the NWP mesoscale model and forecasters are likely to benefit from additional ascents, which are mainly inland. The data will also be used in NWP impact studies to assess their value for meeting the user requirements for upper-air data.

Sub-hourly observation reporting

The UK land synoptic network includes some 140 stations that are capable of producing observations automatically. While the weather is continuously monitored by these, in common with other countries, the practice has been to transmit data only once per hour. To exploit fully the capability of these stations, to the benefit of very short-range forecasting, we proposed sub-hourly reporting. We completed a feasibility study and recommended an implementation project, which will involve changes to a number of systems that produce, transmit, display and archive observations, using a more flexible coding format.

Climate data

We maintain a comprehensive archive of climate data, which is routinely kept up to date with current UK and marine observations. We perform detailed quality control checks on all data; corrections are made where the observation is clearly in error and estimates provided where a value is missing. Painstaking quality control like this has been performed for many years and as a result we are able to offer a detailed climate record dating back in places to the previous century, which is as accurate and as complete as possible. Not all climate records are available on computer in the climate database; to increase the amount of digitised data from stations open in the early days of observing, we are keying in manuscript forms dating back as far as 1850.

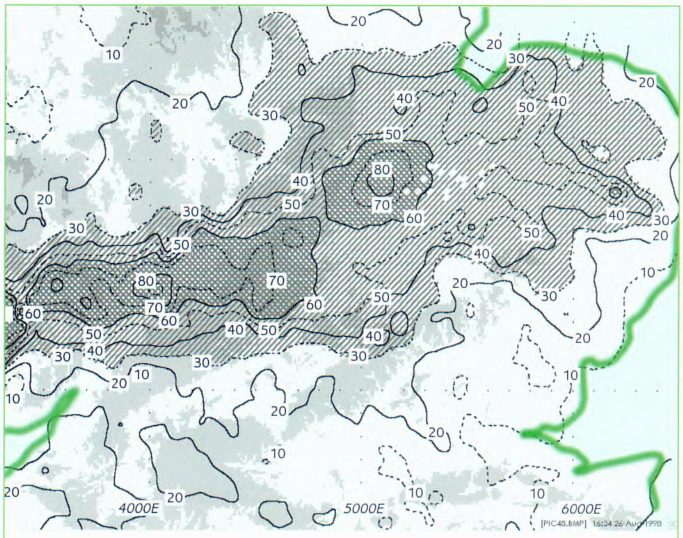


Figure 1. The total rainfall (mm) experienced during the 48-hour period ending at 0900 on 10 April 1998.

UK Climate Studies Group

We made climate data studies to investigate the quality of observations and to help in designing networks. These included a project to compare temperatures measured electronically by SAMOS with comparable values from traditional liquid-in-glass thermometers in order to assess whether electronic measurements might become generally acceptable (or even preferable) for UK climate change and variability studies. We found the observed mean difference of maximum temperatures at 76% of the 49 stations in the sample was less than 0.1°C. For minimum temperatures the percentage was only 53%, but minimum temperatures from liquid-in-glass thermometers are known to be less reliable.

In addition, we performed analyses for several unusual climatic events — in particular the rainfall associated with the flooding at Easter 1998. Figure 1 (previous page) shows the total rainfall experienced during the 48-hour period ending at 0900, on 10 April 1998. At any given station most of the rain fell over a period between 11 and 16 hours; the highest recorded total was 76.6 mm over 14 hours at Pershore.

New technology

UK AMDAR system

For many years, The Met. Office and a number of other members of WMO (World Meteorological Organization) have provided equipment for installation on civil aircraft, which transmit meteorological observations. This system, known as Aircraft to Satellite Data Relay (ASDAR), although very successful, has the drawback of the installation and maintenance costs associated with non-standard equipment on civil aircraft. A solution has been provided, which makes use of the aircraft's existing onboard sensors, avionics software and communications. This software package is known as Aircraft Meteorological Data and Reporting (AMDAR) and provides data of the same quality as ASDAR but at a fraction of the cost.

Following our negotiations with British Airways, an operational AMDAR scheme has now been implemented. Standard KLM AAA AMDAR software (which was provided free of charge by KNMI, the Dutch met. service) forms the basis of the airborne component. This software acquires meteorological data ready processed from the aircraft's avionics system every seven minutes during level flight and more frequently during ascent/descent. Data are then made available internationally on the Global Telecommunication System (GTS) within an hour of observation (see **Internal communications** in **Information Technology**). The 29 systems are now operational and this number will remain as an upper limit until data requirements are better understood. During 1999 we plan to integrate the full AMDAR system into EUMETNET.

Closed-circuit television

We have continued to extend the quality and capability of closed-circuit television to monitor weather conditions. In particular, the systems were confined to operations in daylight hours, and we investigated image intensifiers as a means of overcoming this limitation. These devices were not helpful, but an initial trial of an infrared camera has shown great potential when used in conjunction with a visual camera in daylight and alone at night.

We established a useful collaboration with the US National Weather Service, which has been developing along similar lines but is very interested in the results of our rigorous trials.

The security television systems currently deployed are inevitably biased towards the security need for a rapid image refresh rate at the expense of image quality. These proprietary systems are also sealed so that we cannot tune them to our requirement. Use of telephone lines to transmit the data further degrades the image. Therefore, we decided to develop PC-based interactive image-handling software tuned to the weather observing requirement and giving better image quality prior to transmission.

Use of GPS receivers to derive water vapour profiles

Four Global Positioning System (GPS) receivers have been installed at Camborne, Lerwick, Hemsby and Aberystwyth since April 1998, for investigating the usefulness of providing total column water vapour measurements for assimilation into numerical weather prediction models. The first part of the project is to collect an annual cycle of water vapour measurements at radiosonde stations for comparison with radiosonde measurements (see Fig. 2).

To enable accurate measurements to be made, we need to know the positions of the GPS satellites to the order of a centimetre, a much greater precision than required for navigation purposes. To provide data in real time for weather forecasting, the satellite ephemerides need to be predicted for one day in advance. We expect that this facility will be available by Summer 1999. We purchased a further four receivers along with the necessary surface instrumentation to enhance the network and to enable real-time calculation of integrated water vapour.

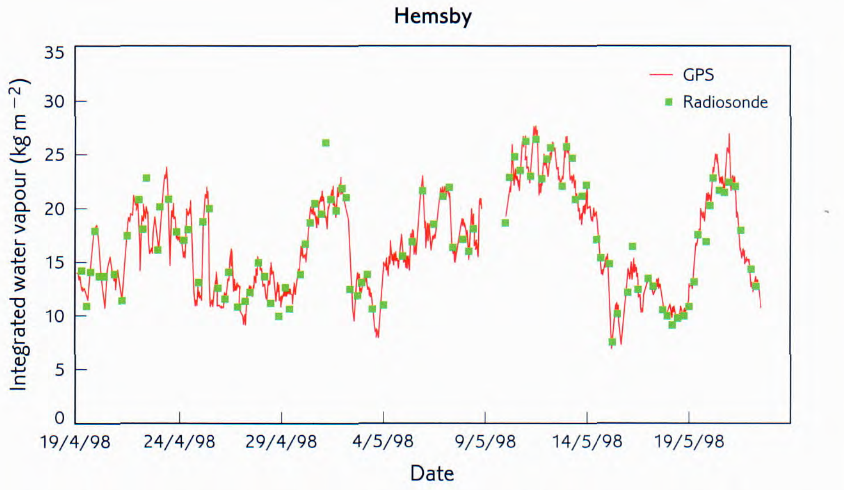


Figure 2. Observations derived from GPS at Hemsby, by the University of Nottingham, for one month at 0000 UTC with the corresponding radiosonde measurements (made three times a day).

Weather radar

Within the past year, we began a programme of replacement for the radar site processing systems, so that these can now function on PC platforms. In addition, we are examining ways in which improvements can be made to the present systems for calibrating the weather radars, in line with user requirements, with minimal disruption to operational services.

In December 1998 we signed a new 10-year agreement with the Environment Agency to secure the future of the weather radar network in England and Wales. This new agreement will support the work towards maintaining radar performance and ongoing replacement programmes of obsolete receiver technology. It will also provide a framework within which to consider the operational benefits of new technology over the next 10 years.

We are assessing the impact of Doppler radar to operational activities, using information from the two Doppler radars within the UK radar network (at Cobbacombe Cross and Clee Hill), and from European radar data collected under the EU-funded DARTH project (co-ordinated by the University of Essex). Early results suggest that, by using Doppler clutter cancellation techniques together with other new scintillation filters, we can improve the removal of unwanted radar echoes. In particular the cancellation of clutter is as effective as the removal of data using the infilling technique from higher elevations. This has the potential to allow the use of much lower radar beam elevations without any significant loss in radar retrievals of rainfall. An example of the clutter removal capabilities of the present Doppler system is shown in Fig. 3. These are horizontal scans of radar reflectivity before and after clutter suppression. The difference between the two gives an estimate of the clutter power, which can then be used to indicate the likelihood of significant clutter contamination in the radar rainfall estimates. The Doppler radar project has also enabled the collection of real-time Velocity–Azimuth Displays (VADs) that provide high-resolution information of wind speed and direction above the radar site.

Space-based observations

EUMETSAT programmes

The EUMETSAT Polar System programme started in earnest in September. Procurement of the space and ground segments for three meteorological operations (METOP) satellites will now proceed, leading to the launch of METOP 1 in 2003.

Meteosat 7 completed its commissioning and became the operational satellite for the Meteosat programme at 0° longitude on 3 June.

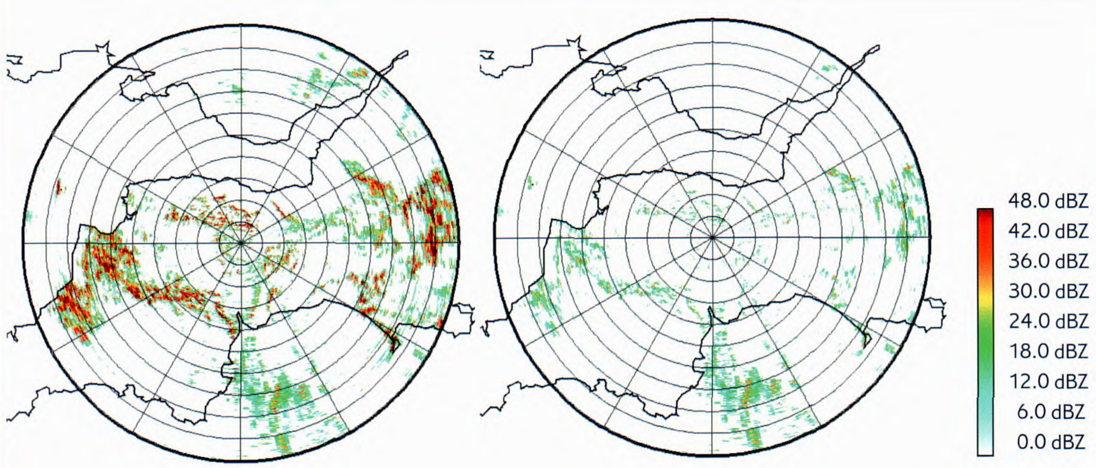


Figure 3(a) and 3(b). Reflectivity estimates before and after suppression for a 0.5° elevation scan for the Cobbacombe Cross radar at 0217 UTC on 11 August, uncorrected Z in (a) and corrected Z in (b). Range circles are at 10 km intervals.

It is providing excellent imagery and services without the need for anomaly corrections as suffered by the previous three satellites. Meteosat 5, having ceased duties as the standby satellite, was relocated to 63° E to support the Indian Ocean Experiment. It began operational services in July, including direct broadcast to all users, providing much needed imagery of the Indian Ocean area.

Instruments for NOAA K and METOP

The first Advanced Microwave Sounding Unit (AMSU-B) provided by The Met. Office, was launched aboard the NOAA K satellite in May 1998. This has channels in the 90–183 GHz range and provides *inter alia* remotely sensed profiles of water vapour on a global scale over the oceans (see Fig. 4). Initial engineering assessment showed that there is a changing bias in some channels induced by interference from some of the spacecraft data transmitters. The cause, a faulty screen, has been identified and subsequent models have been corrected. We developed a recommended correction procedure for the AMSU-B on NOAA K and made it available to users. Apart from this effect, the instrument works well.

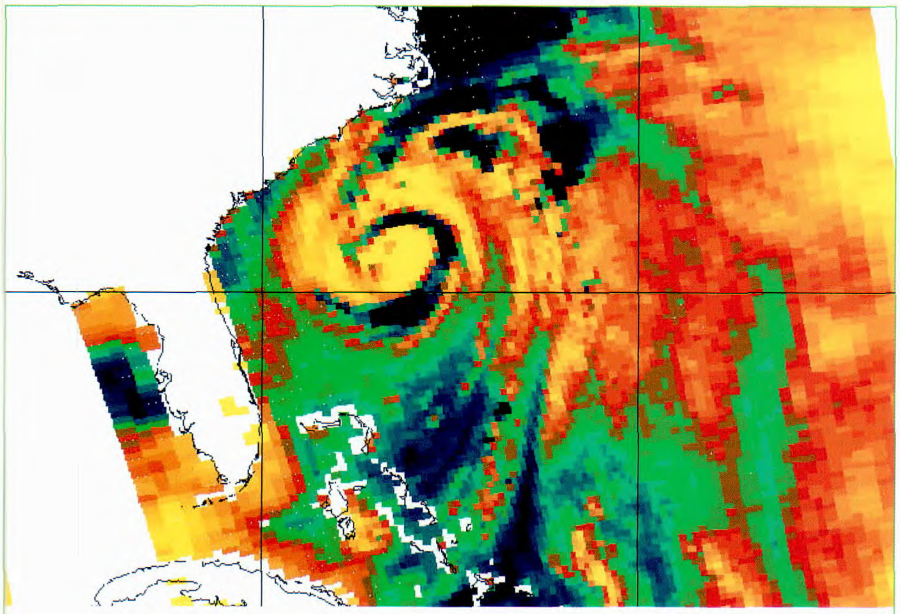


Figure 4. An example of a tropical storm observed by AMSU-B.

The follow-on Microwave Humidity Sounder (MHS) for METOP is being procured by EUMETSAT and we have tested and characterised the first flight model in the same facility that is used for AMSU-B.

Aircraft interferometry for METOP

The Airborne Remote Sensing Group are co-ordinating an international EU-funded project called VIRTEM (Validation of IASI Radiative Transfer: Experiments and Modelling). The VIRTEM project started in July 1998 and will run for two years. VIRTEM will improve the understanding of the radiative transfer in the thermal infrared region of the electromagnetic spectrum in preparation for the Infrared Atmospheric Sounding Interferometer (IASI), a future high-resolution satellite sounder, due to be launched on the METOP satellite in 2003. Such sounders have the potential to significantly improve the vertical resolution of temperature and humidity profiling from space and consequently are expected to have a positive impact on NWP.

A demonstration version of IASI, the Airborne Research Interferometer Evaluation System (ARIES), has been fitted to the Met. Research Flight C-130 aircraft. The VIRTEM project uses ARIES, in collaboration with a similar ground-based instrument operated by the Max Planck Institute for Meteorology (MPIM), to make measurements of the atmospheric radiance spectra and compare these spectra with those simulated by state-of-the-art line-by-line radiation codes. Figure 5 shows an example of such a comparison.

The VIRTEM project started with a ground-based intercomparison and calibration exercise with the key interferometers in the MPIM laboratories in Hamburg. In the summer of 1998, ARIES was operated on the ground at the Deutsche Wetterdienst experimental site in Lindenberg in collaboration with microwave radiometers, water vapour lidars and regular radiosonde launches. These data, along with those gathered during an airborne campaign in southern England, flown in the autumn, will be used to verify our understanding of the radiative transfer in the thermal infrared. In November 1998, we took ARIES to Toulouse, France, for a laboratory intercomparison with the IASI bread-board.

The other members of the VIRTEM project include the Rutherford Appleton Laboratory which has started a programme of measurements using its Molecular Spectroscopy Facility to study the water vapour spectroscopy in the 6–15 μm region and the carbon dioxide spectroscopy in the 3–18 μm. These new laboratory data will be incorporated in the GEISA (Gestion et Etude des Informations Spectroscopiques Atmospheriques) spectroscopic database maintained by the Laboratoire de Météorologie Dynamique (LMD) another of the VIRTEM project collaborators.

Theoretical assessment work on IASI

Traditional infrared sounders, such as those used in the TIROS Operational Vertical Sounder system (TOVS), have their design optimised at around 23 separate infrared channels. Increasing the number of these channels brings diminishing returns; but by using interferometer (rather than discrete-filter) techniques, IASI extends this dramatically to 8,460 channels — potentially bringing substantial benefits in improved ability to distinguish fine structure within atmospheric profiles. This is important, because users have long highlighted poor vertical resolution as the main weakness of traditional satellite-borne sounders.

We have developed the analytical tools needed to understand and assess the benefits (in terms of ability to observe differential profiles). We have demonstrated that the water-vapour band, around 1,150–2,100 cm^{-1} has a potentially dominant role in IASI's ability to observe fine-structure tropospheric temperature profiles.

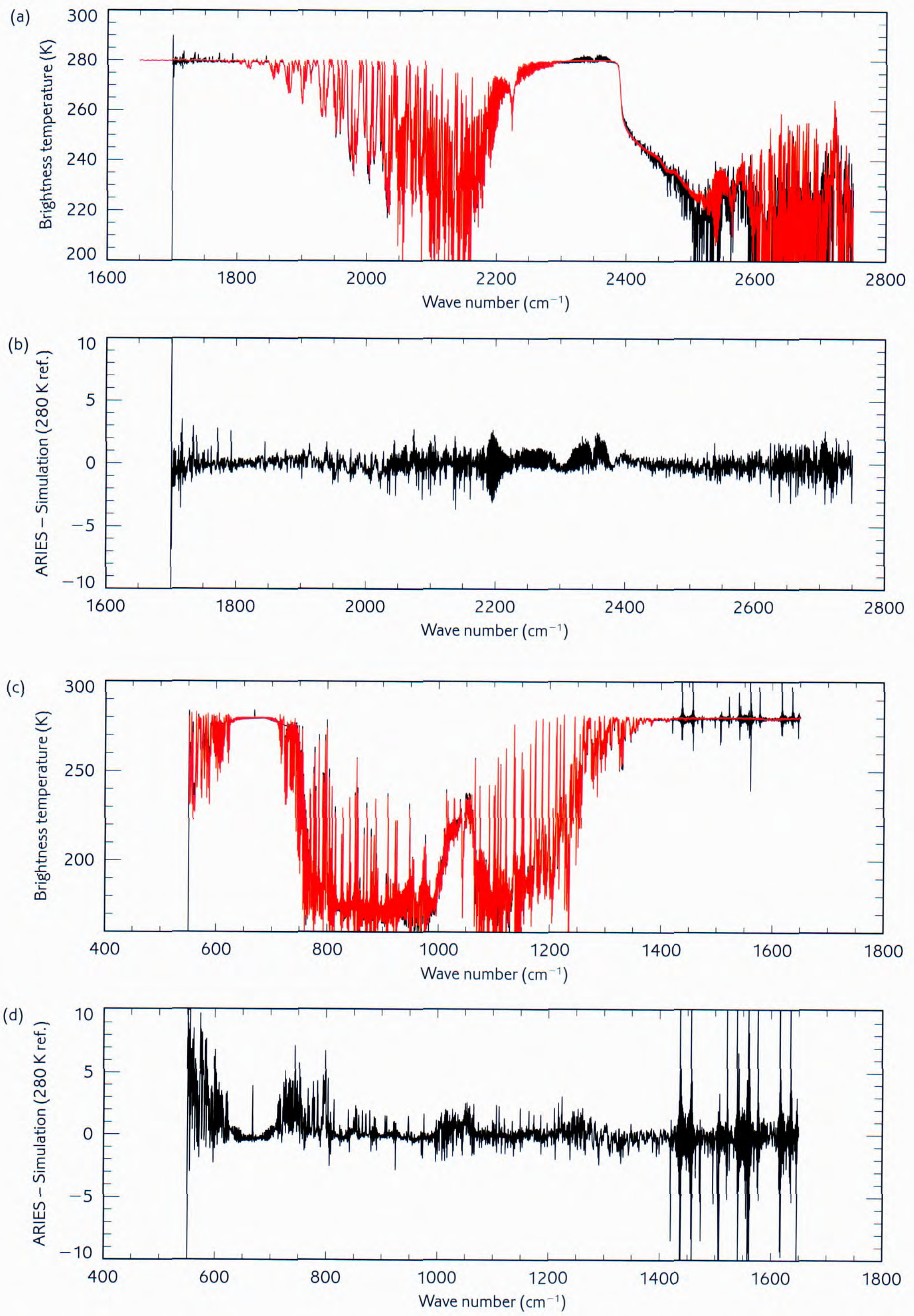


Figure 5. The ARIES spectra shown are from zenith views from an altitude of 200 m over Chilbolton Radar on 19 October 1998. The atmospheric column was clear of clouds. The GENLN2 simulation was initialised using a radiosonde from the Larkhill station at 0800 UTC. Panels (a) and (c) show the brightness temperature (over the range of the two ARIES detectors) measured by ARIES in black and simulated using the GENLN2 line-by-line model in red. Panels (b) and (d) show the difference in brightness temperature referenced to 280 K.

Information Technology

Information Technology

UK telecommunications networks

As soon as observations from the UK area of responsibility have been put into a coded form ready for transmission, the process of collecting and distributing them to a large number of internal users and external customers can begin (see Fig. 6). This is a very complex task, made more so because The Met. Office is in a period of rapid technical change. Looking a year or so ahead, we see observations as sets of data which can be passed around computer networks using standard techniques, derived from those used on the Internet. During 1998 we made some important steps in that direction.

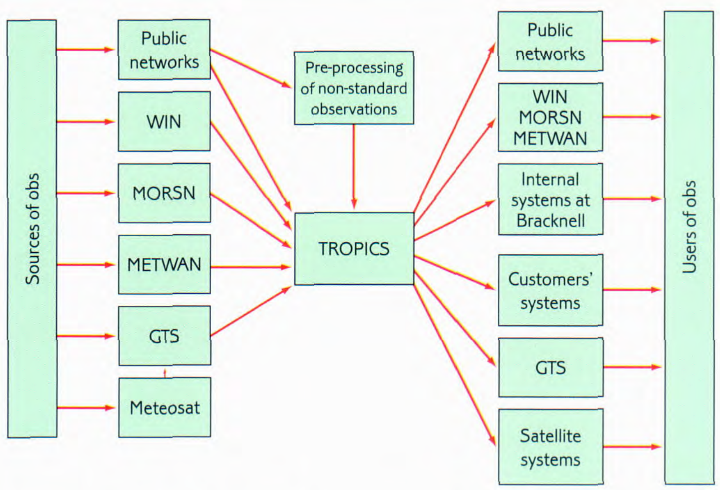


Figure 6. The flow of observations from their source through Met. Office systems to the end users.

At the end of December we ceased using a multi-purpose wide-area network, which was shared with the RAF and had carried much of the UK meteorological traffic since the mid-1980s. This network did not support modern communication protocols, was increasingly difficult to manage and was not year 2000 compliant. Traffic was consolidated onto two other networks, the Weather Information Network (WIN) and our Wide Area Network (METWAN), which are being made year 2000 compliant. WIN uses industry-standard message-passing technology (X.400 over X.25); METWAN supports 'legacy' applications. Neither of these networks is using the Internet protocol (IP) suite, so in 1998 we began planning a new network, the Met. Office Remote Sites Network (MORSN), and the first installations took place by December. MORSN is built using Cisco routers and a BT-managed network service, giving us wide-area connectivity based on IP.

We also collect observations using the public telephone network (very economical for certain types of data) and plan to make wider use of this method. Collecting by satellite is cost-effective and reliable for data from marine and other remote locations; for example, the European geostationary satellite Meteosat is used to collect observations from buoys. Some observations come from equipment operated by other agencies and are typically not in a standard meteorological format. We developed a new system during 1998 which dials up the tide gauges around the British coast and converts the retrieved data into a standard binary format defined by the World Meteorological Organization (WMO). This approach may find other applications as we make wider use of real-time data from platforms, such as commercial aircraft, climate loggers, etc.

Message switching

Once the package of data representing an observation has entered the networks it is sent to Bracknell and passed into the central message switch, TROPICS (Transmission and Reception of Observational and Product Information by Computer-based Switching). This message switch enables incoming messages from many input channels to be routed individually to many output channels; TROPICS has about 200 channels and receives about 250,000 messages per day but transmits about two million messages. TROPICS can now support IP-based data transfer, in line with new standards adopted by WMO. From TROPICS the observations flow to databases at Bracknell, to outstations for use by forecasters, and out to customers.

