



# Scientific and Technical Review 2000/1







An Executive Agency of the Ministry  
of Defence

**Scientific and Technical Review 2000/1**

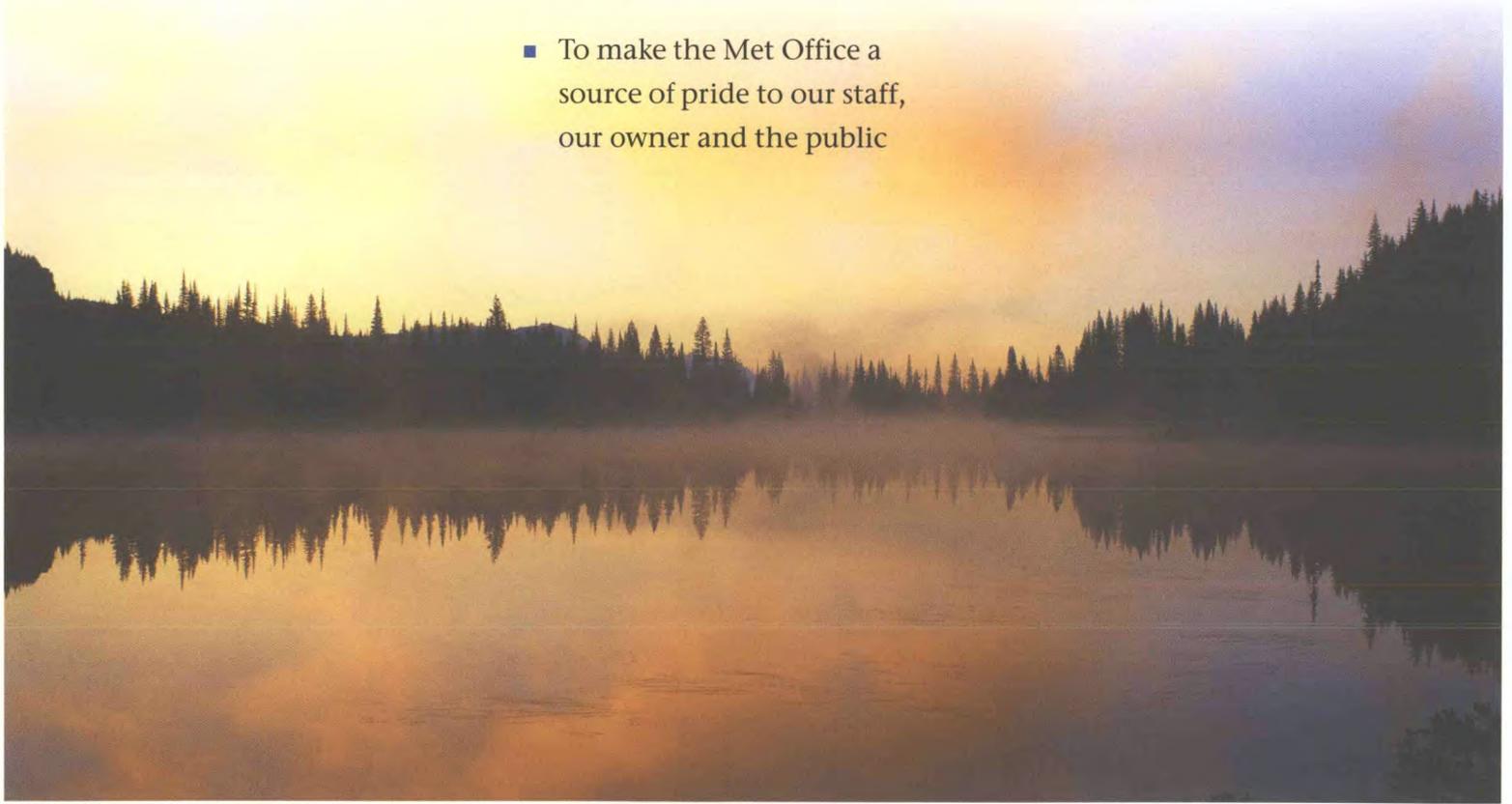
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## **Vision**

Through unrivalled know-how, to enable individuals, society and enterprises everywhere to make the most of the weather and the natural environment.