International communications

We also exchange data with other national meteorological services around the world, passing from one message switch to the next, over a network which forms the main element of the WMO Global Telecommunication System (GTS). The GTS in Europe is about to be re-formed — the culmination of a five-year effort to gain the agreement of nearly 50 countries. The new network will be based on a managed network service provided by Equant. Equant and ECMWF signed the eight-year contract in December 1998 and the network, called the Regional Meteorological Data Communication Network (RMDCN) will be implemented in mid-1999. The network will use IP (but with provision for legacy protocols) and so will enable the GTS in Europe to be modernised. Our staff have contributed to both technical and organisational aspects of this important development, working closely with colleagues in other national met. services and ECMWF.

Early in 1998 we introduced a new link to Washington to carry large volumes of data from the latest US polar-orbiting satellite to Bracknell. The satellite carries instrumentation which we provide (see **Instruments for NOAA K** in **Observations**). This link uses file transfer over IP, with an underlying network service based on frame-relay technology (as in RMDCN). This is the latest step in a series of arrangements which ensure that we have access to worldwide satellite imagery and sounding data.

General Purpose Computing Service

The General Purpose Computing Service (GPCS) is an IBM 9672-R45 which processes meteorological observations and results from numerical model runs on the supercomputer, a Cray T3E. We also use the GPCS to create weather products which we then transfer to TROPICS and other systems for onward transmission to the customer. Figure 7 shows how our major computer systems are connected. We also use the GPCS to process some financial data and to produce invoices for customers.

We have 50,000 tape cartridges with about 100 terabytes of data. These data include both meteorological observations and information generated by our supercomputer.

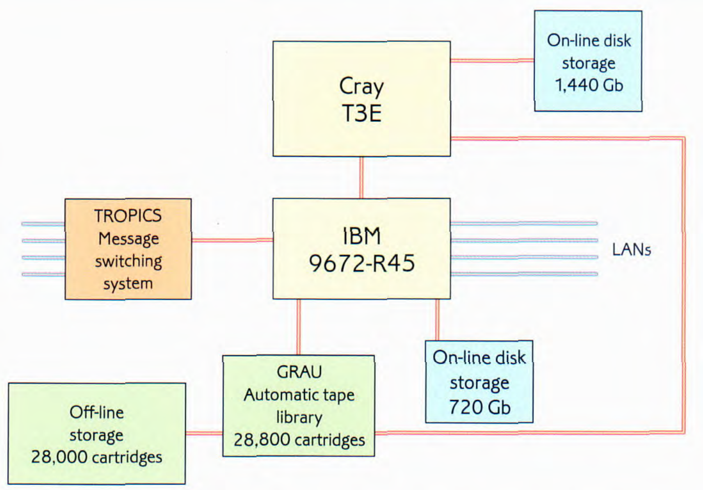


Figure 7. The connectivity of the main Met. Office computer systems.

Meteorological databases

We store observations received in real time in the Meteorological Database (MetDB). These data are then retrieved for numerical weather prediction (NWP) and other applications. The database stores information about their quality and also associates them with equivalent values from the output of the NWP suite. This allows statistical processing of the differences between observed and modelled values, which is essential if we are to improve the NWP process. We have enhanced the MetDB to introduce additional observation types, and it is confirmed as year 2000 compliant. In September 1998, the Synoptic Data Bank (MetDB's predecessor) was turned off after 27 years of service (see Fig. 8).

Figure 8. Colin Flood, Forecasting Director, switching off the Synoptic Data Bank.

The MetDB is designed for short-term storage of observations, accessed most easily by their time of validity. However, observations for climatological applications are stored in another database, Met. Office Integrated Data Archive System (MIDAS) which is based on a commercial database management system and is year 2000 compliant. We now store the majority of climatological observations in MIDAS, and will transfer the remaining climatological observations to it during the year 1999/2000. The former Climatological Database ceased taking in data in July 1998, after serving for almost 30 years. It was devised in an era when computing power and storage space were scarce and expensive, and was designed for efficiency in both respects. It was highly dependent on bespoke software, written in IBM assembler. This had become very difficult to maintain, which limited the accessibility of the data, the flexibility to store new types of climatological data, and its portability to other types of computer. MIDAS offers greater flexibility in how to access the observations.

Cray T3E supercomputer

The Cray T3E is capable of over 700 gigaflops (1 gigaflop is 1,000 million floating point operations per second). We use it for numerical weather prediction, and climate and environmental research. There are several forecast runs every day, processing observations passed from the GPCS; these are assimilated into initial atmospheric states. We use these as input for forecast models to provide the states (or 'fields') of the atmosphere for several days ahead. These fields are then passed back to the GPCS for distribution to internal and external customers. The climate and environmental processing, much of which we conduct for the Department of the Environment, Transport and the Regions, takes place over several days, running alongside the daily operational forecast runs.

IT Operations Centre

The IT Operations Centre handles calls and maintains services to both internal and external customers, through a variety of networked systems, including the GPCS, the Cray T3E, TROPICS, and a number of distributed systems. We run the centre 24 hours a day, 365 days a year, with about ten people on duty at any one time.

We have installed systems management software (Tivoli) from IBM to manage all the scheduled production work. This has reduced the need for staff to continuously monitor the systems, while maintaining a consistent level of customer service. The system is capable of reducing, or eliminating, the number of messages displayed at the systems consoles and provides facilities to allow more-automated event management on the different platforms.

Nimbus

We require access to many types of information to create a forecast. We are replacing the display systems used for this purpose by the Nimbus system (Fig. 9), which has already been installed at several Weather Centres and other sites — the present plan calls for 67 sites by the end of the installation process.

Nimbus has two main functions:

- visualisation of meteorological information, e.g. satellite imagery, radar rainfall, text bulletins, numerical model products;
- product generation and dissemination, i.e. allowing forecasters to produce and send forecasts to customers.

Nimbus runs on PCs using Windows NT and takes information from WIN, storing it in a local database held on a local server. Forecasters can then make use of the data from their own PCs (many of which have twin screens), and produce the forecasts for their users. Working to a flexible production schedule, Nimbus can automatically create products from the information

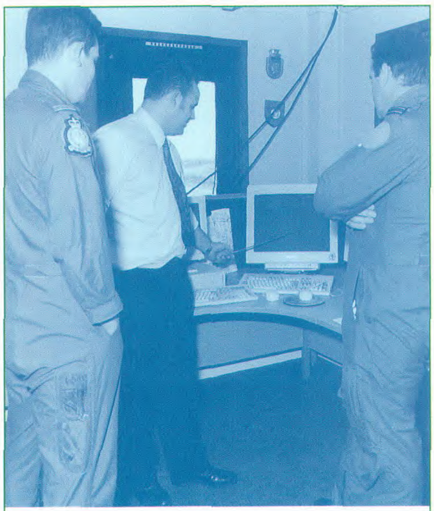


Figure 9. A forecaster briefing RAF aircrew using Nimbus.

it receives, and distribute them to customers using methods such as fax.

Administrative and financial systems support

In addition to supporting over 800 PCs used for general administration purposes, the administrative support group runs the financial management system. Although the present financial accounting system has served us well, it cannot readily provide managers with the information they need to run our business. To improve the ability to manage finances, and to reduce the cost of supporting legacy systems, we expect to have a new financial management information system ready for April 2000.

During the year we replaced the majority of personal computers used for administration and management. We are now using Windows NT, and applications are standardised around Microsoft Office 97 and Exchange.

Developer support

With the growing complexity of the software systems on which we build our business, it is increasingly important to manage the development process. We have a central team to give advice and assistance on managing software development and agreed standards. We have been implementing software tools to help with configuration management, for example to assist the Horace and Nimbus projects. Another area in which central facilities are provided is in computer graphics, where a team designs utilities that are required by several groups of software developers.

Workstation support

PCs are generally used for administrative purposes, but UNIX workstations provide the computational and presentational facilities many scientific and technical staff need for their work. The network of around 120 UNIX workstations and 300 X-terminals is supported by a central team.

Project 2000

We set up Project 2000 to minimise the potential risk to our services from certain critical date changes, including the century change (the 'millennium bug'). The number of critical systems covered by compliance projects has increased since the last report was written. We achieved our target of completing interim compliance reviews of 88 critical systems on 23 December 1998. The reviews assured us that we could continue to provide meteorological services through the year 2000 date change and beyond.

In particular this means that we have:

- identified the processes critical to the provision of meteorological services;
- created inventories of all the components that make up each critical process;
- checked to find year 2000 date-related problems;

- fixed any date-related problems that were found and that were within our control, with due regard for direct supplier and customer links;
- created a series of test plans for each critical process that conform to our testing guide;
- tested each fixed system according to its test plan and returned it to operational use;
- put in place configuration management and change-control procedures to clean manage each system to ensure ongoing compliance and an adequate audit of change history;
- created a risk register for each critical system, and for the programme as a whole, that includes consideration of areas that have not been checked and other possible unexpected date problems;
- managed these risks, and those developed from scenario planning, by the development of countermeasures and contingencies for any problem arising from year 2000 issues;
- advised and trained staff so they can reasonably identify and deal with year 2000 triggered events;
- completed plans and allocated resources to complete outstanding compliance, testing and contingency planning work while maintaining clean management for the few critical systems yet to complete the above.

We have commenced end-to-end testing of systems and aim to have final certification by August 1999.

Forecasting

Forecasting

Forecasting for specific sites

Early in 1998, The Met. Office started work on the Forecasting for Specific Sites: System Implementation (FSSSI) project to build an operational system for running the site-specific forecast model, a single-point version of our Unified Model (UM). The core of the system is a UNIX workstation hosting an Oracle database which contains all the required information for each forecast location. We extract input data from the mesoscale and global versions of the UM and from the main observations database. The system also then initiates runs on the supercomputer of our site-specific forecast model and stores the results. Then the system runs the Kalman filter model output statistics suite and initiates ancillary tasks to create automated first-guess Terminal Aerodrome Forecasts for aviation, road surface temperatures for the OpenRoad service, and other products (Fig. 10). In late January 1999 we started a full trial for nearly 600 sites in the UK and 11 overseas.

Horace development project

We continued to develop the Horace workstation system to meet the operational requirements of the National Meteorological Centre (NMC) at Bracknell, RAF HQ Strike Command at High Wycombe, the Royal Navy's Fleet Weather and Oceanographic Centre at Northwood, the Thailand met. service and the US Air Force in Germany. During the year, we introduced new data manipulation facilities to insert or edit observation parameters and to edit numerical weather prediction (NWP) grid-point data. A calculator facility can operate on single parameters, NWP fields and images, and our algorithm library is available to calculate a wide variety of derived parameters. Our MetWatch software monitors the arrival of data and examines the contents against user-defined criteria before triggering an automatic process or an alert.

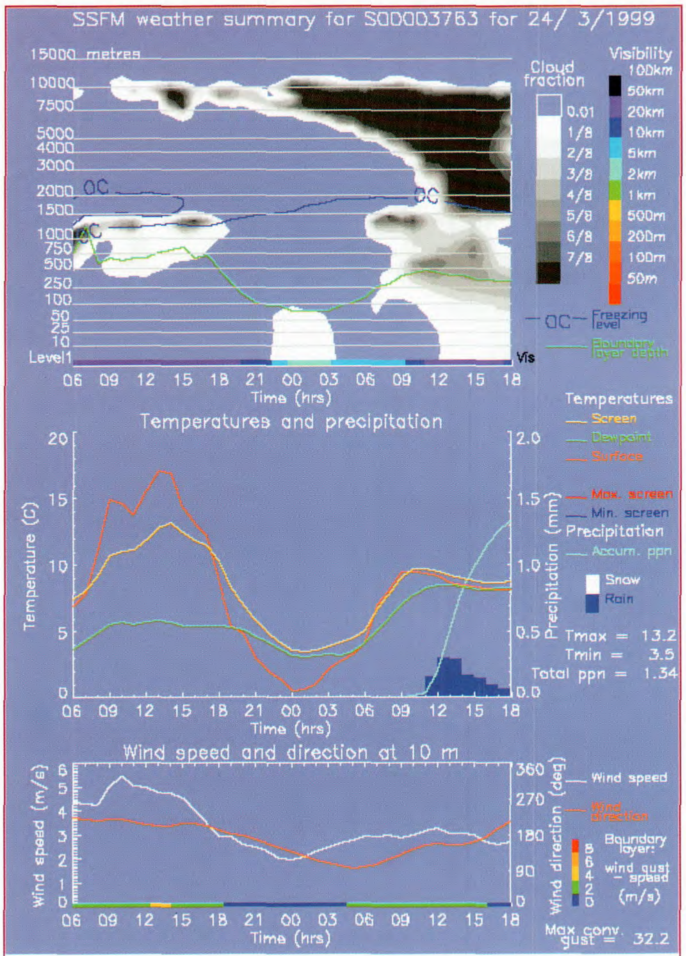


Figure 10. A sample display from the FSSSI system monitor.

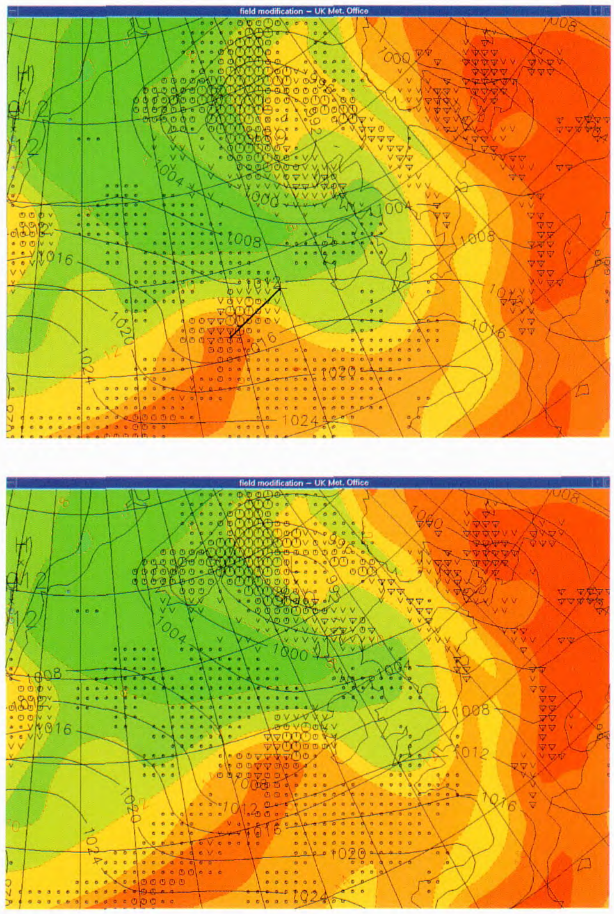


Figure 11. Raw model output fields with user-defined movement (top) and resulting modified fields (bottom).

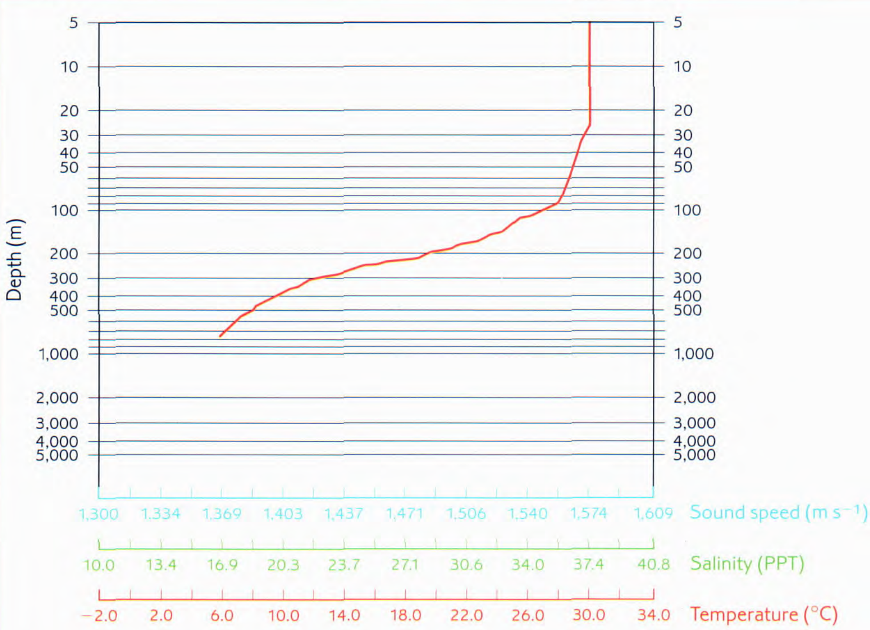


Figure 12. Horace display of a vertical profile of temperature from a bathythermograph.

The new USAF system projects a variety of updating Horace visualisations and animations of imagery, rainfall, sferics, etc., across the walls of the forecast office at Sembach, Germany, and has exploited the production capabilities to prepare graphics for their web site.

We have increased our operational use of software, which has enabled consistent modification of NWP model output fields by forecasters. In particular medium-range chart products are now created automatically from modified fields (Fig. 11). We are developing procedures to transfer these 'quality controlled' fields from Horace to our mainframe computer so that other automated production tasks can use them.

As part of a project for the Royal Navy (Horatio), the field modification system has been extended to operate on oceanographic fields from The Met. Office's Forecasting Ocean–Atmosphere Model. We have written a variety of other software for displaying oceanographic data, such as that displaying a vertical profile from bathythermographs (Fig. 12).

We have introduced Horace software to enable graphical interaction with the objective analysis of observations. The forecaster is able to quality control observations and draw fronts before producing the final chart product. During 1999 we expect this procedure to replace existing manual methods within the NMC.

Nowcasting and short-range forecasting

Nimrod forecasting system

The Nimrod nowcasting/very short-range forecasting system provides fine-resolution analyses and six-hour forecasts of precipitation, cloud, visibility, and related variables to forecasters and to external customers directly.

In June 1998 we enlarged the domain used for the Nimrod system in line with the increased domain of the mesoscale NWP model. At the same time we introduced improvements in several areas, notably in the visibility forecast. In November we introduced an improved lightning prediction scheme, including extrapolation of recent strike locations, and we improved how we predict the accumulation of rime.

Radar data

The value of radar products from the Nimrod system was highlighted in two severe flooding events during 1998. In both cases (at Easter over the Midlands and in late October over Wales), estimates of surface rainfall derived from radar data provided evidence of the extent and severity of the rainfall events (see Fig. 13).

Thunderstorm forecasting

Following another summer trial for the Thames flood warning area of the Environment Agency, we are extending the experimental

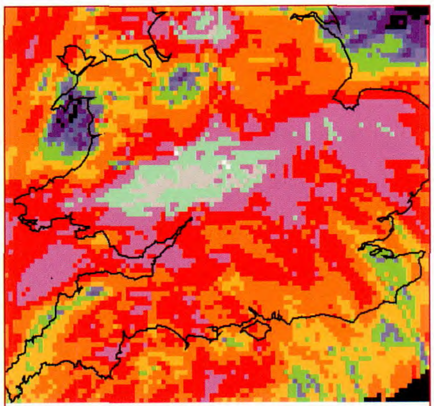


Figure 13. Radar rainfall accumulations for 9 April 1998 of more than 64 mm over a wide area, from the Welsh Borders to the East Midlands.

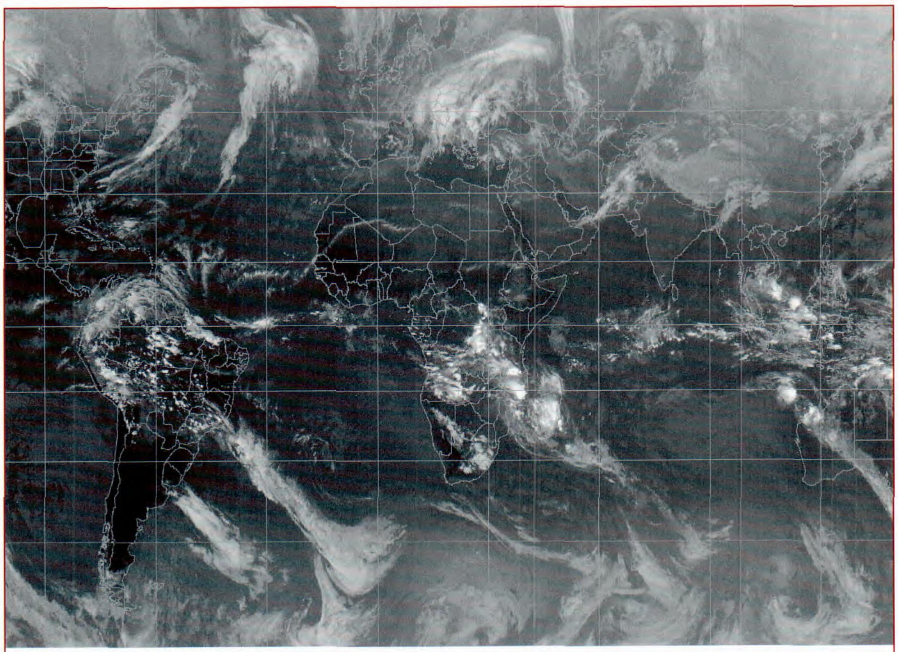


Figure 14. A sample composite image showing a global pattern of convective storms in the inter-tropical convergence zone and mid-latitude depressions in both hemispheres.

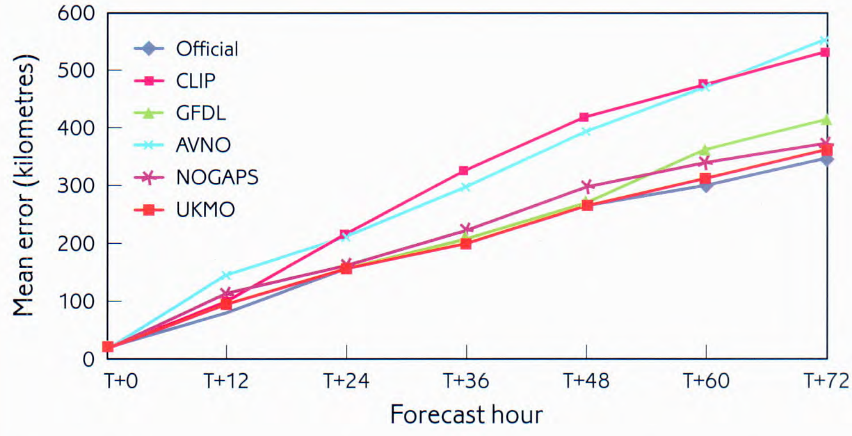


Figure 15. Intercomparison of models available to NHC for the 1998 North Atlantic hurricane season (carried out at NHC), showing mean forecast positional errors.

GANDOLF thunderstorm prediction system to the whole of England and Wales. Initially the system will continue to operate on one radar at a time, but we are working on a composite forecast and to integrate this into Nimrod.

Our summer trial of the convection diagnosis project in the NMC demonstrated that probabilistic interpretation of atmospheric diagnostics from the mesoscale UM could provide significantly enhanced guidance on the locations of *in situ* thunderstorm development. We implemented this system early in 1999.

Satellite data

EUMETSAT redeployed a redundant Meteosat operational satellite (Meteosat 5) over the Indian Ocean during July 1998 as a contribution to the multinational Indian Ocean Experiment (INDOEX). The data were relayed by the operational Meteosat satellite in geostationary orbit above Africa, which enabled the INDOEX data to be received in Europe. When combined with geostationary satellite data from American and Japanese satellites already transmitted routinely to Bracknell, we achieved near global coverage for the first time (see Fig. 14).

Forecast evaluation

Five cities forecast

Scores are being calculated for three-day forecasts of maximum and minimum temperature, wind speed and direction, and probability of precipitation (POP) for the five cities (London, Manchester, Glasgow, Cardiff and Belfast) which are published daily on the Internet (see www.met-office.gov.uk/datafiles/verify.html). For maximum and minimum temperature, we base the score on root-mean-square (r.m.s.) forecast and persistence errors. For wind speed and direction, a categorical score is based on contingency tables of forecast and persistence. For POP, we use the Brier skill score based on Brier scores for forecast and (previous month) persistence. An index is calculated by taking a weighted average of the scores of the five parameters at the five cities for the three days.

Hurricane guidance

Independent evaluation by the US National Hurricane Center (NHC), Miami, has revealed that in 1998, Met. Office forecasts of tropical cyclone tracks in the Atlantic and north-east Pacific regions were better than all other forms of guidance available. Figure 15 shows mean forecast errors for the Atlantic region. Our forecasts were significantly better than climatology/persistence and the National Center for Environmental Protection aviation model. They were also better than the highly respected Navy Operational Global Atmospheric Prediction System (US Navy at the Fleet Numerical Meteorology and Oceanography Center) and the Geophysical Fluid Dynamics Laboratory models, and were as good as official NHC forecasts produced with the aid of Met. Office model forecasts.

Civil aviation

Significant weather automation

We started work on development of an improved automated first guess for the upper-level significant weather charts issued by World Area Forecast Centre (WAFC) London. Our initial focus is on the depiction of jet streams — ensuring a coherent and readable product.

Clear air turbulence

The two new clear air turbulence (CAT) indices have been further developed. One predicts CAT arising from shear and the other predicts CAT arising from breaking mountain waves. We have carried out successful operational trials of both algorithms, and we plan to bring them in operationally during 1999.