## **Goals**

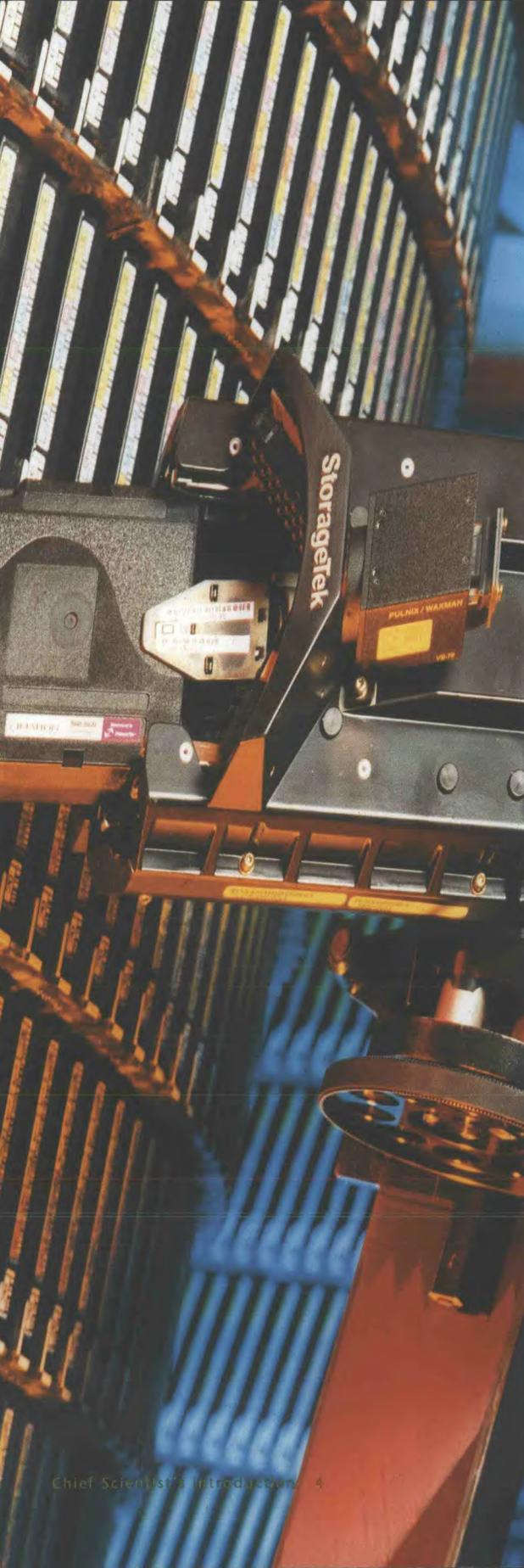
- To lead the world in advice on the weather and the natural environment
- To make the Met Office a source of pride to our staff, our owner and the public



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## Chief Scientist's introduction

This year has seen many notable achievements, with improved accuracy weather forecasts and higher quality climate predictions resulting from developments in research carried out at the Met Office.

It has also been the year in which we entered into a partnership with the Natural Environment Research Council (NERC) atmospheric science community to use a new research aircraft — the BAe 146 based at Woodford, Manchester. This follows the last missions by our old workhorse, the Meteorological Research Flight's C-130 'Snoopy' before its return to the Defence Evaluation and Research Agency (now QinetiQ). We now look forward to designing and fitting out equipment on the new aircraft, due in service next year.

The accuracy of numerical weather forecasts, as judged from the NWP index and other measures, has noticeably improved this year in large measure because of the introduction of three-dimensional variational data assimilation. This improvement results, in part, from the better use of satellite data with the new system.

What does the future hold? We are making considerable progress on the project to introduce a new numerical model formulation, called New Dynamics, which also uses a new physics package based on that in the HadAM4 climate model. Forecasts from the new model are still in development but are already competitive with those of the current operational model in winter and consistently better in summer. There is also evidence that the new model provides improved predictions of extreme events such as the French and Danish storms of 1999.

In addition we are developing a new data assimilation system — four-dimensional variational analysis — which incorporates the ability to use data at the time at which the observation is taken. This, combined with the ever-increasing volume of satellite data, means that there is the prospect of even better utilisation of data than in the current system.

The Hadley Centre's prediction and research programme continues to be influential in the climate change arena both in IPCC reports and in government negotiations. This year saw the introduction of a fully coupled carbon cycle model, such that ecosystems in the model respond to the changing climate. This has led to the first model predictions of the feedback between the biosphere and climate. Because of reduced rainfall and increased temperatures, the Amazon rainforest dies back in the model simulations and thereby releases more carbon dioxide into the atmosphere. This positive feedback, and one associated with soil carbon, means that we can expect several more degrees of global warming than previously imagined prior to the introduction of the interactive carbon cycle.

Our operational ocean forecasting system, FOAM, means that we can deliver many products to the Royal Navy and others concerning the sea-state and ocean circulation. Research has continued this year to develop this system, including attention to the shelf seas component.

As always, the activities of the Met Office are underpinned by the advances in observations and information technology, both areas of which are developing rapidly.

Separate from the central major research initiatives, there is a broad range of activity involved in generating new products and services to customers. These continue to advance not only in traditionally meteorological forecasting areas, but also increasingly in wider natural environment services. These new services often involve partner organisations with specialised skills in aspects of the new products or service.

Our research and development has always involved partnerships and international collaboration. This will continue with our NERC-funded colleagues in universities and research centres, other meteorological services and government departments and agencies. Notable links established this year included opening the Joint Centre for Hydro-Meteorological Research with the Centre for Ecology and Hydrology to ensure co-ordinated research in this area.



## Chief Executive's overview

The past year will probably be best remembered for two notable events — floods throughout the UK and the outbreak of foot-and-mouth disease. In both these events the Met Office has played a crucial role, illustrating the breadth of our activities and the positive impact we can have on individuals, society at large and business. The heavy rainfall leading to flooding was well forecast by the Met Office, giving timely warning to the general public and the emergency services, while our work on the airborne dispersion of the foot-and-mouth virus has helped keep the spread under control as well as informing critical policy decisions.

More generally, our success over the past year is confirmed by the fact that we met five out of six key performance targets, with forecast accuracy, service quality and overall efficiency significantly above target. At the same time, we exceeded our profit target while investing over £13.6 million to ensure our future success. The one disappointing area was the financial contribution from our commercial services, but even here we made real progress, with revenue and profit both up on last year.

I am also delighted to report that our internationally renowned work on climate change won further recognition through a formal review which concluded that our Hadley Centre was '...the number one climate modelling centre worldwide'. At the same time, our new mobile internet service, *Time and Place*, won the 'Most Innovative Service (Mobile Internet)' award in the Mobile News Awards 2001. These illustrate our determination and success in maintaining our pre-eminent position in the science of meteorology and in the services we offer our customers. But we must do even better if we are to succeed in the future.

Relocation to new custom-built accommodation is vital to our future business success. In November we chose Exeter as the location for our new 'home'. We expect to have selected and agreed terms with a final development partner by September 2001. Alongside our work on relocation, we have been reviewing, refining and documenting our main processes prior to moving, so that we can achieve the ISO 9001 standard as well as ensuring we are lean and fit before we move.



Peter Ewins, Chief Executive

We are already responding to new opportunities within the natural environment — collaboration with the Centre for Ecology and Hydrology to open the Joint Centre for Hydro-Meteorological Research (JCHMR) in Wallingford is just one example. Indeed collaboration is high on our agenda, as reflected in our new agreements with Météo-France and Met Éireann, our French and Irish counterparts.

We will also continue to develop our underpinning science, investing in new infrastructure — especially greatly increased supercomputing capability — research and development and innovation. Our continuing success in numerical weather prediction (NWP), our automation programme and our new ‘Weather and Health’ service all serve to illustrate our commitment to science and technology and to our success in exploiting them.

Successful business development is heavily dependent on well-qualified and highly motivated staff. This year we have invested strongly in ‘people training’ and have been successfully re-accredited as an *Investor in People*. Our commitment to training, both performance and management, remains as strong as ever, and our training programme will continue while we make the move to Exeter.