Wake vortices

Work on the European Turbulent Wake Incident Reporting Log (ETWIRL) project was concluded during the year. We now have a large number of wake vortex events in our database, together with coincident atmospheric conditions, and we have undertaken some preliminary analysis.

Defence

Horace/Horatio

See **Horace development project.**

New Gulf model

During Autumn 1998, we introduced a new extended version of a fine-resolution model to provide more-detailed information over the Persian Gulf.

Computerised Meteorological System (CMETS)

The main components of the CMETS were trialled during the autumn demonstrating the benefits of our nowcasting approach to local short-term weather prediction. We now have a facility to help in determining the optimum locations for obtaining additional sounding data for use in our system.

Aircraft icing

We began a new project to find an improved aircraft icing diagnostic for both civil and military use. We will compare information from a new cloud microphysical scheme, now implemented in the mesoscale UM, with the climatology developed in the European collaborative project (EURICE), and with *in situ* measurements obtained using the Met. Research Flight C-130 aircraft.

Business

Business

The Business Division is responsible for UK and international commercial sales and marketing, for commercial consultancies and some weather information services. This may involve the selling and marketing of products and services developed elsewhere in The Met. Office. However, some services and consultancies are developed within the Business Division, often with an element of science or technology in them. This a summary of new or unusual developments, emphasising their scientific and technical content.

Marine business

In addition to our standard forecast models, we also have wave models for ocean areas which we run daily. These provide high-quality guidance to forecasters serving the offshore and marine sectors. As well as our forecast products, we produce 'hindcasts' of winds and waves which are archived to build up a data set covering all the global oceans, with European waters at higher spatial resolution. This archive provides a growing record of marine environmental conditions continuous both in space and time — qualities not matched by any other marine data source. During the year we have carried out additional work to further exploit the content of this archive.

Particular note may be made of an investigation into a severe storm, which caused damage to a floating production vessel operating in the Atlantic Ocean west of Shetland in November 1998 (ex-hurricane Mitch). Our model showed that significant long-period swell energies from the south-east (with wave periods in the range 15 to 18 seconds) had become established before the arrival of westerly swell of similar frequencies generated during the storm's progress across the North Atlantic. *It is very likely that* the damage to the vessel's hull was caused by the interaction of swell energies of these critical frequencies from the two directions. This is shown in Fig. 16 by the peak energies occurring at the same time as a very rapid change of mean direction in the two spectral bands. Questions which then arise are: how often do such critical conditions occur? Should they be incorporated in offshore engineering design standards? The availability of the wave model archive will allow such questions to be answered.

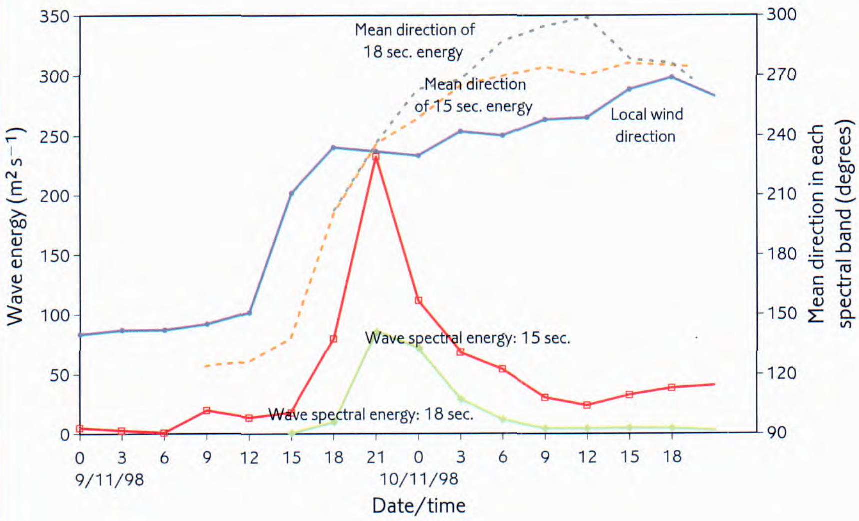


Figure 16. A time sequence of wave energy and wave direction showing the peak in energy as the direction changes.

Air pollution

The air pollution unit was fully involved in an international exercise known as 'Best Endeavours 1999' organised by the Department of the Environment, Transport and the Regions (DETR). This exercise was a test of the response procedures in the event of a nuclear accident. If an accident should occur at an overseas location, which causes a radioactive cloud to appear across the UK, then part of the response is to monitor the gamma radiation using a network of detectors and to combine these data with the output from a forecast model.

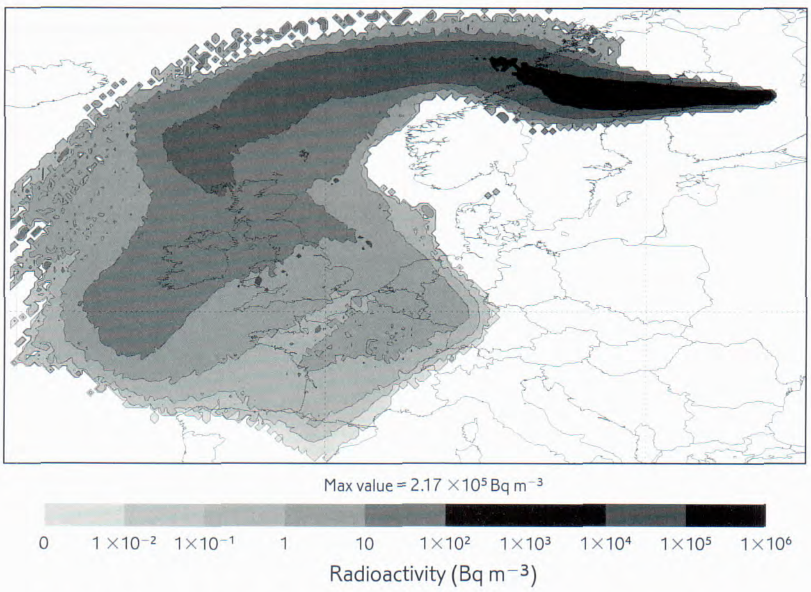


Figure 17. An example of the plume shape calculated by the NAME model for the 'Best Endeavours 1999' exercise. The map shows the total dosage of a radioactive contaminant during the passage of a plume from a hypothetical accident in Finland.

We used The Met. Office's Nuclear Accident Model (NAME) to supply data and forecasts for the accident simulation. For the purpose of the simulation we assumed an accident had occurred in Finland and we used a historic weather sequence for the calculations. The radioactive cloud arrived over Scotland a few days later and proceeded to move south across all the UK. We ran NAME to provide simulated estimates of radioactivity from the gamma radiation monitoring sites and also to supply forecasts of the movement of the cloud and the deposition of radioactivity onto the ground. The exercise lasted for five days during which we supplied the NAME output in real time. Figure 17 shows the estimated path of the plume from its source in Finland to the UK. We are now developing NAME for use as a short-range dispersion model for use in localised chemical, nuclear and pollution incidents.

Pesticide usage

A multinational consortium has been established to investigate the optimum control measures for a range of raspberry pests in Finland, Switzerland, Scotland and Italy. This project, known as RACER (Reduced Application of Chemicals in European Raspberry Production), aims to reduce the amounts of pesticides applied to food crops. A model of the growth of a raspberry pest (the cane midge), developed in the UK, is now being tested for use in the participating countries. Useful estimates of the pest life cycle have been obtained from the first year's results.

Climate display system

Following our production of a bespoke version of the Global Agroclimate, Land-use, Elevation and Soils database (GALES) for a government customer, we have re-formed the underlying databases into a multi-purpose query and display system. High-resolution global information is now available on temperatures (means and extremes), frost-free growing season, evaporation and rainfall in an easy-to-extract format. The potential applications include the environmental field as well as agriculture (see Fig. 18).

Service delivery

Mobile telephone message service

Our Information Services Business Unit is responsible for providing standard products over delivery channels, such as the telephone, facsimile and the Internet, serving our customers for both leisure and business purposes. Our innovative approach has led to sustained customer satisfaction through the provision of services that fulfil their precise needs. The Met. Office was the proud winner of the prestigious 'Marine Industry Service Award' at the 1998 British Nautical Awards for its variety and quality of services to mariners, the latest of which is the Short Message Service (SMS).

Our SMS was launched in August and provides current and accurate marine weather information to all mobile telephone users using the Vodafone network global system. The weather information is received as an incoming call in the form of a text message on the handset, after a user has made a single call to select the type of forecast and area required. We provide both one-off and regularly updated forecasts. Among these are: hourly reports from coastal stations on wind speed and direction; visibility and barometric pressure; the shipping area forecasts for 24-hour periods updated every six hours and forecasts for seven new inshore forecast areas off the south coast, updated three times a day. Messages cost from as little as thirty pence and can be received abroad. By making weather information more accessible, the marine community can plan and adapt sea journeys according to changing weather conditions. We are currently extending SMS to more market areas, such as aviation.

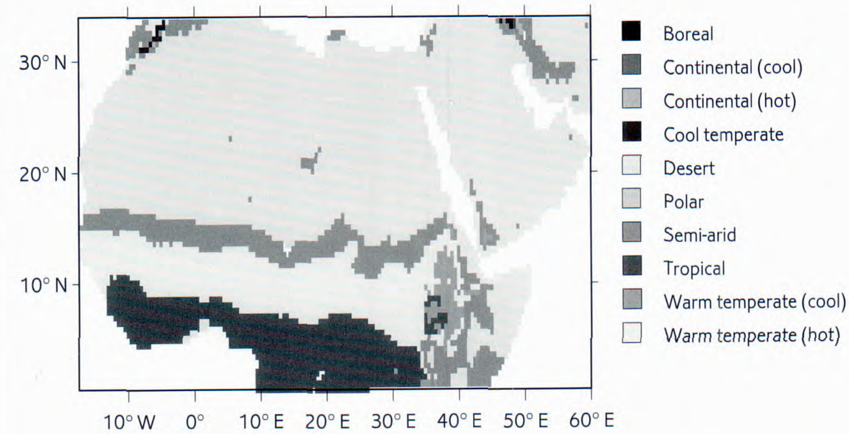


Figure 18. GALES display for the northern part of Africa.

Interactive use of the Internet

Recently we provided a unique service in support of one of the participants in the 1998 round-the-world balloon attempt. Hot-air balloons are at the mercy of the wind so it is essential to have forecasts both before and after launch. As part of this service we provided a fully automated global trajectory model over the Internet. This meant that information was available to the customer at any time, and could be accessed from the balloon in flight. Several scenarios of height and position were submitted to the model through password-controlled pages on our server. Since going live, we produced over 7,000 trajectories successfully and the system was praised by the Cable and Wireless team for its 'very high level of operational efficiency'. This technique, which permits our customers to run Met. Office models from remote locations, has numerous other applications in the environmental sector, for example in providing emergency dispersion modelling.

Insurance consultancy

The insurance industry has used climate and weather information for a number of years to assess claims. Recently we have provided climate information in the buildings insurance area in a form suitable to assess the risk at a finer resolution. The most important weather factors that can damage buildings are subsidence, strong winds and lightning. Subsidence can be a problem on certain soil types that shrink when the soil has become dry. We used the Met. Office Rainfall and Evaporation Calculation System (MORECS) to provide an assessment of the climatic risk of dry summers throughout the UK at a 10-km resolution. In addition we also used the output from MORECS in an experimental operational system to estimate the likely claims caused by subsidence for the year ahead. The insurance industry will find such information important for the assessment of future claims.

We made climate data of strong winds available on a Geographical Information System. This allowed the wind data to be resolved down to postcode level for the UK. A similar analysis was done with lightning data. We used the archive of Arrival Time Difference data for the UK, which contains point information on the locations of lightning flashes from 1990, to determine lightning risk down to postcode resolution.

Another activity in the insurance area has been to develop a catalogue of severe wind storms. In order to answer such questions as to whether the frequency of severe storms has increased in recent years it is necessary to check the historical record. However, this is not straightforward because of changes in observing practices and the density of reporting stations. We have prepared a catalogue of storms from 1950 by using the sea-level air pressure gradient as the criterion. This ensures that storms have been selected with the same criterion for the entire period.

Numerical Weather Prediction

Numerical Weather Prediction

The Met. Office is one of the world's leading centres in numerical weather prediction (NWP). NWP forms the basis of nearly all our forecast services, ranging from forecasts of weather over the UK for a few hours ahead to experimental global seasonal forecasts. The accuracy of these forecasts is comparable with those issued by any other centre.

Uniquely, we operate a single computer model, the Unified Model (UM), for all our NWP and climate prediction. We maintain and routinely run global and regional versions of this model in the operational suite of computer programs. In addition to its use for operational short-range forecasts, both globally and in a high-resolution configuration over the UK, we also use the UM for experimental medium-range ensemble forecasts, for monthly probabilistic forecasts made on behalf of specific customer groups, and for experimental seasonal forecasts.

Our UM computer code is available for use by UK universities and is freely exchanged internationally, and we offer the complete system with consultancy to other centres on a commercial basis. This wider use of the various configurations of the UM results in feedback on their performance, and hence benefits our customers.

We are achieving improved standards of performance and efficiency through a sustained programme of research, maintenance and development concerning both the model itself and the methods for exploiting observational data. This programme is carried out mainly in our NWP Division and, in the context of the UM, aims to:

- reflect improved knowledge and representation of atmospheric behaviour;
- utilise information from new data sources;
- improve the use (or assimilation) and quality of the observational data;
- improve the efficiency and productivity of the model operation;
- facilitate or respond to the removal of manual forecasting resources.

The Joint Centre for Mesoscale Meteorology (JCMM) is run jointly by The Met. Office and the Department of Meteorology, University of Reading, and part of our NWP Division is located there.

Development of the operational forecasting models

Enhancements to the global model

In May 1998, to correct large systematic errors over Antarctica, we changed the specification of terrain height (orography) in the UM. The original orography, derived from data provided by the US Navy, was too high by up to one kilometre to the west of the central plateau and too low by a similar amount to the east (Fig. 19(a) overleaf). The British Antarctic Survey (BAS) provided us with a revised orography based on more-recent geodetic surveys of Antarctica. The gradient of the orography is a key component in determining the surface 'drainage flow' over Antarctica. The errors in the US Navy orography were leading to erroneous anticyclonic and cyclonic circulations in both weather analyses and forecasts over the region where the orography was too high and low respectively (Fig. 19(b)). By correcting these orographic errors, we have corrected the corresponding circulation errors in both weather analyses and forecasts. At longer forecast ranges, the improvements to Antarctic orography have also led to improved forecasts in southern hemisphere mid-latitudes.

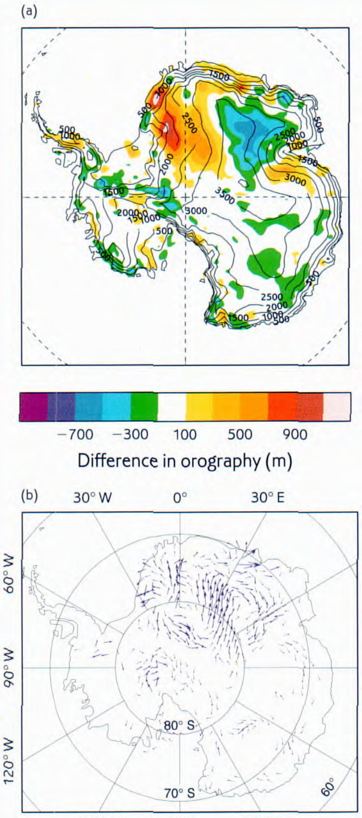


Figure 19. (a) The new orography from the BAS and the difference between the US Navy and BAS orographies, i.e. 'error' in US Navy orography.

Figure 19. (b) Difference (US Navy minus BAS) in 10-metre wind analysis (anticlockwise circulation corresponds to anticyclonic/higher pressure). US Navy orography is more anticyclonic where orography is too high, and cyclonic where too low.

Maps of surface pressure are displayed most conveniently by depicting values over land reduced to a common level, i.e. mean sea level. The reduction of pressure to mean sea level from elevated terrain involves the vertical extrapolation of a 'surface temperature' at an assumed and constant lapse rate of 6.5 °C per kilometre. We know that this procedure is unreliable over high ground. In particular, the errors present in the temperature field are magnified by a large factor and this results in a 'noisy' mean sea-level pressure field (Fig. 20(a)). We have developed a new method to determine which pressure gradient at sea level best represents the surface geostrophic winds. These winds are calculated from the balance between the Coriolis and the pressure-gradient forces at the surface. The new method better reflects the surface flow (Fig. 20(b)), which is of more use to forecasters and avoids the erroneous noise present with the old method.

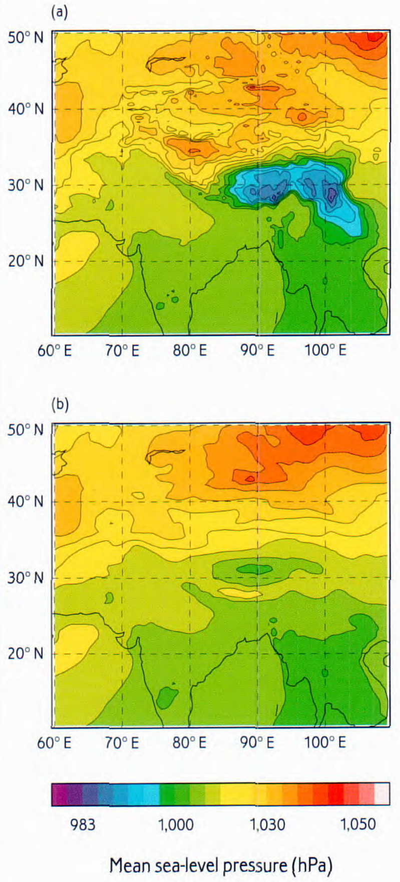


Figure 20. (a) Mean sea-level pressure map over the Himalayan/Tibetan region using old method. (b) The reduction in noise with new geostrophic wind method.

Enhancements to the UK mesoscale model

In August 1998 we implemented a new large-scale precipitation scheme in the operational mesoscale model, which includes a separate representation of cloud ice. Our tests confirmed the better prediction of supercooled cloud and fog in winter and also showed improvements to summer precipitation, especially in reducing the incidence of erroneous

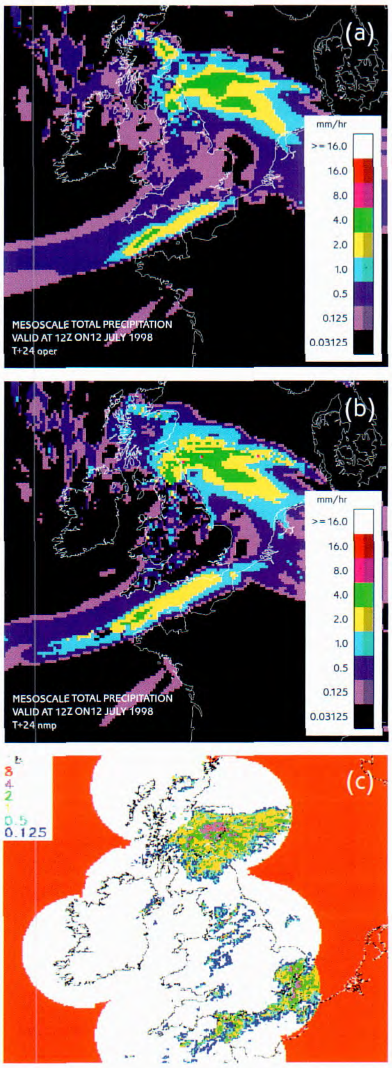


Figure 21. Twenty-four-hour forecasts of (a) precipitation rate (mm h^{-1}) using the old precipitation scheme and (b) the new scheme. (c) The verifying composite radar image.

light rain and drizzle. Figure 21, showing the 24-hour precipitation forecasts, confirms the latter. The old scheme predicted extensive rain and drizzle over England and Wales, which is not evident on the composite radar image. The new scheme is much less misleading in this aspect, and trials confirm that forecasts of surface temperatures and visibilities also improved significantly.

We replaced the regional limited-area model in April 1998. We achieved this by using a preliminary forecast with the global model to provide more-accurate lateral boundary values to the mesoscale model which we use for more-detailed forecasts over the UK. We enlarged the domain of the mesoscale model and improved the resolution to a 12-kilometre grid spacing, improving the representation of the orography and finer-scale weather features. The combined impacts of these improvements, and the new precipitation scheme, can be seen in the better skill of our forecasts of wind and surface temperature since April 1998 (Fig. 22).

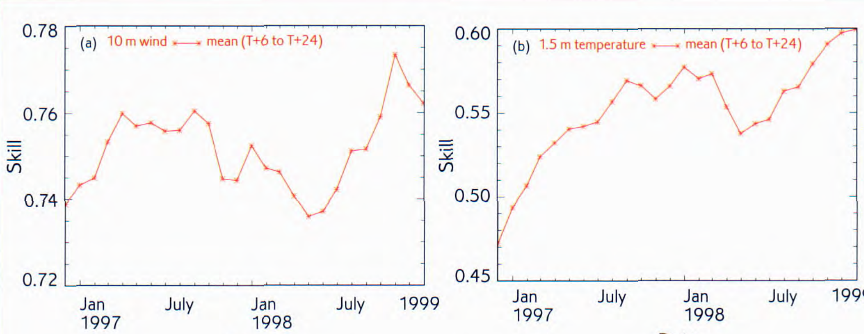


Figure 22. The annual mean skill scores of (a) surface wind and (b) temperature, updated each month from December 1996 to February 1999. The skill is the average of the forecasts 6, 12, 18 and 24 hours ahead compared to persistence forecasts which assume the same atmospheric situation as the previous day.

Representation of land-surface and boundary-layer turbulent-mixing processes

We have now tested a more advanced treatment of land-surface processes in both the global and mesoscale weather forecasting models. This was initially developed for our climate model. The new Met. Office Surface Exchanges Scheme (MOSES) introduces four soil moisture levels coincident with the model's soil temperature levels, freezing and melting of soil moisture with associated latent heating, an interactive resistance to evaporation from vegetation, a surface skin temperature, and a revised specification of vegetative root depths.

Figure 23 (overleaf) shows that MOSES reduces the current scheme's moist bias and improves the relative humidity through its more-realistic limitation of evaporation from plants during the night. MOSES also reduces the current cold bias, reducing the root-mean-square (r.m.s.) errors in this case study. Our tests of MOSES in the global model have shown that the warming of the land surface resulting from soil-moisture freezing reduces the r.m.s. temperature errors in northern Europe and Asia. The improvement over the current operational scheme increases with the length of the forecast.

Accurate modelling of turbulent mixing in the atmospheric boundary layer is also important for good forecasts of near-surface temperature, humidity and wind, as well as for fog, cloud and precipitation. Guided by studies carried out in Atmospheric

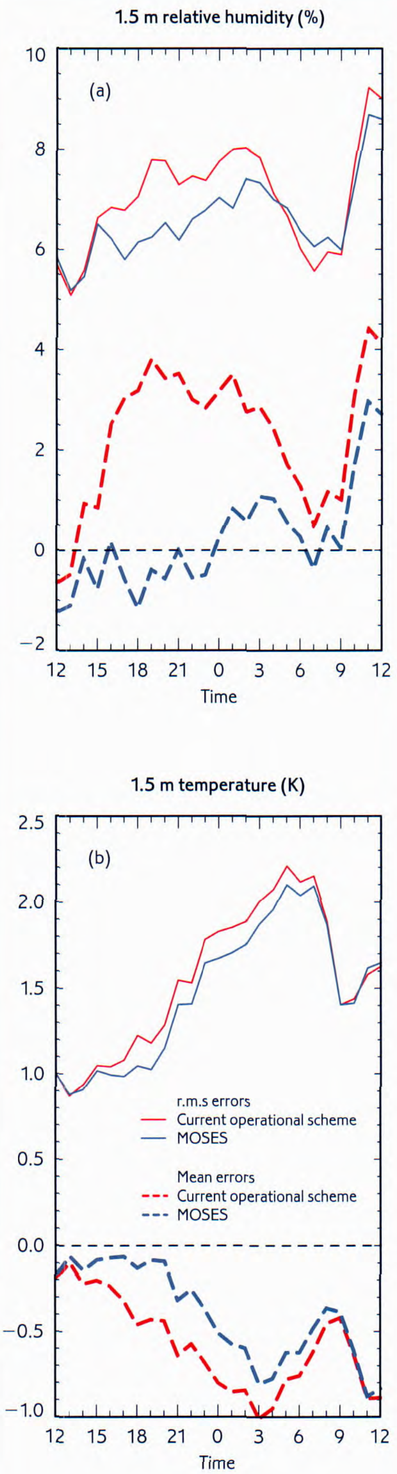


Figure 23. Model comparison of (a) temperature and (b) relative humidity with observations at 289 locations around the UK for the period from 1200 UTC 16 February to 1200 UTC 17 February 1998.