The weather business is changing. We must anticipate that change and keep at least one step ahead. We now have a clear vision to help provide a focus, and new accommodation will be vital to our success. I know that the next two years will be very challenging — keeping to our plans for growth while moving nearly 200 miles will not be easy. But, at the same time, those two years will be exciting, and a major step in the development of the Met Office.

My directors and I are committed to delivering a wider range of quality services to our customers. We are also committed to making our move to Exeter as painless as possible for our staff, with no more than minimal impact on our customers. We are well on the way to creating the Met Office of the future and to adding another chapter to our proud history.



## Observations

### Observing networks planning

We completed an examination of the user requirements for UK upper-air data. An integrated network of radiosondes and wind profilers, complemented by the Aircraft Meteorological Data and Reporting system (AMDAR) aircraft data, was selected to best meet those requirements.

The project to improve collaboration with the Environment Agency for the rain-gauge network in England and Wales continued. We established the joint user requirement, proposed a network design, and drafted policies for data exchange and network management.

### AMDAR

The Aircraft Meteorological Data and Reporting system consists of a software package installed within avionics on commercial aircraft to capture data from existing on-board sensors. Data are provided on ascent and descent, and in level flight. Co-operation has continued with British Airways with installation on the Boeing 747 fleet to make a total of 128 aircraft capable of providing data.

The Met Office has continued to manage the European Meteorological Network (EUMETNET) AMDAR project. In June, ten of the E-AMDAR participants agreed to contribute towards procurement of AMDAR data from European airlines, allowing operational European AMDAR activities to begin.

The Met Office Technical Co-ordinator has continued to monitor network performance using statistics from the Quality Evaluation Centre hosted by the Royal Netherlands Meteorological Institute (KNMI). The Met Office was selected to provide the operational data acquisition system and software has been specified and written by a contractor.

Some initial work has been done on a network optimisation scheme, as uncontrolled transmission by all AMDAR aircraft flying at any one time would result in redundant data and unnecessary costs. The amount of data received from British Airways aircraft has deliberately been reduced from 26% of the total to 21%, with emphasis on data-sparse routes. Overall, data coverage has increased, with the average number of profiles per day increasing from 420 to 730 this year.

## Upper-air network

Following the successful implementation of AMDAR and a clear demonstration of the utility of the Vaisala automatic radiosonde balloon-launching system (autosonde), we reviewed the manned radiosonde network.

After the installation and commissioning of a wind profiler at Wattisham, the Hemsby manned site was closed at the end of the year. We identified Albermarle Barracks near Newcastle, Castor Bay, Northern Ireland, and Herstmonceux, Sussex, as sites which would receive autosondes next year. These installations will be followed by the closure of the manned radiosonde operations at Boulmer, Hillsborough and Herstmonceux respectively. We began a competitive tender exercise to purchase a tropospheric profiler to replace the Stornoway radiosonde, scheduled for 2002.

## Surface observing automation

An enhanced version of the Windows NT-based Semi-automatic Meteorological Observing System (SAMOS) was produced. This is capable of being used on sites where manual observations had previously been thought essential. We deployed two systems for trial at Hemsby and Manston in May 2000. A second phase of the trial was begun at Hemsby and Aviemore in November, with additional snow-depth and icing sensors. More significantly, these systems employ a software-based algorithm which uses all available data to produce a better representation of current conditions than that from the present weather sensors alone. Towards the end of the year, the system was further developed to produce observations every ten minutes. The successful completion of the trial at the end of March 2001 will allow the automation of surface observing on a number of sites, particularly the dual function radiosonde sites. They can thus be completely demanned with a corresponding efficiency gain.

In parallel with the development of the enhanced automatic SAMOS, the Windows NT interactive version was accepted by operators and rolled out to approximately half of the 108 sites which already have DOS-based systems.

To meet network requirements, we also deployed seven PC-based CCTV systems for trials. The operational systems were generally located at sites which were more demanding than those occupied by publicly available web cams. Some camera images

are available on the Met Office web site. The images are used in the provision of forecasting services.

## **Marine networks**

We signed a Memorandum of Understanding with the Marine Institute (Republic of Ireland), the Department of the Marine and Natural Resources and Met Éireann to develop an Irish open-ocean buoy network. Two Met Office pattern buoys have been provided, one on loan and one funded by the Marine Institute, to initiate the network.

We have made a very significant input to the specification of a second-generation buoy, with inbuilt flexibility to allow operation of a range of sensors to achieve enhanced oceanographic measurement capability. The Marine Institute is funding the contract to develop the new system and the Met Office will have full use of the new design to upgrade the existing UK buoy network. This is particularly important in view of the demands of operational oceanography and also the Global Ocean Observing System (GOOS).

We also devised a simple method for deploying Argo floats from a moving vessel so that they can be distributed by ordinary merchant vessels rather than research ships. The method is likely to be adopted worldwide, having worked perfectly when deploying the first five UK Argo floats in the Irminger Sea in January.

## **Marine voluntary networks**

The Met Office has continued to inspect and train voluntary observers on merchant ships recruited to the Voluntary Observing Fleet, with the UK contributing a little under seven per cent of the global observing fleet. Six Port Met. Officers carried out approximately 1,100 visits to ships during the year. They have made strenuous efforts to persuade observers to use the Turbowin PC-based observation handling software provided by KNMI, and have converted about 10 per cent of the fleet so far. The system has the advantage that it is less error prone than manual methods and relieves the Met Office of the costs associated with handling and keeping data entered into manuscript logbooks.

The UK Automated Shipboard Aerological Programme (ASAP) installed on the container ship *CanMar Pride*, has launched radiosondes at 12-hourly intervals throughout all its North Atlantic passages during the year. Two hundred

successful ascents were made during the year with an average terminal sounding height of 30 hPa.

## **Meteorology in space**

This was a disappointing year for meteorology in space. Both the EUMETSAT Polar System (METOP) and Meteosat Second Generation (MSG) programmes suffered significant delays due to difficulties in developing the ground facilities to support future satellites. First launches are now estimated as December 2005 for METOP 1 and January 2002 for MSG 1. Nevertheless the current operational systems are in good condition; no serious gap in coverage is anticipated. The Met Office continues to promote policies and strategies in EUMETSAT aimed at reducing the cost of data from space in the longer term.

The role of EUMETSAT has been broadened under an amended convention which came into force on 19 November. The Met Office has considered a new proposal for EUMETSAT to provide oceanographic data on an operational basis. It is working with the oceanographic community to identify sources of funding for a UK contribution to an optional programme in this field (the Jason 2 altimeter mission), in which EUMETSAT would participate, with 25% funding alongside the Centre Nationale d'Études Spatiales, NASA and NOAA.

## **Maximising the benefits of new satellite data**

High-spectral-resolution sounding instruments have the potential to significantly improve the vertical measurement of temperature and humidity in the atmosphere. They are expected to have a large positive impact on numerical weather prediction modelling.

We fitted our Airborne Research Interferometer Evaluation System (ARIES) interferometer to the Met Office C-130 research aircraft, to study the radiative transfer in the thermal infrared region of the atmosphere in preparation for the Infrared Atmospheric Sounding Interferometer (IASI). IASI is a future high-resolution sounder to be launched on the METOP satellite in December 2005.

High-resolution infrared spectra measured by ARIES are being used to develop a cloud detection algorithm to be used on IASI data. Figure 1 shows the preliminary results of this scheme. In the cloud detection scheme, each measured radiance spectrum is projected on to a set of empirical orthogonal functions that represent cloud-free

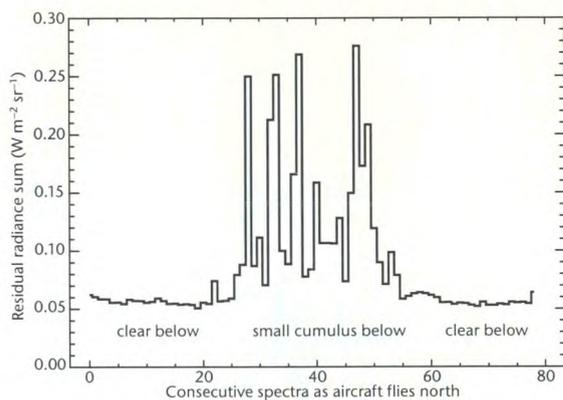


Figure 1. The sum of the residual radiance in the window region 3.4 to 4.2 microns from an aircraft run above clear skies and shallow cumulus clouds.

atmospheres. The eigenvectors generated in this way are then used to reconstruct the measured radiance and the difference between the reconstructed radiance spectra and the original measurement is evaluated. In the presence of clouds, the magnitude of this residual is increased as the radiance spectra contain structures that are not representative of clear skies.