Processes Research (see **Atmospheric Processes Research**) and elsewhere, a 'non-local' specification of the turbulent fluxes for unstable layers has been developed. The scheme includes explicitly a representation of entrainment into the tops of turbulently mixed layers. It also identifies and treats differently well-mixed turbulent layers coupled to the surface, cumulus-capped layers and decoupled layers driven by cloud-top cooling. The turbulent diffusivities depend on scaling quantities representative of the sources of turbulence. Mixing in stable layers remains dependent on a locally determined measure of stability but we have obtained improved forecasts by making the turbulence decrease more strongly with stability as indicated by field studies.

An example of the improvement in a mesoscale model forecast when the new scheme is used is shown in Fig. 24. Satellite and radar pictures and surface observations on this day (12 May 1998) showed that the south-eastern half of Britain had thunderstorms and much less cloud than the operational model predicted. Use of the new turbulent-mixing scheme removed erroneous layer cloud from the model and the forecasts of temperature and convective shower distribution were much improved. Tests in a range of other weather situations showed generally improved scores for model accuracy, even though the impacts were not always as large as in the case shown.

New methods of assimilating data

In a data assimilation cycle, a 'background' forecast model state summarises, in an organised way, the information from earlier observations. We process the current batch of observations to calculate their deviation from the background, and erroneous observations are

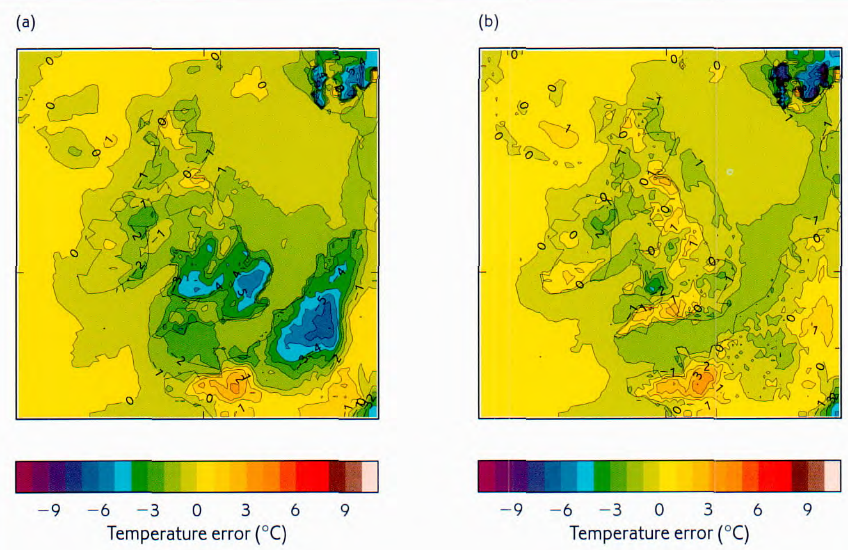


Figure 24. (a) The 1.5-metre temperature error at midday on 12 May 1998, 12 hours into the operational mesoscale model forecast. (b) The same but with the new boundary-layer turbulent-mixing scheme.

rejected. Then we analyse the deviations to give an optimal correction to the background, taking account of the characteristics of both the observations and the forecast errors. We incorporate this correction in a forecast, to give a background for the next batch of observations, and so on. Statistics about the fit of the model to different types of observation are collected, in order to monitor and diagnose problems with particular observing systems, or with the model and assimilation.

This year has seen the complete renewal of the computer software providing the observation processing system, three-dimensional variational analysis (3DVAR) and the suite control system for organising multiple cycles. The new software runs efficiently on our Cray T3E supercomputer at high resolution. The extended trials, necessary to assess the impact of changes to the observing system, data assimilation, or forecast model, are now much easier to perform. The software is easily extended to assimilate new types of observation. For instance, we have already used it to assess the impact of observations from the polar-orbiting Advanced TIROS Operational Vertical Sounder (ATOVS). The software is also being extended for use in collaboration with researchers from the Centre for Global Atmospheric Modelling at the University of Reading to assimilate ozone and other environmentally important parameters in a troposphere–stratosphere configuration of the model. The variational analysis algorithm is capable of using observations which are related only indirectly to model variables, giving scope for better use of many types of satellite data. Developments for these are in progress (see **New applications of satellite data**).

Because behaviours vary in different meteorological situations, and the inherent 'noisiness' of forecast errors, it is important to test changes in data assimilation techniques in long parallel runs, in several seasons. We did this for the introduction of the global 3DVAR analysis, which has improved forecasts (as verified against later observations) by, on average, 1–2% (Fig. 25 overleaf).

Our mesoscale model produces automatic forecasts of visibility, calculated as a complicated function of the atmosphere's predicted humidity and aerosol content. 3DVAR gives the opportunity to use visibility observations, varying the model's humidity and aerosol to fit them. This code demonstrates that it gives a good fit to the visibility observations, without damaging the fit to the many other types of observation also available.

New applications of satellite data

Satellite soundings

Since 1979, TIROS Operational Vertical Sounders (TOVS) on the NOAA polar satellites have provided information on the atmosphere's three-dimensional temperature and humidity structure. Global data received from the USA is processed and assimilated into the global NWP system. In May 1998, an improved version of TOVS (i.e. ATOVS) was launched on the NOAA 15 satellite. ATOVS provides enhanced temperature and humidity information in cloudy areas.

Much of the development work for ATOVS has been achieved through international collaborative projects. The Met. Office contributed calibration and pre-processing modules to the EUMETSAT-sponsored ATOVS and AVHRR (Advanced Very High Resolution Radiometer) processing package and we have worked with the European Centre for Medium-range Weather Forecasts (ECMWF) and Météo-France on a new fast-radiative-transfer model. These efforts were focused on being able to use ATOVS operationally early in 1999.

Experiments have demonstrated that ATOVS data have a very large positive impact in the extratropical southern hemisphere (Fig. 25) and a small positive impact in the northern hemisphere and Tropics. Beyond this, we are working towards gaining further improvements in forecast performance by putting the radiance data directly into the NWP model. We have also started work to prepare for advanced infrared sounders planned for European and US satellites in the next decade.

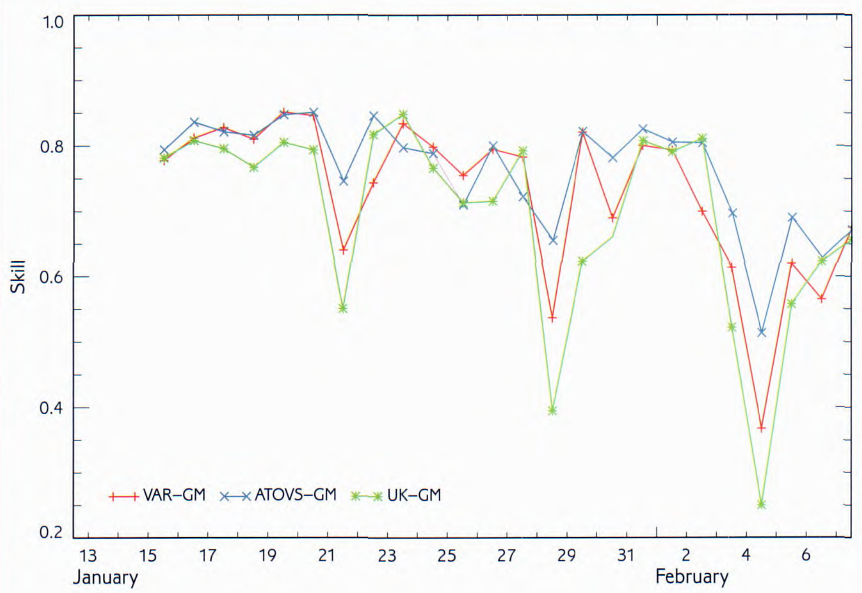


Figure 25. Skill score for southern hemisphere mean sea-level pressure 3-day forecast. The green line denotes the skill of the forecast from the then operational data assimilation scheme, the red line from 3DVAR without ATOVS data and the blue line 3DVAR with ATOVS data. 3DVAR and ATOVS consistently have higher skill than the operational scheme.

Global Positioning System

The radio occultation (RO) technique has been used to probe planetary atmospheres for over 20 years. With the deployment of the Global Positioning System (GPS) satellites, similar sounding of the Earth's atmosphere is possible using receivers on Low Earth Orbiting satellites. One of our earlier studies confirmed that the retrieved temperature sounding data from a US demonstration satellite were of high quality. During the year we developed a one-dimensional variational retrieval scheme which is better at reducing background errors than conventional RO processing methods. We will use data from the Oersted satellite, launched in February 1999, to test the impact of RO data within the global UM.

Broadcast GPS signals received by ground-based instruments designed for geodetic applications can also be used to determine the amount of integrated water vapour above the antenna. In collaboration with the University of Nottingham, we are investigating the feasibility of processing GPS data in near-real time for use in the 3DVAR implementation of the mesoscale forecast model (see **New methods of assimilating data**).

Satellite image applications

Large amounts of latent-heat energy are released by convective precipitation in the Tropics (a generally data-sparse region), and we need to find ways of observing this activity and assimilating the information into the UM. Infrared images from five geostationary satellites are combined in The Met. Office's Automatic Satellite Imagery Handling System (AUTOSAT) to provide near-global snapshots every three hours. These images allow us to estimate cloud-top temperatures, which in turn can be related to the locations and amounts of tropical convective rainfall (Fig. 26). We have used these for model validation, by comparing the satellite-derived estimates with UM analyses and forecasts, and we are preparing to assimilate the information into the UM by a technique known as 'latent-heat nudging'.

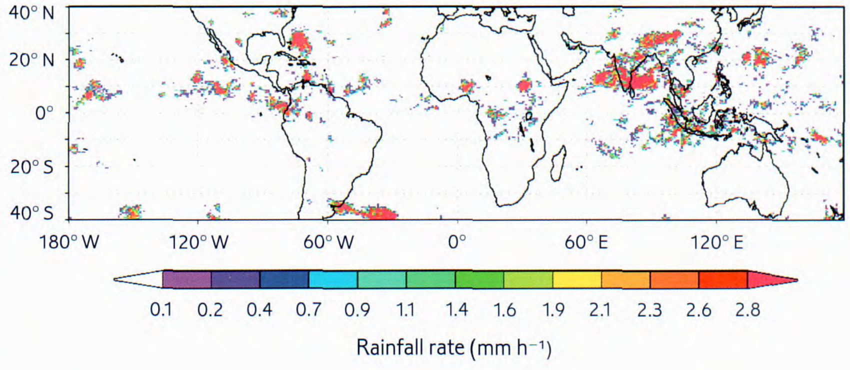


Figure 26. The convective rainfall derived from global composite infrared imagery for 1200 UTC on 25 August 1998. Note that the estimation method limits the maximum rainfall rate to 3 mm h^{-1}. Note hurricane Bonnie, which can be seen off the eastern coast of the US.

NWP Satellite Applications Facility

We are continuing our effort to enable NWP models to make the best use of data from both existing and planned satellites. In November 1998, The Met. Office and EUMETSAT signed a co-operation agreement for a Satellite Applications Facility (SAF) for NWP. The Met. Office will lead the SAF (which is funded partly by EUMETSAT), in a five-year collaboration with ECMWF and the Dutch and French national met. services to develop satellite data-processing software for use in NWP.

Use of FASTEX data

Secondary wave cyclones developing over the North Atlantic Ocean represent an important forecasting challenge. They can develop rapidly (perhaps over 12 hours) and often lead to severe weather over north-western Europe. Data from the international Fronts and Atlantic Storm Track Experiment (FASTEX), which took place in January and February 1997, are being used to test and validate aspects of the UM.

In addition to studies of the impact of extra, 'more-traditional' observations on the forecast, we are using dropsonde data from the Met. Research Flight C-130 aircraft to describe the detailed cyclone structures, together with data from other observing systems such as airborne Doppler radar.

These cyclone structures may develop either through interactions between relatively long-lived features of the flow or because of rapidly developing instabilities (such as conditional symmetric instability). Improved treatment of the first may best be achieved by improvements to the initial state through assimilation of data, while the second may be much more sensitive to the model dynamics and representation of the physical processes.

We studied each particular cyclone during an 'intensive observation period' (IOP). An objective analysis of the dropsonde data provides vertical cross-sections through various parts of a system (Fig. 27). We have compared these with the results from different configurations of the UM (Fig. 28). Our tests have shown that simulations at operational mesoscale resolution greatly improve the predicted overall cyclone structure compared with the approximately 50-kilometre resolution of the limited area model (LAM) operational at the time.

Additionally, a relatively small further enhancement to the vertical resolution greatly improves the simulated strength of intense slantwise circulations, vertical motion and precipitation associated with the development of cloud heads. The strength of these circulations is also sensitive to the rate of cooling through ice sublimation. This demonstrates an additional feedback mechanism and will enable us to test alternative formulations of the ice microphysics scheme in the UM.

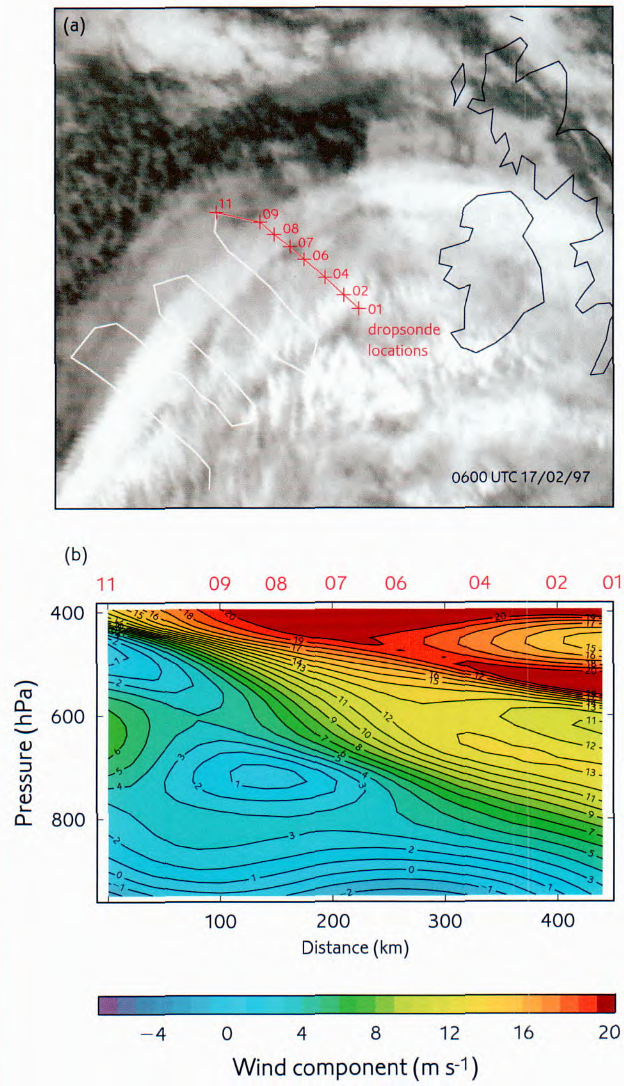


Figure 27. (a) Meteosat infrared satellite image of system studied during FASTEX (17 February 1997). Superimposed is the C-130 aircraft track relative to the system, with the dropsonde position on run 1 highlighted. (b) Objective analysis of wind component along run 1 from dropsonde data (positive is towards the right).

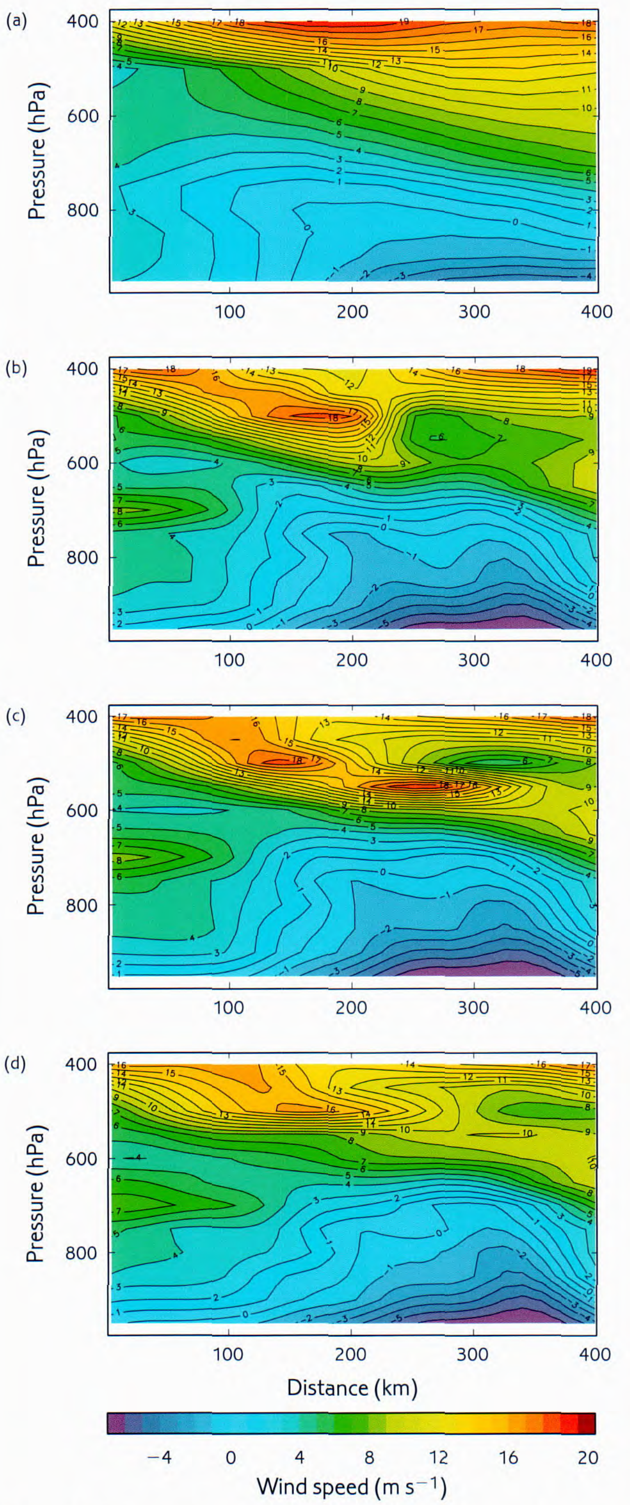


Figure 28. Cross-sections of horizontal wind speed across the system, shown in Fig. 27 from FASTEX IOP 16, run 1. (a) Operational LAM forecast. (b) 11-km horizontal resolution, 38 levels. (c) as (b) except 45 levels. (d) as (c) except sublimation cooling disabled.

Atmospheric Processes Research

Atmospheric Processes Research

Atmospheric processes research involves observational campaigns, numerical modelling and theoretical studies with the ultimate aim of improving the representation of physical processes which cannot be represented explicitly in low-resolution forecast or climate models.

Our observational work centres around two groups; the Met. Research Flight (MRF), Farnborough that uses the instrumented C-130 aircraft (Fig. 29) and the Met. Research Unit (MRU), Cardington, with the tethered kite balloon and surface instrumentation (Fig. 30).

Figure 29. In Autumn 1998, the C-130 took part in an experiment, together with the French Arat and the German Falcon aircraft, and a variety of ground-based equipment, to study the potential of cloud radar and lidar as future space instrumentation. This photograph was taken from the Falcon.

Figure 30. The helium-filled kite balloon at the Cardington surface site.

We base our main modelling tool on large eddy simulation (LES) of flows down to turbulent scales. We have developed this relatively high-resolution model for specific problems and validated it using observational data. This enables us to develop techniques (parametrizations) allowing low-resolution models to treat the physics of particular processes in a realistic manner.

Flow over orography

The size of the grid boxes used in the Unified Model (UM) is typically several tens of kilometres. Therefore, the effect of small hills on the atmosphere is on a scale much smaller than the UM can represent using the current resolution. These effects are critical to the accurate evolution of the model and are incorporated into the UM through the use of a parametrization scheme. We have validated this scheme using high-resolution models, which explicitly represent small-scale hills. However, in order to represent the effects of turbulence these models have, in the past, used very simple parametrizations, which are known to be inaccurate.

In contrast, LESs explicitly model turbulent motions but are computationally very expensive and so they have not previously been applied to simulating flow over hills. We are now making attempts at LES of flow over a periodic array of ridges. To validate these results we commissioned a wind tunnel experiment of a similar configuration at the EnFlo Laboratory, University of Surrey (Fig. 31 overleaf). Our initial results from the LES did not agree well with the data. This was due to a problem caused by the very high vertical grid resolution required to accurately model flow over hills which conflicted with the surface boundary condition applied. We introduced a new boundary condition, based on the more explicit

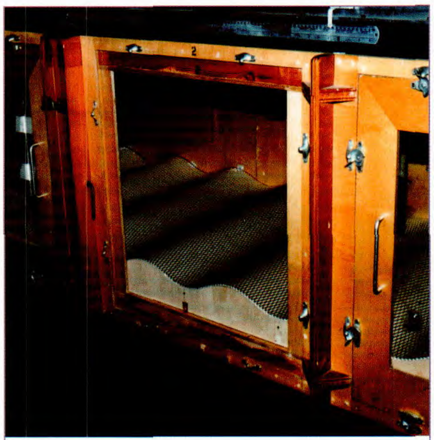


Figure 31. The wind tunnel at the EnFlo Laboratory (University of Surrey) showing the hills used in the experiment. The surface of the hills is covered in a wire mesh to increase its roughness.

representation of the surface roughness elements, and our results now show much better agreement (Fig. 32). This is a major step towards the first rational LES of neutrally stratified flow over hills.

New boundary-layer scheme

In the current boundary-layer scheme of the UM, the degree of turbulent mixing is determined from only the local atmospheric stability. This is a poor assumption in convectively mixed layers, particularly in determining the amount of entrainment at the top of stratocumulus-capped layers. Entrainment is the process whereby positively buoyant and relatively dry air from above the capping inversion is mixed down into the cloud layer and so it can have an important effect on the cloud's evolution. Numerous idealised LESs, performed at high resolution (around 10 m) have allowed a generally

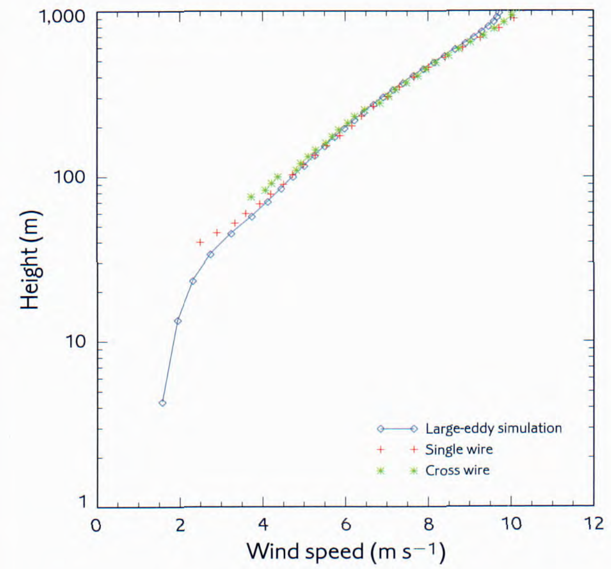


Figure 32. Profiles of wind speed plotted against height on a logarithmic scale for both the wind tunnel data and the results from a large eddy simulation.

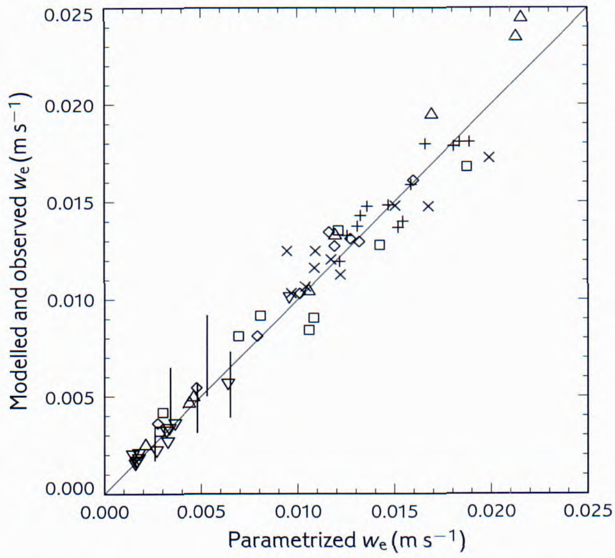


Figure 33. A comparison of modelled and observed entrainment rate, w_e, with the parametrization. △, ▽, □, ×, and + indicate the large eddy simulations under various turbulence forcing regimes, and the vertical lines indicate stratocumulus observations.

applicable parametrization of this process to be determined. As can be seen in Fig. 33, very good agreement is obtained both with the LES results and with available observations, made by MRF and MRU.

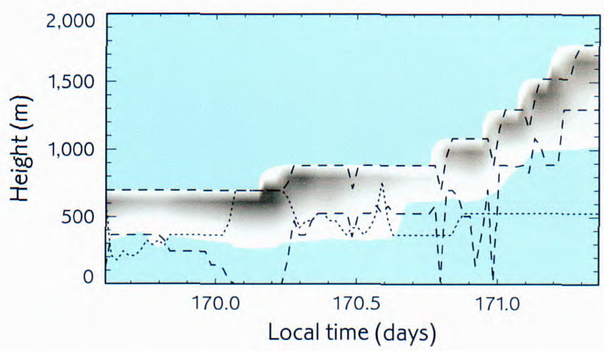


Figure 34. A time–height contour plot of liquid-water mixing ratio from a single-column simulation of the ASTEX Lagrangian I. The dotted line is the top of the surface-driven turbulent layer (or the lifting condensation level if cumulus is diagnosed) and the dashed lines are the upper and lower boundaries of any well-mixed decoupled cloud layer.

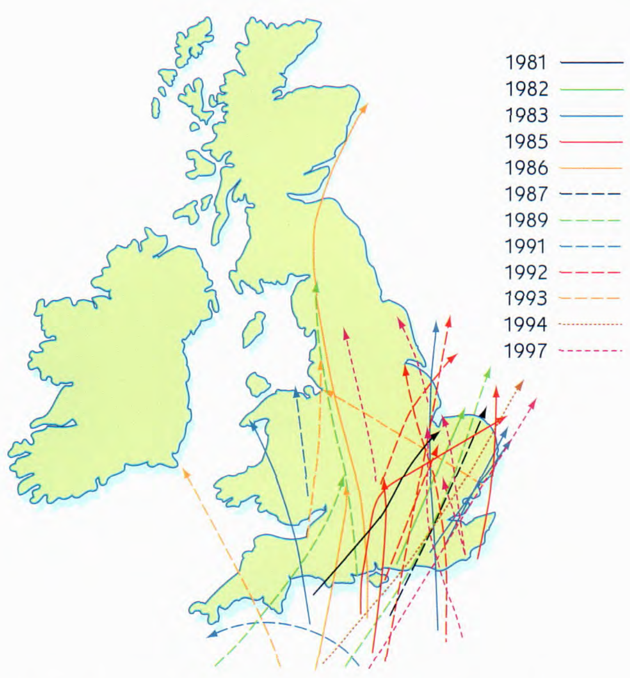


Figure 35. A map of the British Isles showing the tracks of MCSs observed in the period 1981–97. Note that more MCSs were observed in the 1997 than in any other year of the study.

We have combined this entrainment parametrization with a new specification of the eddy-diffusivity profiles within mixed layers. Again we have used the LES results to help determine parametrizations for these profiles which allow for turbulence generation both by surface heating and cloud-top radiative and evaporative cooling. This allows us to model decoupled stratocumulus as well as uniformly mixed boundary layers. Figure 34 shows the evolution of the liquid-water mixing ratio and mixed-layer boundaries from a single-column model simulation driven by the observed sea-surface temperature and subsidence from a 'Lagrangian' type aircraft experiment. We still use the current boundary layer and mass-flux convection schemes for mixing in stable and cumulus-cloud layers respectively (the former were observed at the surface for the first 10 hours of this simulation and the latter under the decoupled stratocumulus layer later on). Our results compare well against the observations and also show relatively smooth transitions between these mixing regimes.

This new boundary layer scheme has now been tested in all atmospheric versions of the UM. At climate resolution, the models' climatologies of well-mixed, decoupled and cumulus-capped boundary layers suggest that we are representing the transition through these regimes in the sub-tropics well. Cross-sections of cloud amount demonstrate how the explicit parametrization of entrainment has lifted the 'fog' off the coast of California, produced by the current scheme in the UM, into more-realistic stratocumulus. We have also found the mesoscale forecasting model tests very encouraging, and a parallel trial is under way.

Understanding mesoscale convective systems

Mesoscale convective systems (MCSs) are clusters of thunderstorms within a much larger contiguous cloud shield, known as the anvil, which can be several hundred kilometres in diameter. These predominantly occur in the Tropics and summer hemisphere continents, where they are the main mechanism of rainfall production. However, we also observe MCSs over the UK and these can present a serious problem in forecasting severe weather. We have conducted a study into the frequency of MCSs over the UK for the period 1981–97. On average, two a year cross the UK as a whole, with an average of one per year over the south-eastern parts of the country. Most UK MCSs occur between May and August and predominantly at night. We show the tracks of the 32 storms identified between 1981 and 1997 in Fig. 35 on the previous page.

There are often two distinct regions to an MCS. The embedded thunderstorms are concentrated in the smaller convective region, which is characterised by very heavy precipitation, strong convective-scale updraughts and strong downdraughts causing gusty squalls at the surface. The remainder of the anvil is known as the stratiform region and is associated with a large area of more moderate precipitation, with much weaker updraughts and downdraughts. Cloud-resolving model simulations of MCSs, using data from the west Pacific warm pool region, show that these mesoscale updraughts from the stratiform region can provide as much heating as the convective updraughts in the upper levels of the systems (see Fig. 36). We have used the results to develop a parametrization for the mesoscale updraughts, which we are testing in the single column version of the UM.

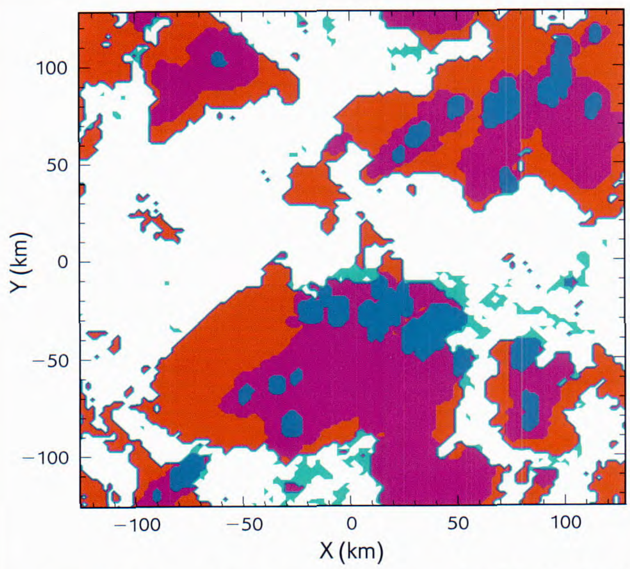


Figure 36. A mesoscale convective system simulated by the cloud-resolving model. Convective regions are blue, stratiform regions are purple, non-precipitating anvil cover are brown and shallow clouds are turquoise.

Ice size spectral evolution in frontal clouds

Frontal clouds around the UK are being studied with the help of the MRF C-130 aircraft. Probes mounted on the aircraft measure the size and number of ice crystals encountered as they fall through the cloud. We achieve this by allowing the aircraft to advect with the wind and descend from cloud top (8–9 km AMSL) to cloud base (1–3 km AMSL) with an

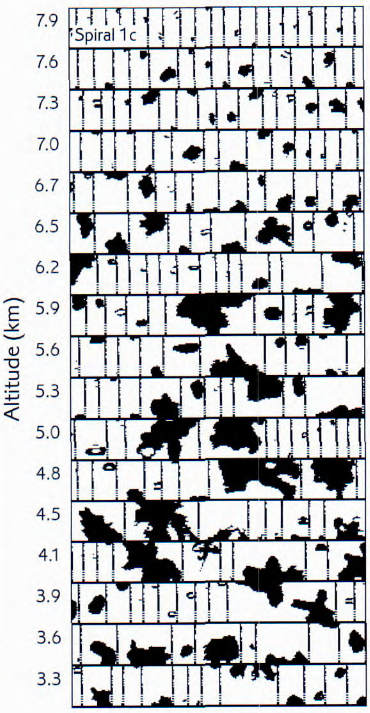


Figure 37. A montage of shadowgraph images observed with the cloud probe. The spacing between the horizontal bars represents 0.8 mm. The data shown at each level are a very small subset of the total data.

average descent rate close to the average fall speed of the observed ice crystals.

Figure 37 shows shadowgraph images obtained on a typical descent through frontal cloud. At the top of the cloud, the particles are small, but increase in size with depth as they grow by aggregation (collision and subsequent sticking of two or more ice crystals to form a larger one) and deposition (water vapour sublimating directly onto the ice crystal surfaces). Figure 38 shows the size spectra, which indicate the concentrations of ice crystals in distinct size ranges. This figure again indicates that large particles are more frequently observed deep in the cloud than at the top. In addition, the size spectra in the figure show a mode, which moves to larger crystal diameters with increased depth in the cloud.

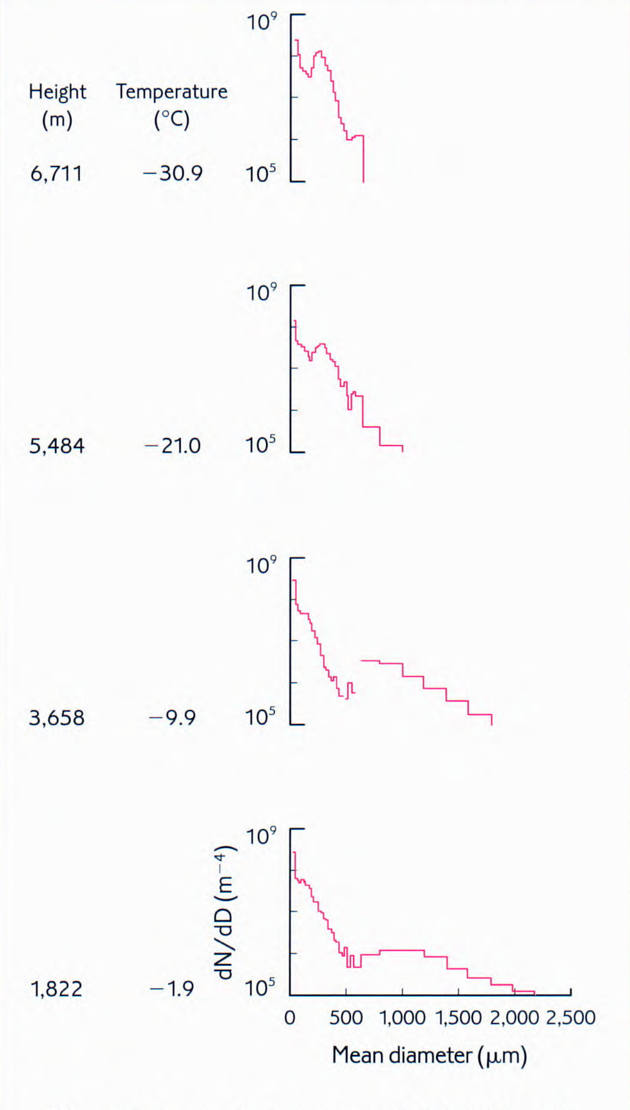


Figure 38. Ice crystals size spectra stacked in height order. The horizontal axis represents the ice crystal equivalent diameter in microns and the vertical axis is a measure of the ice crystal concentration for a particular crystal size.

We believe that the existence of this mode indicates that the aggregation process is important in controlling the ice spectral evolution throughout the entire depth of the frontal cloud. A detailed micro-physical model at the University of Manchester Institute of Science and Technology is being used to interpret the observations. Through continued characterisation and understanding of the ice crystal spectral evolution, we are validating and improving the current precipitation scheme.

Radiative properties of ice clouds

The radiative properties of cirrus clouds have a significant effect on heating and cooling in the upper troposphere. Therefore it is important to characterise the relevant physical processes accurately, and to ensure that any treatment is applied consistently across different spectral regions.

Figure 39 (overleaf) shows some results from a flight carried out off the Scottish coast, when the MRF C-130 sampled a thin layer of cirrus. Measurements of the transmitted radiance were carried out using

SAFIRE, a filter radiometer developed by The Met. Office. Using different combinations of wavelengths, we can deduce quantities such as the cloud optical thickness and the effective ice crystal size remotely, and then compare these quantities with values measured directly with *in situ* probes mounted on the aircraft. Consistency between inferred and measured quantities across different spectral regions would be a good indication that our underlying assumptions are correct.

Figure 39(a) shows a comparison of effective crystal sizes based on hexagonal plate and a more complicated aggregate particle. The aggregate is seen to agree with the *in situ* data better than the plate, and gives a consistent result for both spectral regions. However, when the optical depth is considered in Fig. 39(b), this good agreement is no longer apparent, and the aggregate shape gives relatively poor agreement with the 11.0 μm value (which is independent of the assumed crystal shape) and with the *in situ* data. Clearly, neither shape considered here provides a satisfactory solution, although both assumptions are much better than assuming the particles to be spherical. More work is required to determine whether it is in fact possible to find a single model crystal shape which adequately describes the single-scattering properties of real ice particles, or whether a greater degree of complexity is required.

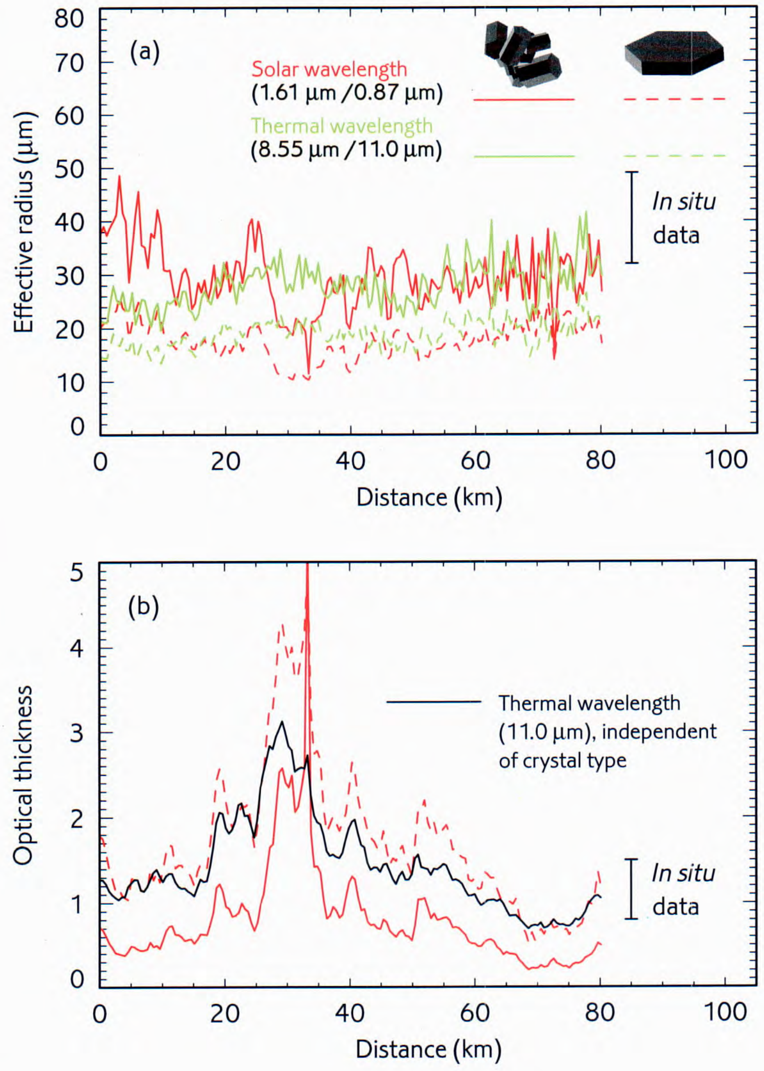
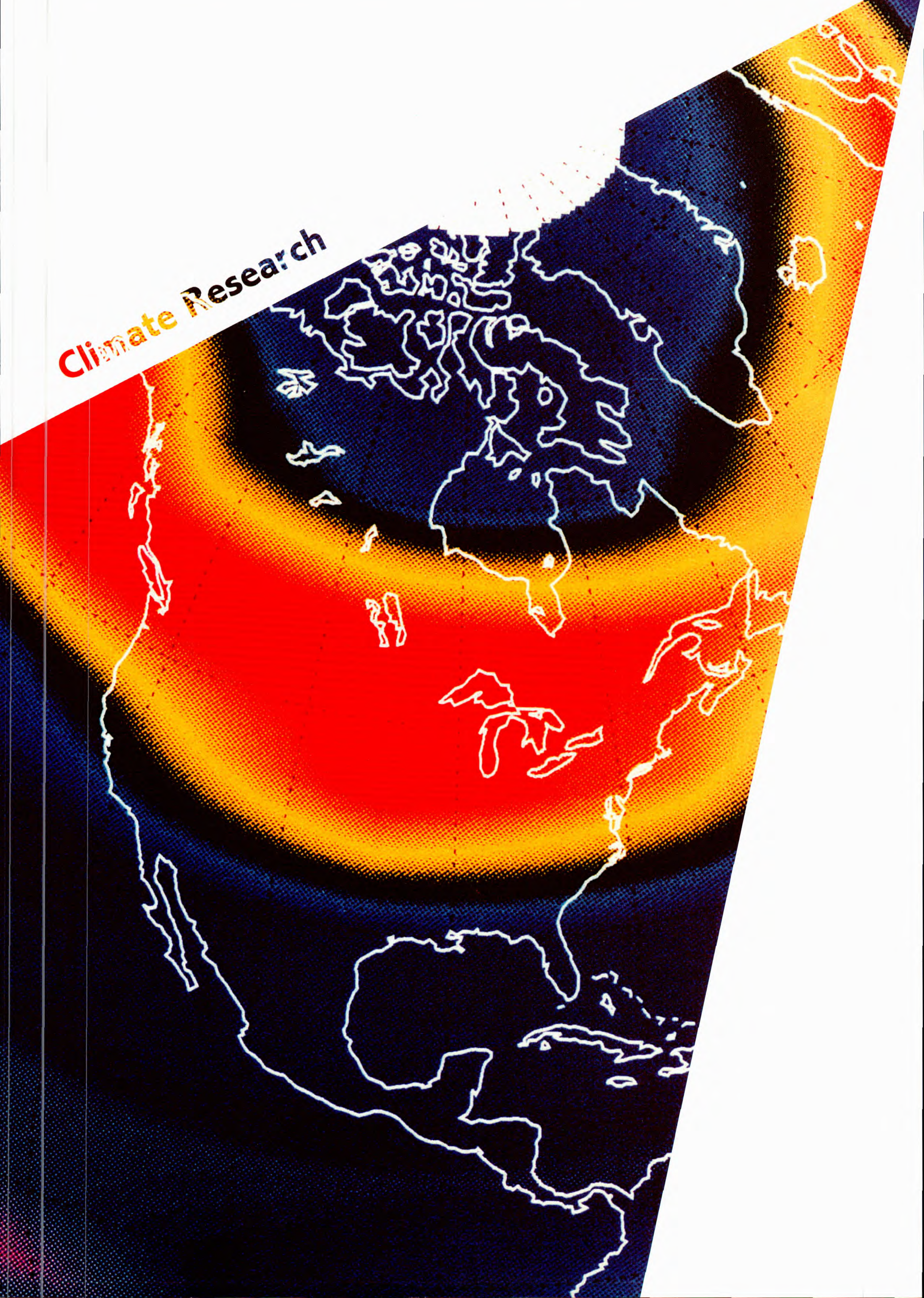


Figure 39. Comparisons of retrieved and measured values of (a) ice crystal effective radius, and (b) optical thickness, from an aircraft run below a thin cirrus layer. Retrievals, assuming randomly orientated hexagonal plates, are shown as dashed lines, those from aggregates are shown as solid lines.

Climate Research



Climate Research

Climate Research serves two main customers. First, the Department of the Environment, Transport and the Regions seeks the best possible estimates of future climate changes due to human activities, in order to inform UK policy towards the United Nations Framework Convention on Climate Change (UNFCCC). Second, the Public Meteorological Service, owned by the Ministry of Defence, funds the development and validation of the climate model, climate monitoring, and work on atmospheric dispersion and atmospheric chemistry.

During 1998, staff from the Hadley Centre for Climate Prediction and Research participated in the 4th Conference of Parties to the UNFCCC, at Buenos Aires, and made presentations to delegates, which included the Deputy Prime Minister.

Recent climate and extremes

Globally, the warmest year so far recorded was 1998, being an estimated 0.57 °C higher than the 1961–90 average and 0.14 °C higher than the previous warmest, 1997. This difference is statistically significant. A major contributor to the increase of 1998 was the very strong 1997/98 El Niño Southern Oscillation (ENSO) warm event. Over the 138 years of credible global records, the global average surface temperature has risen about 0.5 °C.

Over much of the UK, 1998 was notably wet, in strong contrast to the 1995/97 drought. The provisional annual total of England and Wales precipitation at 1,061 mm was the largest since 1966 and 116% of the 1961–90 average, though 1960 was much wetter (1,195 mm at 131% of the average). Although 1998 was not a record warm year in the UK, both maximum and minimum Central England Temperatures continued to be above normal; the decade 1989–98 is the warmest in the 300-year record.

Predictions of climate change

We have now run the new Hadley Centre climate model HadCM3, which does not require artificial flux adjustments, for a period of over 1,000 years. There is very little drift in global mean surface climate. HadCM3 includes the option of a model of the sulphur cycle, which allows the calculation of sulphate concentration, and its direct and indirect effect on climate, from sulphur emissions.

Last year we presented the results of a model experiment from 1860 to 2100, using a future non-interventionist greenhouse gas emissions scenario, and we have added a further experiment including sulphur emissions. The global mean temperature change from both experiments, together with observations from 1860 to 1998, is shown in Fig. 40. The effect of adding aerosols is to reduce the simulated warming to date, but both simulations underestimate the early century warming, perhaps because the effects of natural factors were neglected.

We expect that emissions of sulphur will change little over the next century, and hence we predict

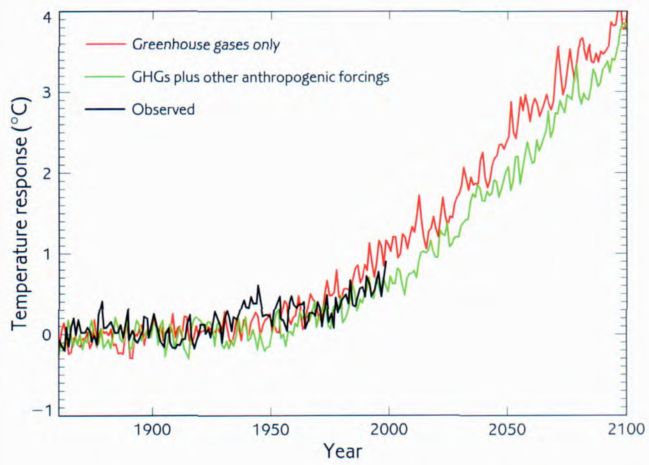


Figure 40. Global mean surface temperature changes due to increases in greenhouse gases, and greenhouse and aerosols.

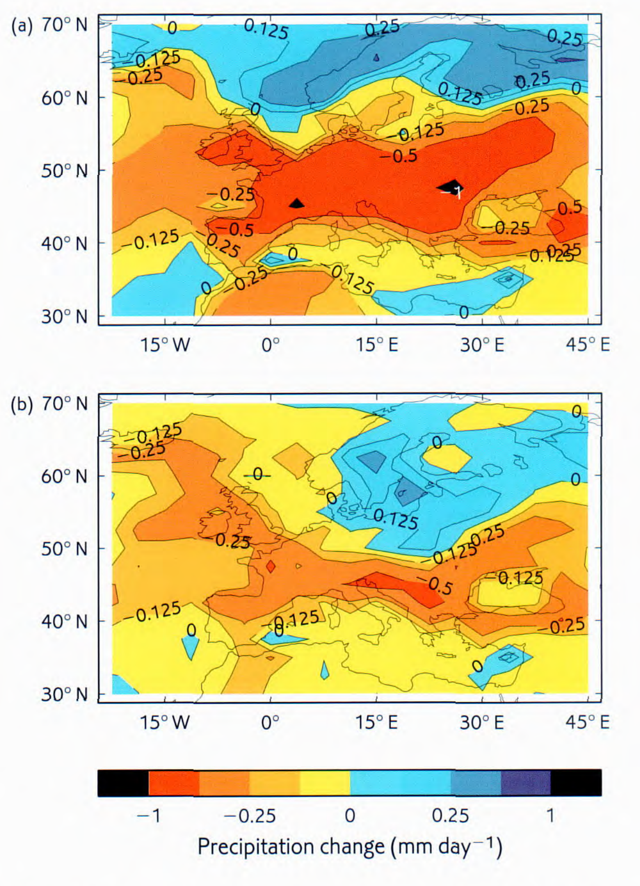


Figure 41. Changes in summer precipitation by the middle of the next century due to (a) increases in greenhouse gases and (b) increases in greenhouse gases and aerosols.

that the global-mean warming will be similar (about 3 °C), with and without the inclusion of sulphur emissions. However, the geographical distribution of emissions will change, and this can lead to regional effects. For example, without aerosols, there is a pronounced reduction in summer rainfall over Europe (Fig. 41(a)). When aerosols are included, the reductions over southern Europe are much smaller (Fig. 41(b)) confirming the link between reduced warming due to aerosols and changes in the patterns and intensity of summer rainfall found in earlier models. The aerosol cooling effect in HadCM3 is weaker than in the earlier studies, and the predicted precipitation changes consequently smaller. Precipitation increases in the Indian monsoon region are smaller when we include the effects of aerosols.