ARIES data are also being used to validate a new radiative transfer model that can simulate cloudy spectra at the high spectral resolution of IASI so that the full use of the data from the satellite can be realised. The model, developed at the Physics Department of the University of Bologna, is used to synthesise IASI spectra to allow realistic systems and software testing before the instrument's launch. IASI data will eventually be assimilated over boundary-layer clouds in the storm tracks; this is particularly important to numerical modelling of synoptic development.

Figure 2 shows three spectra. One is an ARIES measurement above stratus cloud over the North Sea. The other two spectra are from the model, using atmospheric and cloud microphysical data measured by the C-130 aircraft. One of the modelled simulations only accounts for absorption within the cloud, the other includes scattering. The results show that the model must take full account of scattering in this water droplet cloud to achieve close agreement with the measured data.

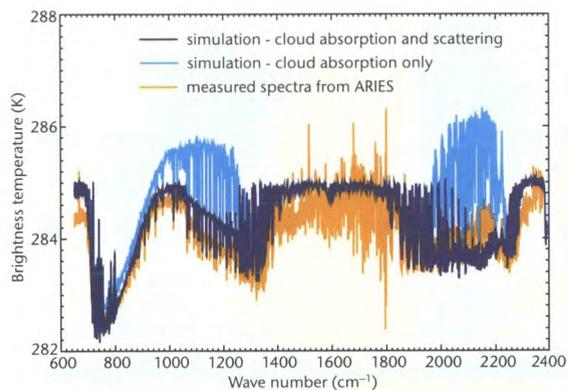


Figure 2. Brightness temperature (K) as a function of wave number for ARIES measurements over cloud (orange line) and two model simulations absorption only (light blue) and absorption and scattering (dark blue).

## Enhanced lightning location facility

Our Arrival Time Difference (ATD) sferics lightning location system has been undergoing a major upgrade. The culmination of years of software and hardware development came in March 2000 when a new computer took control over the network of seven ATD outstations. Previously limited to fixing the location of just 400 lightning flashes per hour, the capability has increased to a rate of 10,000 per hour.

The large control station facility has been replaced by a desktop HP machine that requires minimal user intervention. The increased automation provided by this new control station has also led to improved reliability, much appreciated by users of the ATD information.

The maximum rate achieved to date has been greater than 4,500 fixes in one hour. The long-range capability of the ATD system has become even more apparent with this

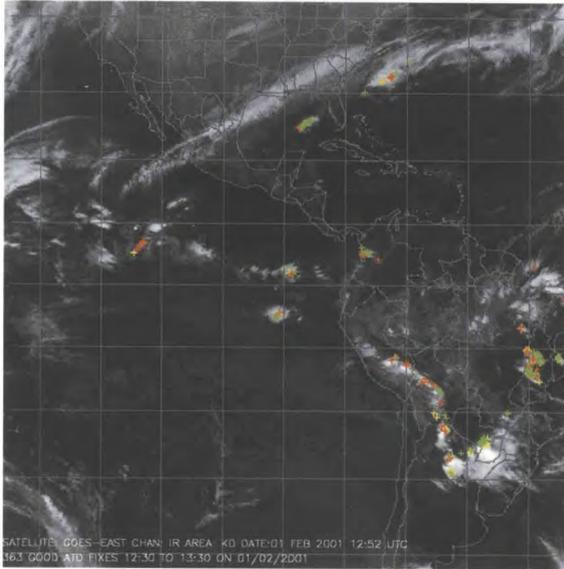


Figure 3. Infrared satellite image taken by the GOES-E satellite at 1252 UTC on 1 February 2001. The yellow crosses represent lightning strikes detected between 1230 and 1250, the red crosses represent strikes between 1250 to 1310, while the green crosses are for 1310 to 1330. The position of the lightning strikes match well with the satellite cloud images even at these long ranges.

higher fixing rate, as lightning is now detected regularly as far away as South America. At these long distances, the accuracy of the lightning fix can be judged by comparison with satellite images, Fig. 3.