Most climate models indicate that increases in greenhouse gases can lead to a slowing down or collapse of the deep ocean circulation which brings warm salty water into the north-eastern Atlantic (the thermohaline circulation). It has been speculated that such changes could lead to a local cooling over Europe, even if the globe as a whole gets warmer.

The HadCM3 model has a much higher resolution than most models in the ocean, 1.25° x 1.25°, and this leads to a greatly improved simulation of present-day currents. In the model experiment using non-interventionist greenhouse gas emissions, the thermohaline circulation does slow down (Fig. 42, overleaf), but it does not collapse, nor does the climate of Europe get cooler. Also shown here is the change from an idealised experiment in which carbon dioxide was increased at 2% per year to four times the current value and then held constant. Again, the climate of Europe does not cool.

The warming of the ocean leads to an increase in thermal expansion of sea water which does not occur uniformly. Under the non-interventionist greenhouse gas emissions scenario, sea-level rise by the end of the century varies from zero around parts of Antarctica to over 60 cm in parts of the northern oceans (Fig. 43). In addition, the global-mean rise is enhanced due to melting of glaciers. In practice it is not the change in mean sea level that is of concern, but the effect on extremes occurring during storm surges; the 1-in-100-year storm surge at some North Sea ports could occur on average once every 20 years (Fig. 44). If changes in meteorology are also taken into account, this return period decreases even further.

The cause of recent climate change

The extent to which the rise in global average temperature over the last 130 years is due to human activity or natural variability is an important question both scientifically and politically. If the model estimates of ocean–atmosphere variability are correct, then this temperature change has certainly been unusual (Fig. 45). It is more difficult to distinguish between a possible human influence on climate and natural contributions (for example, changes in solar output or in stratospheric dust from volcanic eruptions). We have made simulations of the climatic response to both

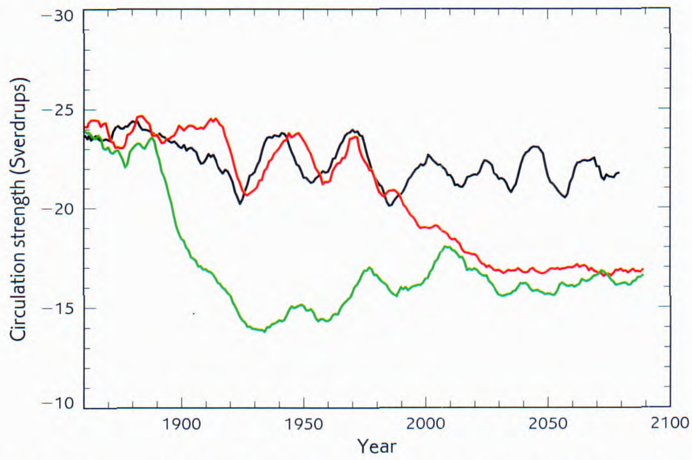


Figure 42. The strength of the North Atlantic Ocean circulation in the control simulation (black), with an non-interventionist greenhouse gas emissions scenario (red) and an idealised scenario in which CO_2 is increased at 2% per year to four times its pre-industrial value (green).

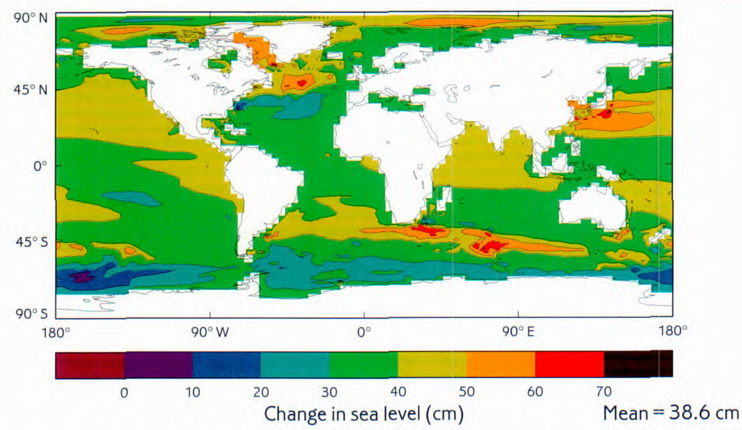


Figure 43. Changes in sea level due to thermal expansion over the next century under the non-interventionist greenhouse gas emission scenario.

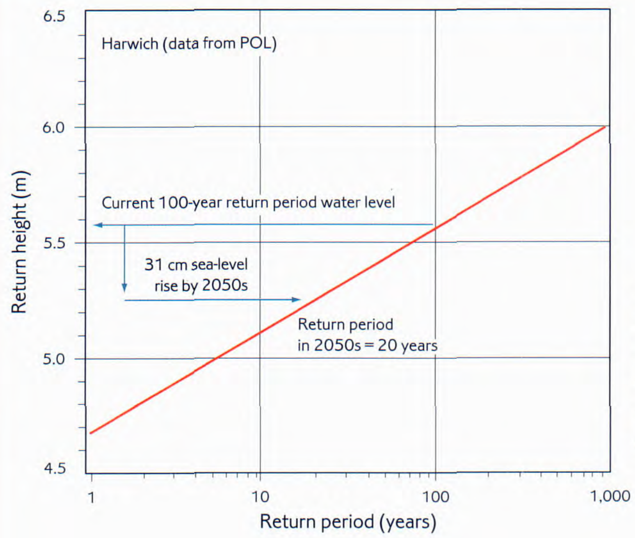


Figure 44. Frequency of storm surges at Harwich based on current conditions and based on sea-level predictions for 2060.

anthropogenic and natural factors over the last century. Advanced statistical techniques, which take into account both the temporal and spatial variations of the model response, indicate that natural factors may have contributed to the early century warming (for example, Fig. 40) but, on their own, they cannot explain the accelerated warming at the end of the century.

In Fig. 45 the red line is the observed global average temperature change, from 1860 to present, relative to the average of the last 40 years of the nineteenth century. The green area shows the range of 'chaotic' climate variability as simulated in the control simulation of HadCM3 (note how this range changes with time, reflecting the change in the number of observations). The blue line is the average temperature of the globe computed from an ensemble of simulations using HadCM3 but forced with changes in solar irradiance and stratospheric aerosol from volcanoes.

Where the blue line is within the green area then the model is consistent with the observations; apart from a small excursion during 1910 or so, consistency remains until approximately 1960 when the model indicates a cooling largely due to the effect of three volcanoes (Agung, El Chichon and Pinatubo). This cooling is not seen in observations, probably due to the increasing amount of greenhouse gases in the atmosphere.

If these results are correct then the warming from 1970 onwards cannot be due to natural causes. All plots are running 10-year means and all model data were masked by the observational data-mask prior to computing the global average.

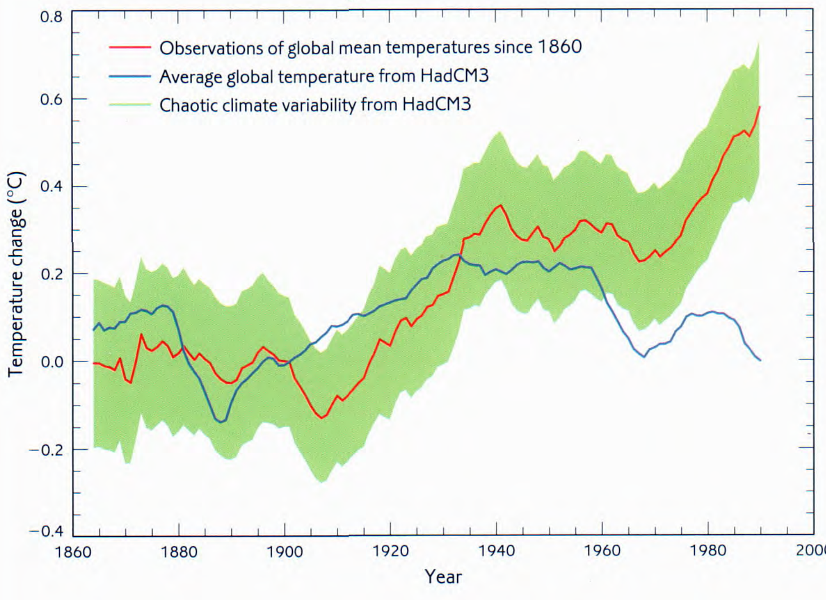


Figure 45. Global mean surface temperature anomalies in a long control run of the Hadley Centre climate model.

Climate variability

The North Atlantic Oscillation (NAO) is a major component of the winter North Atlantic atmospheric circulation. In its positive phase, surface pressure in the Iceland region is lower than normal, and that in the Azores region is higher. This gives stronger or more-frequent winds from the west and south-west. The strength and sign of the NAO patterns strongly influences European temperature and rainfall. There are parallel fluctuations in the position and strength of the jet stream and the storm tracks. We have explored the link between the NAO and the Atlantic sea-surface temperatures (SSTs) using simulations of the climate of the last half century from the HadAM2b atmospheric model forced with observed SSTs and sea-ice changes, and we compared them with observations.

Figure 46 shows the NAO index calculated from the average of six model simulations and from the observations. From additional experiments we can confirm that much of the multi-annual and longer-timescale variability of the NAO over the last 50 years can be reproduced, purely from a knowledge of SST. The link from SST to the positive or negative phases of the NAO involves local changes in surface evaporation and precipitation that tend to reinforce the thermal structure of the NAO. The results are important for understanding the natural variability of European climate. These results have given a predictable component to the SSTs, and are encouraging for multi-annual to decadal predictions of European winter climate.

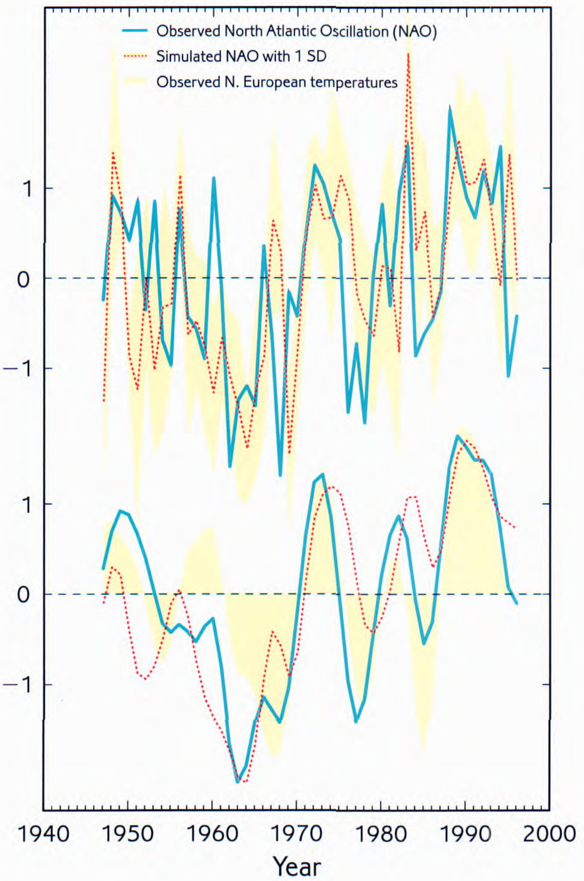


Figure 46. Observed and simulated normalised winter North Atlantic Oscillation (NAO) index. The lower curves have been smoothed to highlight timescales longer than six years. The shading shows observed north European land-surface air temperatures.

In a collaborative UK/Australian/US project, we have isolated two independent large-scale signals, operating at around the 60- to 80-year timescale, in SST and mean sea-level pressure since 1871, *and this has clarified the pattern of global warming.* One of these patterns appears to involve the NAO while the other describes an oscillation which is primarily inter-hemispheric in scale, with some impact on ENSO.

Following participation in a joint Commission for Climatology/CLIVAR Task Group on Climate Indices, we are collaborating in an international effort to collate and analyse daily data, especially temperature and precipitation, to assess changes in the global incidence of extremes such as storm rainfall events and frosts for the Intergovernmental Panel on Climate Change Third Assessment Report.

Temperature change in the free atmosphere

It now seems likely that an increase in the tropical and global lower tropospheric temperature lapse rate has occurred during the past 20 years. Such changes may be the

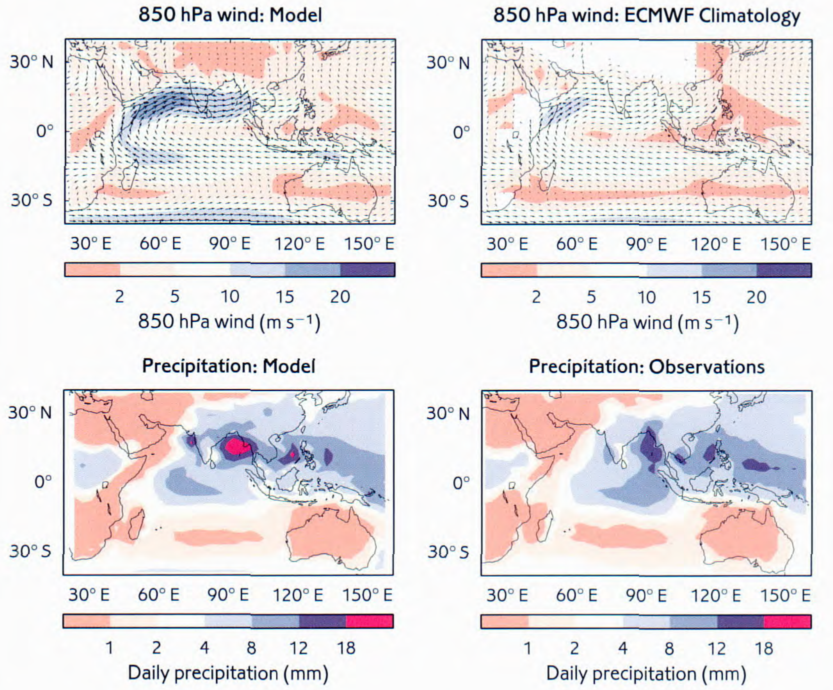


Figure 47. Ten-year seasonal averages (May to September) of horizontal winds at 850 hPa and daily precipitation from the model and from observations, for the region of the Asian summer monsoon.

cause of differences in the rate of warming at the surface and the lower troposphere over this period; despite strong surface warming, warming at about 3,000–5,000 m in the free atmosphere has been very small. The radiosonde data suggest that slow changes in lapse rate may have occurred before. However, considerable uncertainties in the radiosonde and satellite observing systems remain. Novel methods are being used in the USA to try to reduce the errors in the radiosonde data, and the Hadley Centre plays a steering role in this work through the NOAA Comprehensive Aerological Reference Data Set project.

Surface temperatures

We continue to apply new statistical methods to enhance the Global sea-Ice and Sea-Surface Temperature (GISST) and night marine air-temperature data sets and to quantify uncertainties in the analyses since the mid-nineteenth century. The techniques involve optimal estimates of temperature patterns where data are sparse. A recently developed analysis technique known as 'reduced-space optimal interpolation' has been applied, allowing for the fact that the marine data are affected by global warming. We are leading an international task group that is developing a more homogeneous sea-ice concentration database incorporating *in situ* and satellite-based data. The European Centre for Medium-range Weather Forecasts will use the new SST data set for their 40-year atmospheric reanalysis (ERA40).

Model development and parametrizations

Simulating the Asian summer monsoon

Between 1996 and 1999, The Met. Office took part in studies of the hydrology, influence and variability of the Asian summer monsoon (SHIVA), a project part-funded by the European Union and involving scientists from centres in the UK, France and Germany. One of the main aims of the project was to assess the ability of the models to simulate the mean evolution of the monsoon and its interannual and intra-seasonal characteristics, and to investigate the sensitivity of simulations to the representation of physical processes, and to horizontal resolution.

We assessed the quality of the monsoon simulation in the atmosphere-only climate version of the UM (HadAM3). The characteristic monsoon circulation and the spatial distribution of precipitation are in reasonable agreement with the observations (Fig. 47, previous page). However, the model has a tendency to overestimate the strength of the monsoon, and the monsoon onset is about one week early. The large-scale interannual variations in circulation appear to be simulated reasonably well, but there is less skill in simulating the interannual variability of precipitation. The dominant mode of intra-seasonal variability appears to represent the north–south pattern of active/break cycles of the monsoon, in agreement with observations.

The simulation of the monsoon and its variability is insensitive to increasing the model's horizontal resolution, although extra detail is provided in the precipitation distribution. However, the monsoon simulation is sensitive to changes in the representation of physical processes. Changes to the radiation, convection, boundary-layer mixing and land surface schemes altered both the monsoon climatology and the patterns and timescales of its variability.

Aerosols and clouds

For the first time, the Hadley Centre climate model has been used to simulate changes in the distribution of sulphate aerosol and its indirect effects on climate (by changing cloud properties) in the same integration. This fully interactive experiment is a major step forward because, in the real atmosphere, the effects of cloud on aerosol are inseparable from the effects of aerosol on cloud. The estimated annual mean combined indirect effect, due to changes in both cloud albedo and lifetime are shown in Fig. 48. The global mean cooling relative to pre-industrial times of approximately 1 W m^{-2} is somewhat weaker than in previous (not fully interactive) experiments, but is still significant compared with the estimated present-day warming of about 2.5 W m^{-2} from anthropogenic increases in greenhouse gas concentrations.

We have also modelled the climate impact of other types of aerosol, estimated the direct radiative effects of mineral dust aerosol and sea-salt aerosol and carried out a preliminary simulation of biomass smoke aerosol.

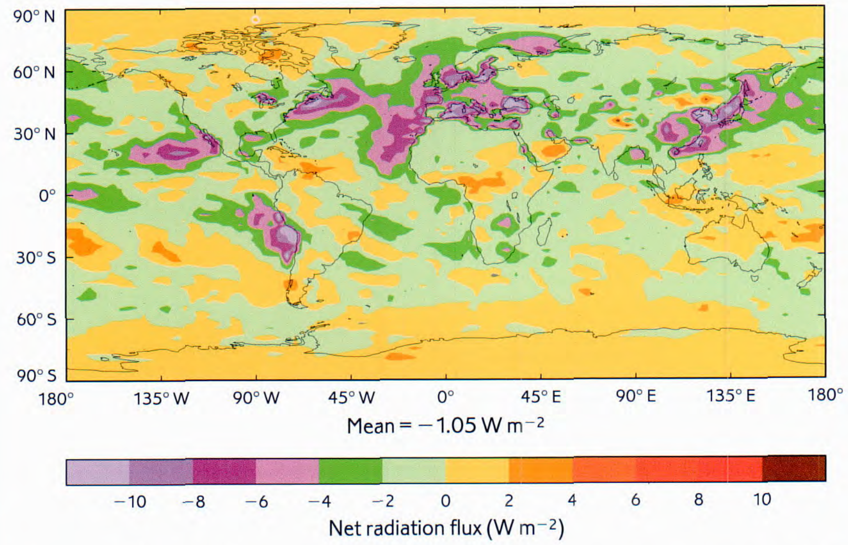


Figure 48. The annual mean difference in net radiation flux at the top of the atmosphere between an experiment including the indirect effects of anthropogenic sulphate aerosol and a control experiment, averaged over five years.

The carbon cycle

Just as the sulphur cycle is now interactive within the climate model, our plans to include the carbon cycle are also advanced. This will allow us to take into account feedback in climate predictions, for example, ocean warming reduces CO_2 uptake and leaves more in the atmosphere. This year we have integrated ocean (chemistry and biology) and land carbon cycle models into a low-resolution ocean version of HadCM3, and we have simulated the pre-industrial carbon cycle. Comparisons with observations (e.g. of the CO_2 seasonal cycle at measuring stations) show encouraging agreement.

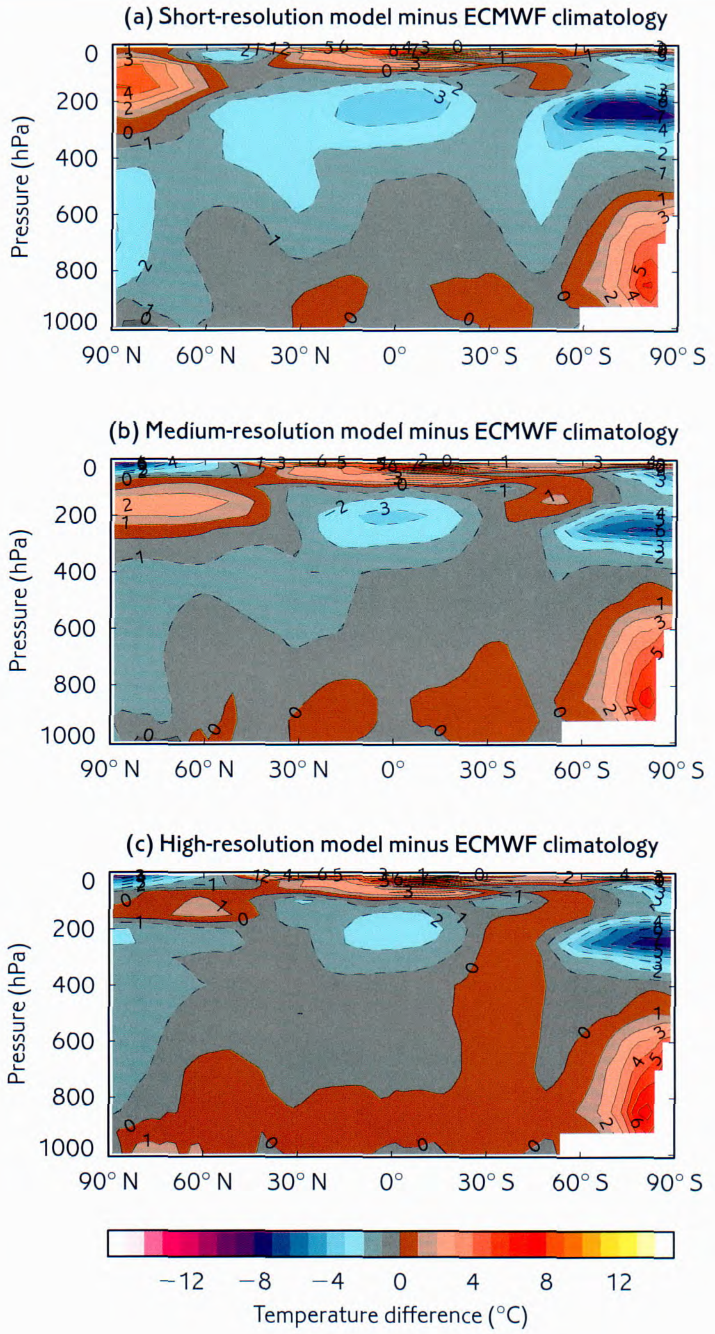


Figure 49. Latitude-pressure cross-sections of the zonal-mean temperature differences between model integrations and the ECMWF re-analysis climatology, for 10-year means of the simulations for December to February. The contour interval is 1 °C.

Resolution experiments with the climate model

In the *Scientific and Technical Review 1997/98* we showed results from experiments in which the number of vertical levels of the atmospheric component of the climate model (HadAM3) increased from 19 to 30. This had a beneficial impact on many aspects of the model's climatology, so we will use the extra resolution in future versions of the model. We have carried out further experiments with the 30-level version of HadAM3, in which we increased the horizontal resolution towards that used in the operational weather forecast model. The standard resolution version of HadAM3 has a horizontal resolution of 2.5° of latitude and 3.75° of longitude, corresponding to about 300 km at middle latitudes. In the additional integrations, the resolution was increased to about 150 km (medium resolution) and to about 100 km (high resolution) at middle latitudes. As with increasing the vertical resolution, the impact of these changes on the climate of the model was mainly positive. For example, Fig. 49 (previous page) shows the impact on the zonal-mean atmospheric temperatures. The troposphere warms, particularly near the tropopause, and this reduces model biases. Most of the improvements are associated with better representation of storms. While it is not possible at present to use a 100 km resolution in climate change simulations, we are considering a modest resolution increase to benefit from these improvements.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was set up in 1988 to provide periodic assessments of current scientific consensus concerning climate change, potential impacts and the range of possible response strategies. The focus of the IPCC Working Group I (WGI), co-ordinated by a Technical Support Unit based at the Hadley Centre, is the physical climate system. WGI produced major assessments in 1990 and 1995, plus several special reports and technical papers. These reports, written by international teams of the world's leading scientists, have played a major role in the negotiation and implementation of the UNFCCC.

This year WGI produced a special report on aviation and the global atmosphere, to be published in June 1999, and has begun preparation of the third major assessment report, due for completion early in 2001. In addition, in partnership with WGII (a task group on climate scenarios for impact assessment), the group has established a data distribution centre to provide a common set of climate scenarios to the climate impacts community.

Stratospheric processes

Assuming standard projections in greenhouse gases and halogen amounts, we have reconfirmed the importance of atmospheric dynamics in simulating future ozone behaviour

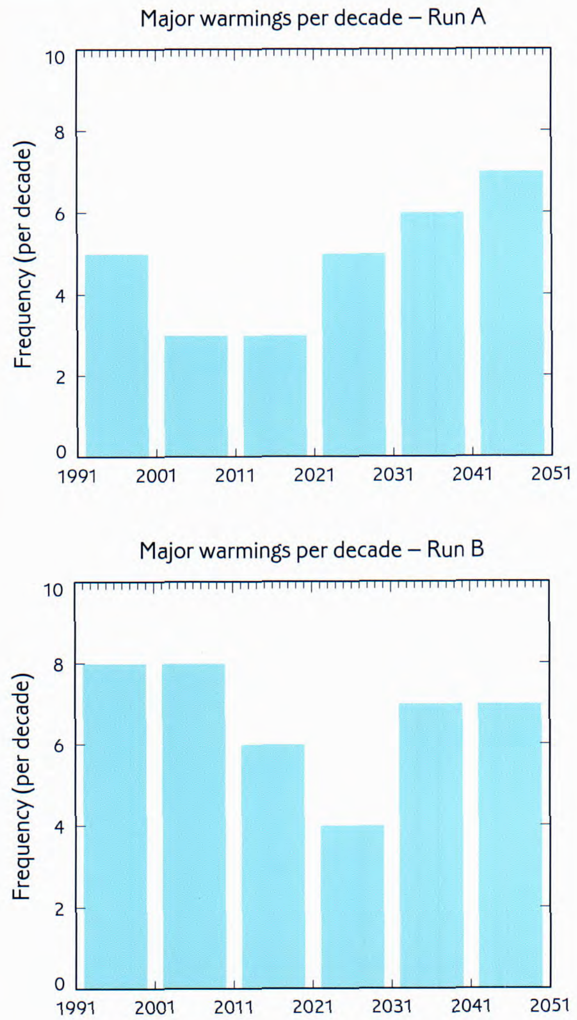


Figure 50. Upper panel: Stratospheric major warming frequency in run A of a 60-year UM simulation. Lower panel: As in the upper panel, but for run B, which had different initial conditions.

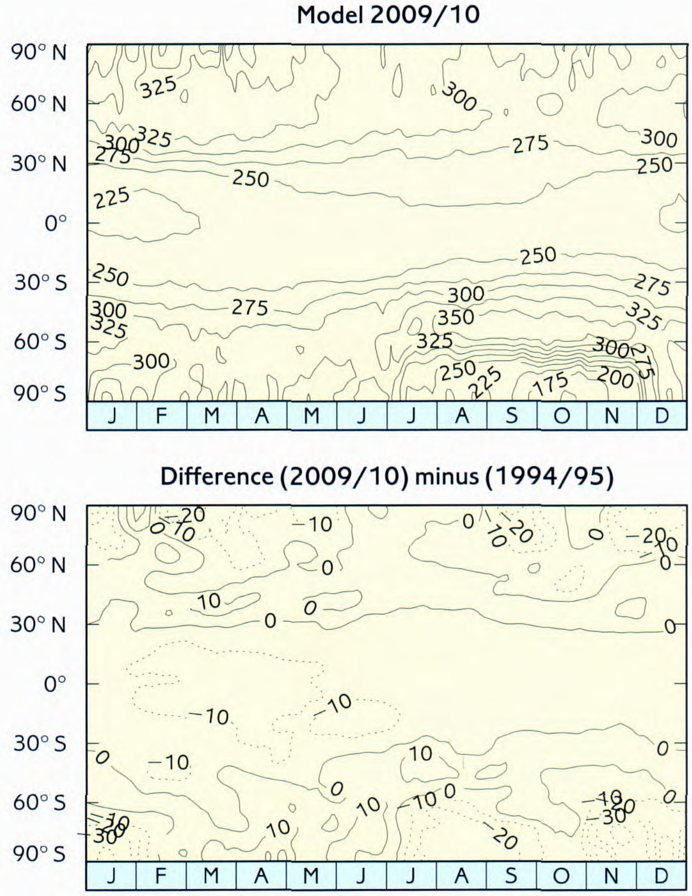


Figure 51. Upper panel: monthly averaged total ozone (in Dobson units) from the coupled chemistry–climate model run for the period 1 July 2009 to 30 June 2010. Lower panel: difference between model results for the year 2009/10 and results for the year 1994/95.

by a sequence of experiments with the UM. Two experiments of the dynamics-only version of the climate model for the period 1991 to 2051, with different starting conditions but similar external forcing characteristics (sea-surface conditions, greenhouse gas concentrations, etc.), reveal differences in decadal stratospheric warming frequencies (Fig. 50). This implies that future stratospheric warming frequencies are unpredictable in the UM (and possibly the atmosphere). This is important given the strong dependence of northern hemisphere ozone on stratospheric warming behaviour.

Model results have been taken from the dynamics-only experiment at five-year intervals and used for initial conditions for 16-month experiments of the UM with stratospheric chemistry. These predict that the lowest value of northern hemisphere spring ozone will occur in about 2009/10, about five to ten years after the peak halogen loading (Fig. 51). The results indicate that, although halogen amounts have decreased by this time, enhanced ozone depletion will occur through a coupling between the stratospheric chemistry and dynamics due to increased concentrations of greenhouse gases.

Atmospheric chemistry

After carbon dioxide and methane, tropospheric ozone is the next most important human-made greenhouse gas. Emissions of methane, carbon monoxide and NO_x from human activities have more than likely led to a doubling of surface tropospheric ozone levels in the northern hemisphere. A global Lagrangian 3D chemistry model, STOCHEM, is being used to quantify tropospheric ozone production and loss, which appears to be dominated by regional-scale photochemical smog formation from human activities and tropical biomass burning emissions. Tropospheric ozone concentrations from pre-industrial times through into the next century have been modelled as an input to climate model simulations and predictions, and will be contributed to the IPCC WGI Third Assessment Report.

Atmospheric dispersion

Understanding the way material disperses in the atmosphere is of importance both for predicting routine pollution levels and for responding to accidental releases of hazardous material. We maintain and develop a number of models for predicting dispersion. These include the Nuclear Accident Model (NAME) multiple-particle dispersion model for mesoscale and longer ranges (see **Environment** in **Business**), the urban box model (BOXURB) for predicting routine urban pollution levels and the Atmospheric Dispersion Modelling System (ADMS) for calculating dispersion over short ranges where the dispersion is dominated by the turbulence in the atmospheric boundary layer. We have developed the latter jointly with Cambridge Environmental Research Consultants Ltd and the University of Surrey.

The ADMS dispersion model has been substantially upgraded over the year, in particular to predict the statistics of short-duration fluctuations in concentration, drawing on experimental work carried out in conjunction with the Chemical and Biological Defence (CBD), a part of the Defence Evaluation and Research Agency. Fluctuations are important in assessing hazards from toxic, flammable, odorous or obscurant materials, and even for routine emissions of substances such as sulphur dioxide, where short periods of high concentration can cause problems in asthma sufferers. The

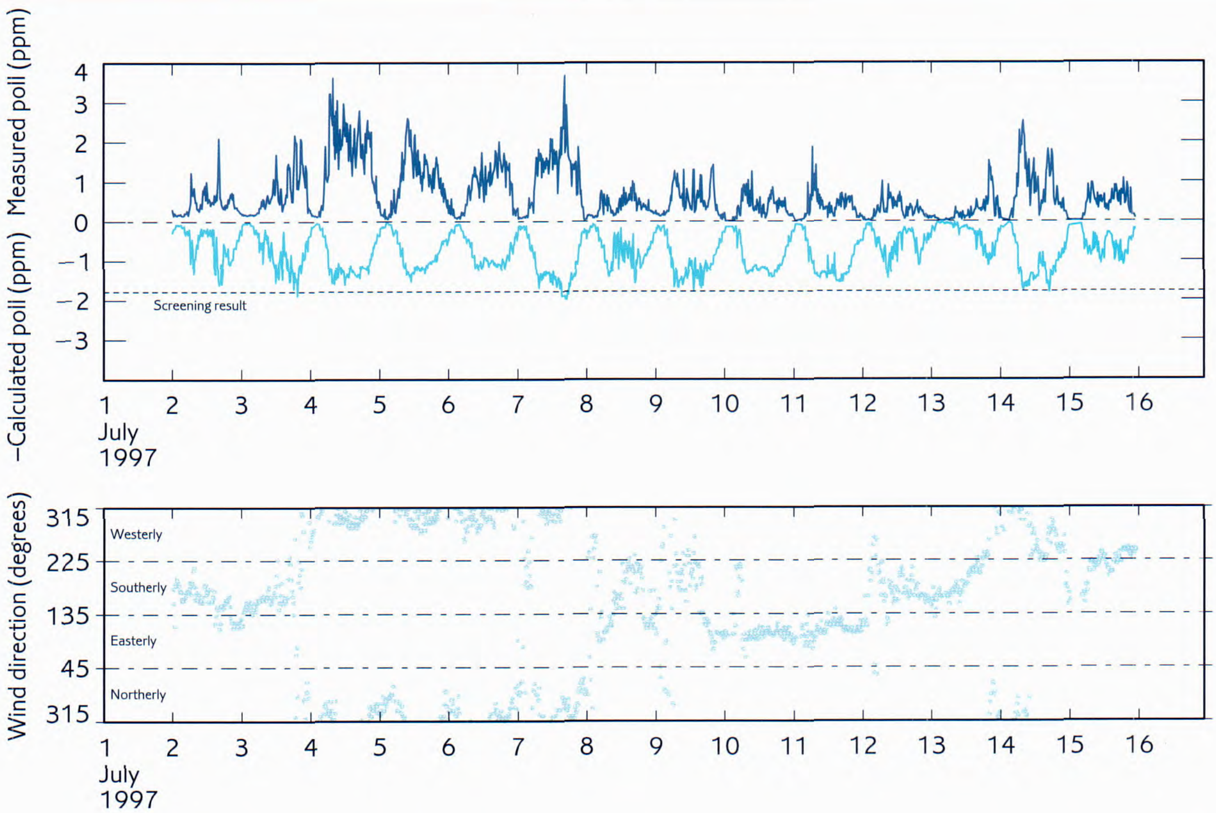


Figure 52. Comparison of time-series of carbon monoxide concentrations predicted using the AEOLIUS street canyon model with measurements taken at Leek, Staffordshire.

model now has improved estimates of the effect of averaging time on fluctuations and, for the first time in any practical model, can predict fluctuations due to multiple sources. Our experimental work carried out jointly with CBD has continued by exploring a wider range of downwind distances. This work will feed through to further model improvements.

Two field programmes aim to improve our knowledge of urban meteorology and dispersion. We completed our analysis of a field study in Leek, measuring winds at different heights above rooftop level, and traffic flow and emissions of carbon monoxide in the street below. We used the results to validate the AEOLIUS 'street canyon' dispersion model. The diurnal pollution pattern was clearly seen (Fig. 52). With the Met. Research Unit at Cardington and the University of Birmingham, we have begun more-detailed urban measurements at a site in Birmingham. We will use the results from this second field study to represent the urban boundary layer in dispersion models and in air-quality forecasting more realistically.

We gave advice to central and local government on a range of air-quality matters, including the processing of oxides of nitrogen data from the national monitors and the use of dispersion models in local air-quality management. We released our revised screening model AEOLIUSQ, and published a nomogram relating street canyon concentrations to wind direction. We continued to apply the NAME long-range dispersion model to the accurate simulation of trans-boundary

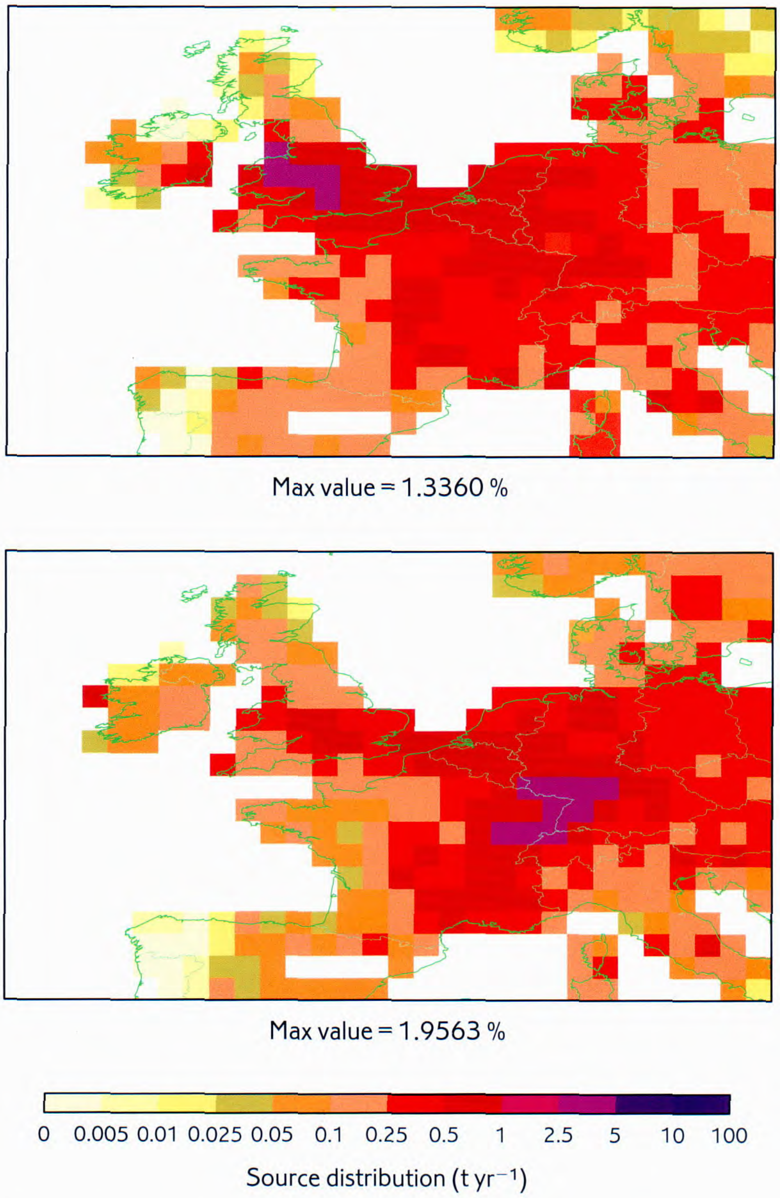


Figure 53. An example of source distributions obtained by applying the attribution scheme of the NAME dispersion model to the Mace Head measurements: estimated emissions for (top) HFC-134a and (bottom) HFC-152a. HFC-134a is mainly manufactured in southern UK, whilst HFC-152a is produced in Germany.

pollutant transports, utilising the long-term measurements of greenhouse gases at Mace Head, County Galway. We developed a new technique to determine the strength and probable distribution of European sources for a range of such trace gases (Fig. 53, previous page). This technique has allowed us to make estimates of UK emissions for a number of important trace gases, many for the first time. We also developed a technique to extract baseline concentrations from observed data, leading to improved estimates of annual and seasonal trends.

We have now added a full dry and aqueous-phase sulphur chemistry scheme to the NAME dispersion model and used it to simulate several years of emission, dispersion and oxidation of sulphur dioxide. Comparison of measured versus modelled SO_2 and sulphate aerosol (Fig. 54) is generally good, although confirming earlier indications of a consistent under-prediction of sulphate in winter.

Sulphate aerosol is a major constituent of respirable particulates (PM10), and the model has simulated significant PM10 episodes in Britain to determine the sources of the pollution. The results showed that, while many cases are the consequence of UK emissions, some episodes are due to the import of pollution from Europe.

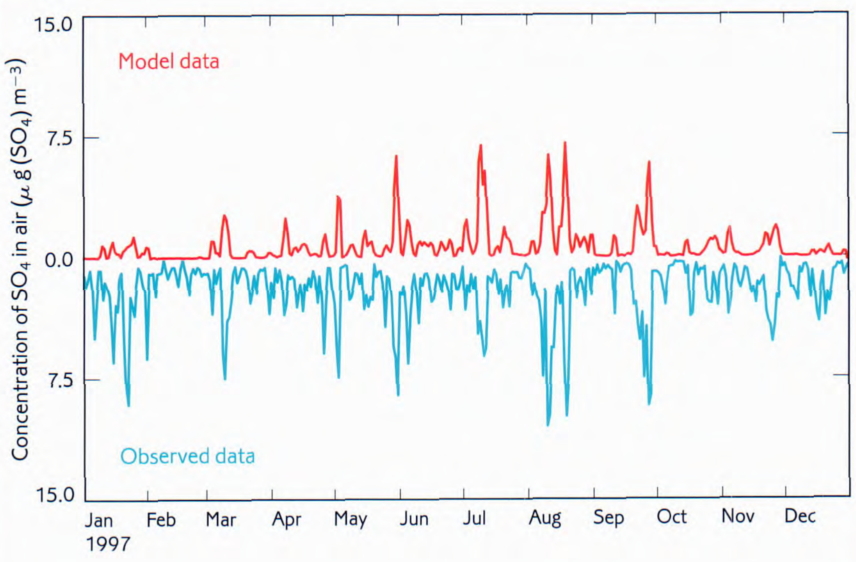
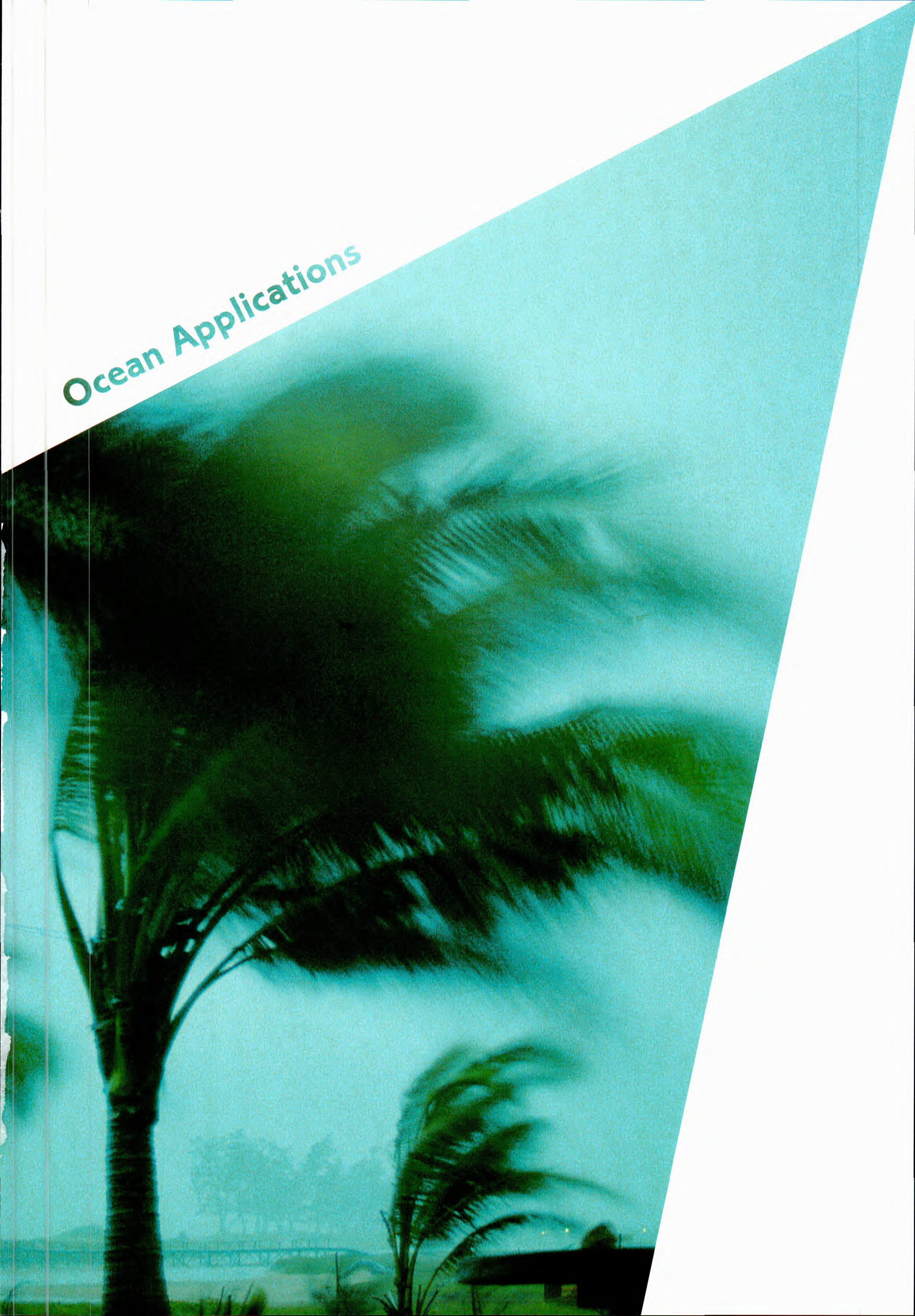


Figure 54. Comparison of daily averaged sulphate aerosol concentrations in air simulated by the NAME dispersion model with observations from Eskdalemuir for 1997.

Ocean Applications



Ocean Applications

Ocean Applications develops, and brings to implementation, the ocean modelling systems required to meet Met. Office customer needs. The Met. Office has had a long commitment to operational oceanography for many years, running operational storm-surge models and global and European wave models. Through development and recent operational implementation of the Forecasting Ocean–Atmosphere Model (FOAM), we also meet a continuing requirement for analysis and forecasting of the global ocean in depth for the Royal Navy. A newer aspect is to develop shelf-seas models for operational use. In addition to operational oceanography, we also support climate research and seasonal forecasting, specifically providing the ocean component of coupled ocean–atmosphere models.

Ocean modelling for climate studies

Ocean general circulation model development

Over the last few years we have made significant improvements to the simulation of climate using the Hadley Centre coupled model. In part, these have arisen from the enhancement of the ocean model horizontal resolution to 1.25°. Even at 1.25° many oceanographic features are inadequately resolved. These include eddies, boundary currents, coastal upwelling regions and sill overflows that drive the deep circulation. To further improve the ocean simulation we have developed a third of a degree 40-level version of the global ocean climate model. Figure 55 shows the temperature and surface current fields from an ocean-only run of this model. The boundary currents are clearly evident, as is the Antarctic Circumpolar Current and the tropical current systems.

It is also important to pursue improvements to the model physics. In the global ocean and coupled models, we have implemented a non-local near-surface mixing scheme. Compared with the present scheme, it gives a more realistic seasonal and spatial representation of the mixed layer. We have also developed more scale-selective lateral mixing parametrizations, suitable for long runs of the fine-resolution model described above.

We made further improvements to the efficiency of the coding of the ocean component of the Unified

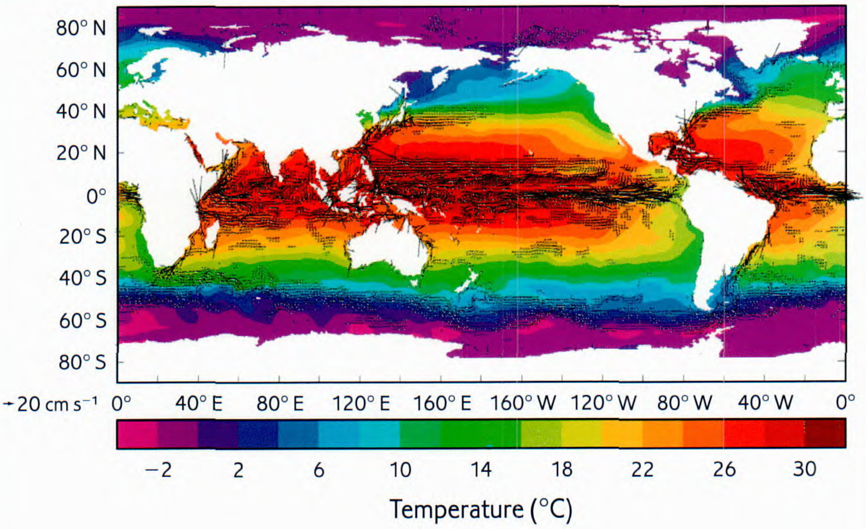


Figure 55. The current and temperature field at 45 m from a global one third of a degree, 40-level model of the ocean.

Model (UM) and we have also provided support to external collaborators using the model.

Ocean model validation

Validation of the ocean circulation in the third version of the Hadley Centre coupled model (HadCM3) has focused on the North Atlantic and Indian Oceans.

The North Atlantic overturning circulation plays an important role in controlling the climate of western Europe. The HadCM3 model has a better representation of this circulation than has been possible in previous versions of the coupled model. We have also identified some shortcomings in HadCM3, but improvements are being developed.

We are analysing decadal timescale variability in the North Atlantic subpolar gyre. Observations show links between the atmospheric North Atlantic Oscillation (NAO) and high-latitude convection. Figure 56 shows the NAO Index and an index of Labrador Sea deep convection in HadCM3. The observed inverse relationship between the NAO and deep convection is clearly present in the model and is supported by observational studies.

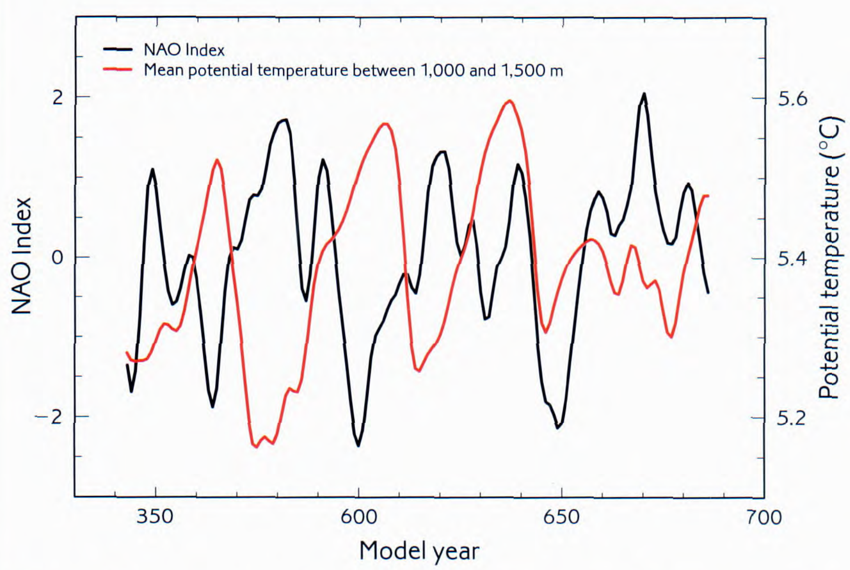


Figure 56. Model simulation time-series of the normalised pressure difference between Iceland and Lisbon (black curve) and an index of deep convection in the Labrador Sea (red curve). The time axis covers approximately 150 years from the HadCM3 control integration. Both curves have been smoothed to remove short-timescale variability.

The throughflow from the Pacific to the Indian Ocean near Indonesia is believed to be too strong in HadCM3, with a possible impact on the modelled heat budget of the Indian Ocean. Our experiments have shown that the magnitude of the throughflow has a strong influence on the model's overturning circulation, but less influence on the heat budget than previous estimates suggested.

Coupled model spin-up

We must run coupled models for a considerable time to allow them to reach near-equilibrium, before starting any climate change experiments. We have developed a technique to allow part of this 'spin-up' run to be performed in ocean-only mode, with a consequent saving of computer time. The amount of time saved depends on the exact configuration of the model.

Seasonal modelling and prediction

Using dynamical physically based models and statistical relationships, we have made predictions of seasonal conditions for widely ranging regions. The source of this predictability lies mainly in sea-surface temperature

(SST), which changes relatively slowly and can itself be predicted on a seasonal timescale.

El Niño to La Niña

Following the onset and development of a major El Niño episode in 1997, there was a rapid decline of tropical Pacific SST in 1998 as the climate system switched to moderate cool La Niña conditions. We monitored these events using the Pacific Ocean general circulation model (GCM), driven by observed winds from various sources, including our atmospheric analyses.

Using the FOAM ocean data system (see **Operational ocean modelling**) we have assimilated *in situ* and remote-sensing ocean observations to improve the accuracy of ocean analyses. The equatorial section of ocean temperature in May 1998, in Fig. 57, reveals the large subsurface signal that preceded the swing toward La Niña.

The ocean GCM provides the information we need to make multi-seasonal forecasts with the coupled ocean–atmosphere GCM. In particular, we made a set of such forecasts relating to the 1997 El Niño event as part of the EC-supported Prediction of Variability on Seasonal Timescales project.

Statistical forecasts

We use statistical methods to make and issue seasonal predictions in selected regions. The skill of such schemes can be measured in many different ways, and proposed guidelines from the World Meteorological Organization were followed in a comprehensive re-evaluation, with emphasis on skill measures that can relate more directly to practical applications.

Operational ocean modelling

Forecasting Ocean–Atmosphere Model

Our Forecasting Ocean–Atmosphere Model (FOAM) forecast system, which has global coverage, is run each day in the operational suite. It provides the Royal Navy with forecasts to five days ahead of the ocean's temperature, salinity and currents and the concentration and depth of sea ice. This year, the systems developed by the Numerical Weather Prediction Division for preparing observations for assimilation and controlling the operational suite have been adapted to replace the systems previously used by FOAM.

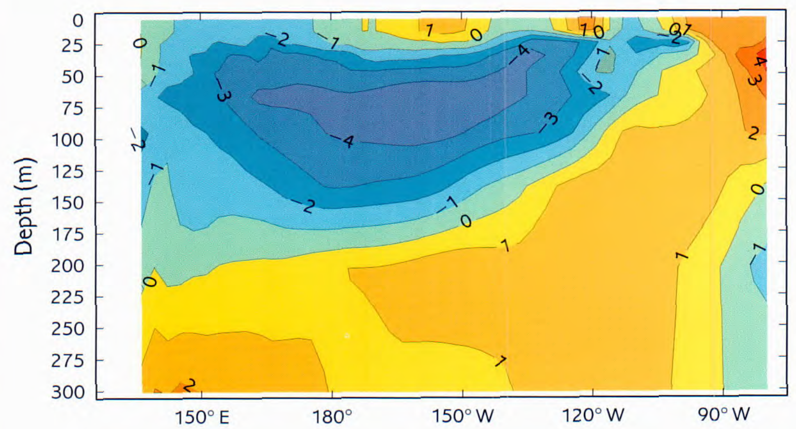


Figure 57. Pacific Ocean temperature anomalies in a section along the equator in May 1998. The section is from the Pacific Ocean model, with assimilation of altimeter data.

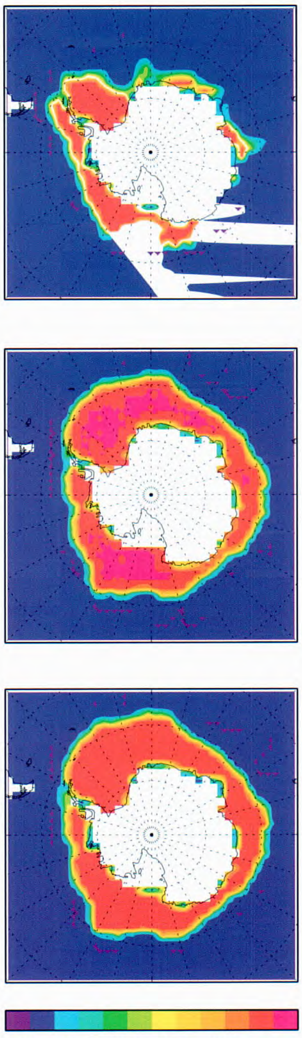


Figure 58. FOAM sea-ice concentration fields for the Antarctic without (top) and with (bottom) sea-ice assimilation. The assimilated field provides a much better match to the observed analysis in the middle.

Passive microwave detectors on satellites provide measurements of sea-ice concentration. The Canadian Meteorological Center (CMC) provides sea-ice analyses based on these data on a daily basis. Our test assimilations of these data into the FOAM model were successful (Fig. 58) and we have started work to introduce this data stream operationally.

The operational FOAM system has a horizontal resolution of 1°. With this resolution it does not represent the very active 'mesoscale' motions in the oceans which correspond dynamically to the weather patterns in the atmosphere. We have set up and integrated limited-area versions of FOAM of one third and one ninth of a degree horizontal resolution nested within the global model. Satellite altimeter data, which provide us with high-resolution information on the ocean's surface height, are being assimilated into these models (Fig. 59).

Shelf-seas modelling

To predict the synoptic-scale evolution of temperature, salinity and current profile over the continental shelf and at the shelf break, we are preparing a baroclinic shelf-seas model for real-time implementation. This model of the north-west European continental shelf has been developed by the Centre for Coastal and Marine Sciences (Proudman

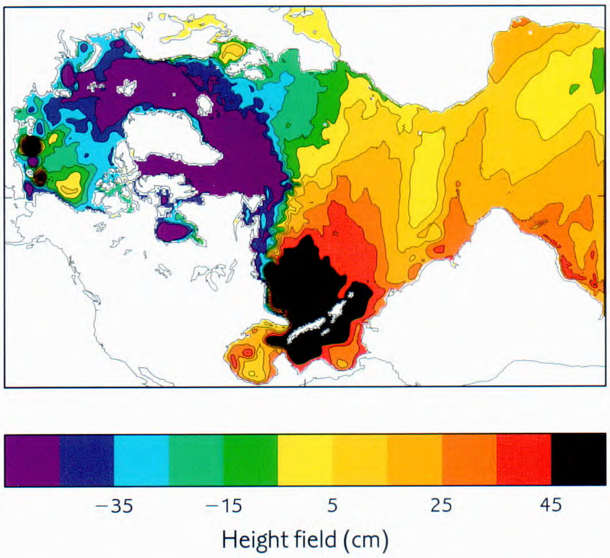


Figure 59. Ocean surface height field from a run of the one third of a degree FOAM North Atlantic model. The Gulf Stream off the US coast is clearly shown.

Oceanographic Laboratory). At the sea surface, our global NWP model provides heat and momentum forcing and, at the deep ocean boundaries, we specify tidal constituents. The model run started from 1 March 1998, and is being brought up to near-real time.

Our comparison of model and observed daily averaged SST shows good agreement away from coasts and rivers. Figure 60(a) shows a steady warming in the English Channel during the period in which the water column remains well mixed throughout. For a site in deeper water, Figure 60(b) shows the onset of stratification (in which temperatures decrease with depth) followed by a faster warming of the SST.

Using six-hourly heat fluxes and hourly winds and pressures, the shelf-seas model can resolve variability on timescales of less than one day. Figure 61 shows an episode of stratification over the Dogger Bank, where the water column is usually well mixed giving uniform temperatures with depth, which coincided with a period of low winds, neap tides and strong heating. A strong diurnal cycle can be seen in the heating and cooling of the top five metres.

The shelf-seas model also represents variability in the current flow along the shelf slope, forced by surface storms. Figure 62 shows that over a 60-day period, several storms can increase the average current to over twice the normal value, over much of the top 200 metres of the water column.

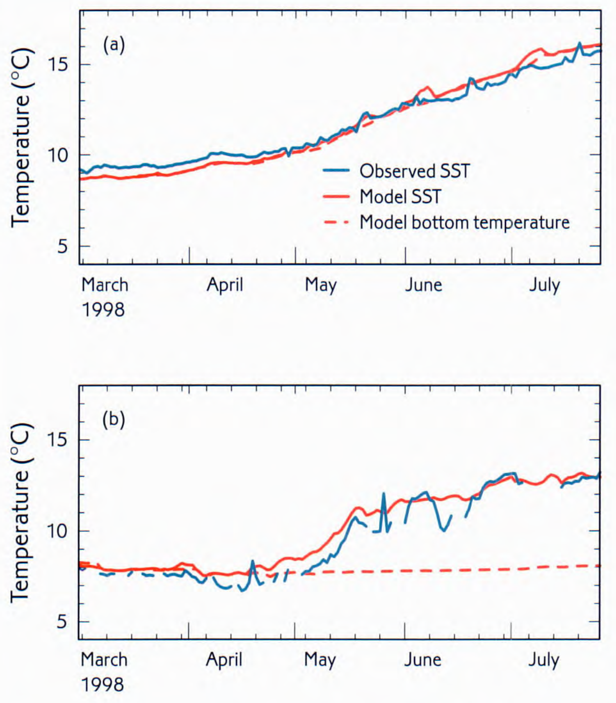


Figure 60. A comparison of observed and modelled daily averaged SST, (a) for a buoy in the eastern English Channel at 50.44° N, 2.38° E, and (b) for a buoy at 58.44° N, 1.83° E in the northern North Sea.

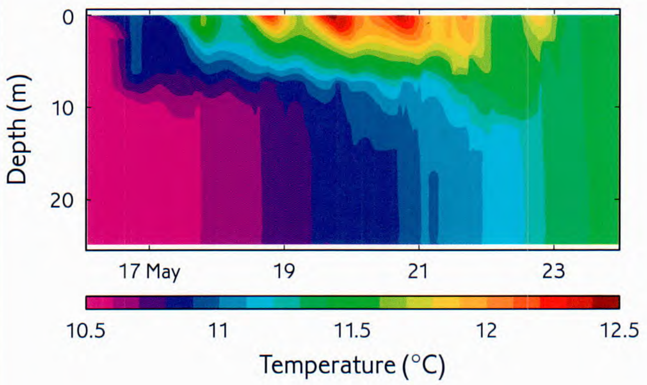


Figure 61. A time-series of hourly values of shelf model temperature profile at the Dogger Bank, 16–24 May 1998 showing the onset of stratification. After several days this stratification breaks down, as winds and tidal currents become stronger. The water column is then about 1.5 °C warmer than the week before.

Wave modelling

We have a new global wave model at the same resolution as the operational global NWP model (0.83° × 0.56°). Including the effects of shallow water in depths less than 200 metres, this model gives better results in areas of complex coastline, and areas such as the North Sea.

We are preparing the model for operational use in early 1999. Figure 63 compares the new model with the present model over the North Sea, for a storm on 25 October 1998, showing a more-realistic distribution of wave heights when shallow water terms are included. The new model grid also includes the Irish Sea and English Channel.

Work is also in progress to use ERS-2 Synthetic Aperture Radar data to provide validation of global wave model spectra and for applications by our Business Division. We are running programs to retrieve observed wave energy spectra from the data in near-real time. We are also preparing the programs in readiness for the launch of Envisat in May 2000.

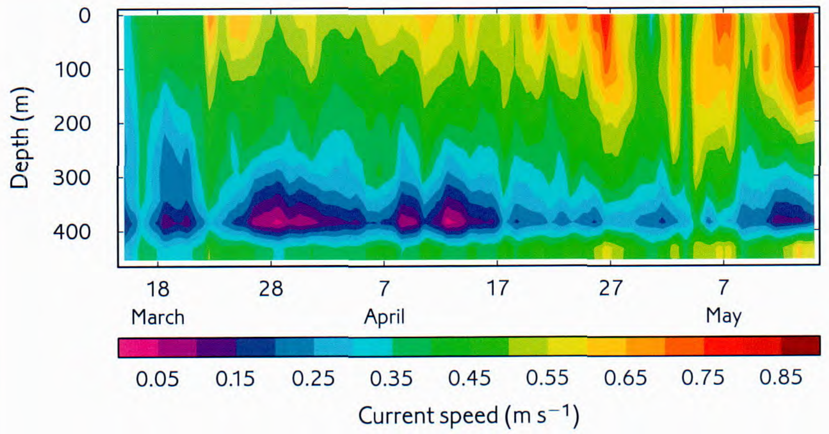


Figure 62. A time-series from 15 March to 15 May of daily averaged current profile to 300 m depth at 60° N, 5° W on the shelf slope.

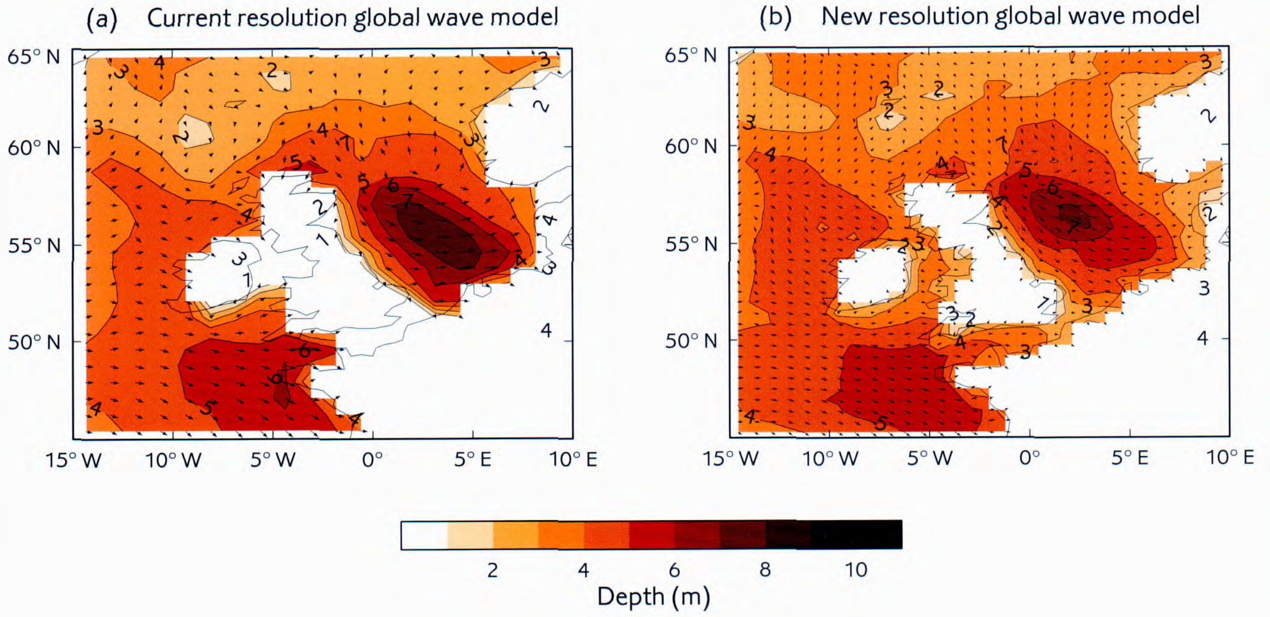
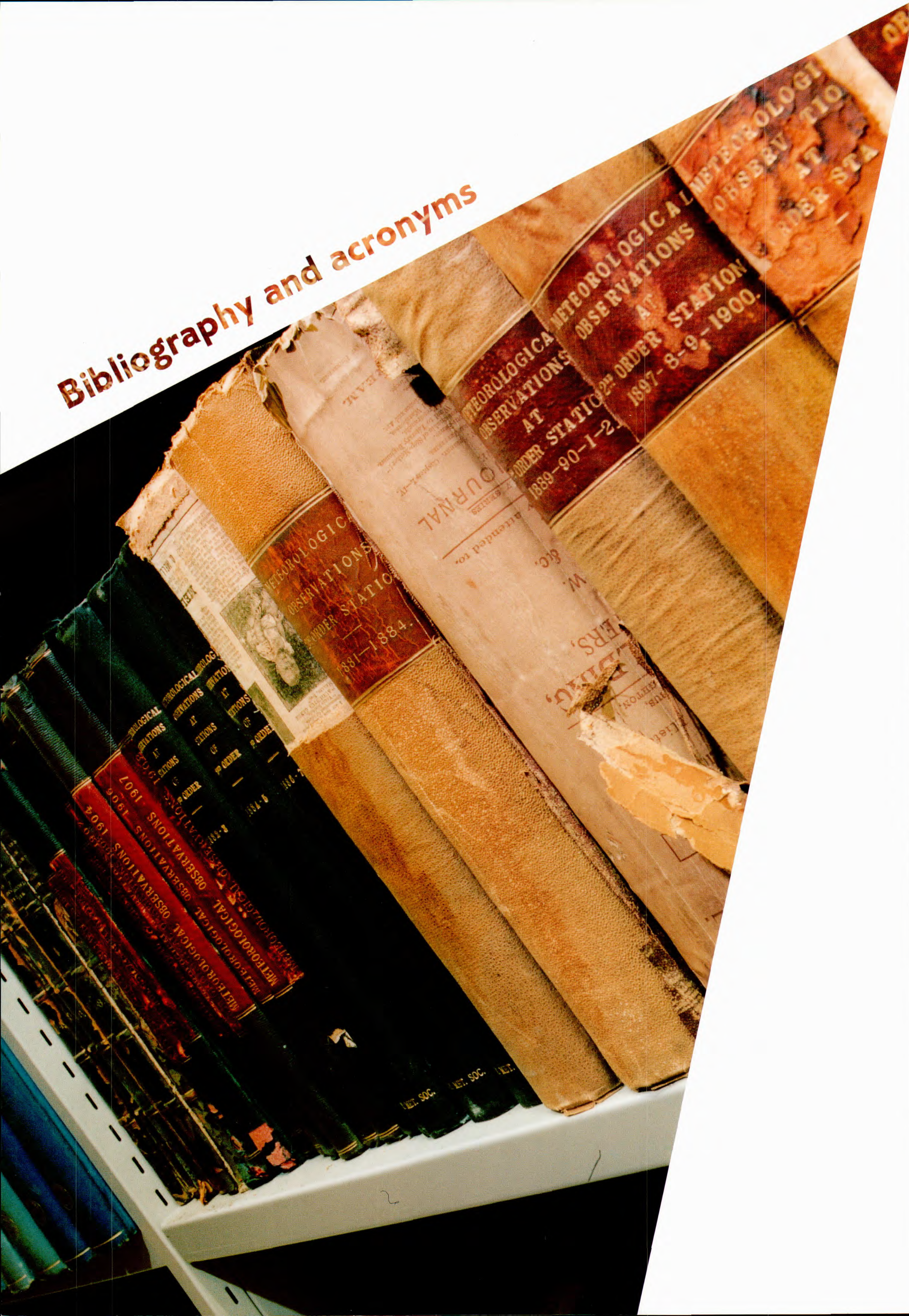


Figure 63. Comparison of significant wave height and direction at 1200 UTC for the new global wave model (b) with the present model (a) over the North Sea, for a storm on 25 October 1998.

Bibliography and acronyms



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ADMS	Atmospheric Dispersion Modelling System
AMDAR	Aircraft Meteorological Data and Reporting
AMSL	Above mean sea level
AMSU	Advanced Microwave Sounding Unit
ARIES	Airborne Research Interferometer Evaluation System
ASDAR	Aircraft-to-satellite Data Relay
ATD	Arrival time difference
ATOVS	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High-resolution Radiometer
BAS	British Antarctic Survey
BT	British Telecom
CAT	Clear air turbulence
CBD	Chemical and Biological Defence
CLIVAR	World Climate Programme climate variability and predictability
CMETS	Computerised Meteorological System
DARTH	Development of advanced radar technology for application to hydrometeorology
DETR	Department of the Environment, Transport and the Regions
ECMWF	European Centre for Medium-range Weather Forecasts
ENSO	El Niño Southern Oscillation
ERS	European Remote-sensing Satellite
ETWIRL	European Turbulent Wake Incident Reporting Log
EUCOS	EUMETNET Composite Observing System
EUMETNET	European Meteorological Network
EUMETSAT	European organisation for the exploitation of meteorological satellites
EURICE	European research on aircraft ice certification
FASTEX	Fronts and Atlantic Storm Track Experiment
FOAM	Forecasting Ocean–Atmosphere Model
FSSSI	Forecasting for Specific Sites: System Implementation
GALES	Global Agroclimate, Land-use, Elevation and Soils
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-surface Flood forecasting
GCM	General circulation model
GIS	Geographical Information System
GPCS	General Purpose Computing Service (formerly COSMOS)
GPS	Global Positioning System
GTS	Global Telecommunication System
IASI	Infrared Atmospheric Sounding Interferometer
INDOEX	Indian Ocean Experiment
IP	Internet protocol
JCMM	Joint Centre for Mesoscale Meteorology
LES	Large eddy simulation
MCS	Mesoscale convective system
MetDB	Meteorological Database
METOP	Meteorological Operations satellite
METWAN	Met. Office Wide Area Network
MHS	Microwave Humidity Sounder
MIDAS	Met. Office Integrated Data Archive System
MOSES	Met. Office Surface Exchange Scheme
MORECS	Met. Office Rainfall and Evaporation Calculation System
MORSN	Met. Office Remote Sites Network
MPIM	Max Planck Institute for Meteorology (Germany)
MRF	Met. Research Flight
MRU	Met. Research Unit
NAME	Nuclear Accident Model
NAO	North Atlantic Oscillation
NHC	National Hurricane Center (US)
NOAA	National Oceanic and Atmospheric Administration (US)
NMC	National Meteorological Centre
NWP	Numerical weather prediction
POP	Probability of precipitation
RDBMS	Relational database management system
RMDCN	Regional Meteorological Data Communication Network
RO	Radio occultation
SAMOS	Semi-automatic Meteorological Observing System
SAF	Satellite Applications Facility
SAFIRE	Scanning Airborne Filter Radiometer
SAR	Synthetic aperture radar
SMS	Short Message Service
SST	Sea-surface temperature
STOCHEM	A Lagrangian chemistry model
3DVAR	Three-dimensional variational analysis
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
TROPICS	Transmission and reception of observational and product information by computer-based switching
UM	Unified Model
UNFCCC	United Nations Framework Convention on Climate Change
UTC	Universal Time Co-ordinated
VAD	Velocity–Azimuth Display
VIRTEM	Validation of IASI Radiative Transfer: Experiments and Modelling
WAFC	World Area Forecast Centre
WIN	Weather Information Network
WMO	World Meteorological Organization

Contact information

If you would like more information on any particular topic, please contact the appropriate person directly, as shown below. Alternatively, you may ring our switchboard and ask the operator for help. For a copy of the *Annual Report and Accounts 1998/99*, call +44 (0)1344 856277, or write to Met. Office Communications at the address below.

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