During 2001 the ATD system will be pushed gradually to much higher fixing rates. Further development is required to enhance system operation with an improved propagation model that will increase fixing accuracy and the addition of extra features such as the determination of the flash strength, polarity, type (cloud to ground strike, or cloud to cloud) and multiplicity (number of strokes per flash).

### Analysing and assessing climate observations

The system for producing gridded values of meteorological elements, based on data from station values, has been updated. Gridding permits the production of consistent and high-quality contours and areal averages, minimising the impact of changes to the station network and its spatial inhomogeneities. The previous system, built entirely in-house and which has served us well for four years, has been migrated to the ARCVIEW geographical information system. During the migration several innovations have been introduced, although the process remains fundamentally the same.

Changes include:

- the introduction of detailed land-use data to better quantify the impact of water and urban areas upon local climates;
- the calculation of areal statistics over a wider range of areas, including post codes;
- the ability to choose from three different local surface fitting methods;
- the ability for non-technical users to construct regression equations, used in generating a global surface fit to the input station data.

Figures 4 and 5 are contoured maps of October 2000 rainfall and the percentage of average created using this new system.

In addition, the new system gives improved means for assessing how representative of the local area current and proposed observing sites are. These are:



Figure 4. October 2000 rainfall (mm) based on a UK network of 500 rain gauges.



Figure 5. October 2000 rainfall expressed as a percentage of the 1961-90 normal.



Figure 6. Tulloch Bridge, 30 km north-east of Fort William, and the areas for which it is representative.

- 3D visualisation of topography giving enhanced perspectives on station locations;
- the analysis of altitude to identify frost hollows;
- versatile combined analysis of topography and land-use data to identify areas which are representative of the local area (Fig. 6);
- contoured maps showing the mean spacing between stations.

Climate observations are used to provide customers with information on the likely weather characteristics of a site, for instance for design of buildings.

## Weather radar

The replacement of the weather radar data processing systems, combined with upgrading of the communications links with the radar sites, has enabled the coverage and resolution of the data to be improved. The diagrams below show the extent of radar coverage prior to 2000 (Fig. 7) and that following the roll-out of the new processors in 2001 (Fig. 8). The main benefits are the large area of contiguous 2 km resolution coverage over England and Wales, and 1 km coverage of several conurbations.

Figure 9 shows a time-series of the r.m.s fractional difference between hourly rain-gauge accumulations and integrations of radar data in collocated pixels. The radar data have been subject to quality control and correction within the Nimrod system. All gauges within the area of radar coverage in the UK have been included in the statistics. A threshold of 1 mm has been adopted to ensure that the statistics are representative of hydrologically significant rainfall. The monthly average statistics show considerable variability month-to-month, but a 12-month running mean of the monthly values shows a fairly steady downward trend over the last five years. This improving trend in radar data quality is ascribed to developments in the radar hardware and in the correction procedures in Nimrod.

## Business process improvement

We began a project to review the documentation used by observers at synoptic and climatological stations — both professional and co-operating — to update and improve observing procedures. We will significantly reduce the number of documents currently

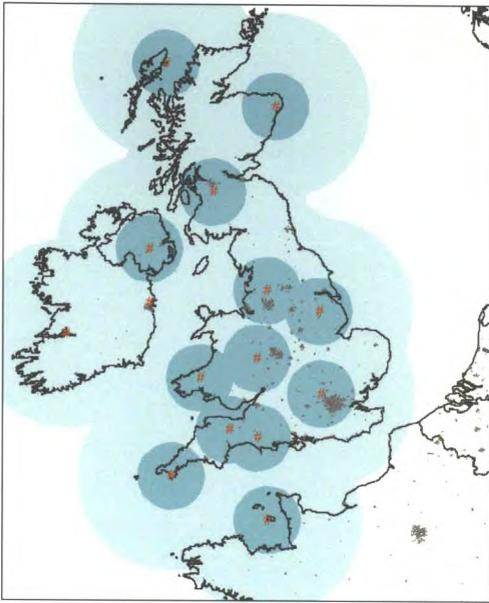


Figure 7. Radar network coverage as at 1 January 2000.

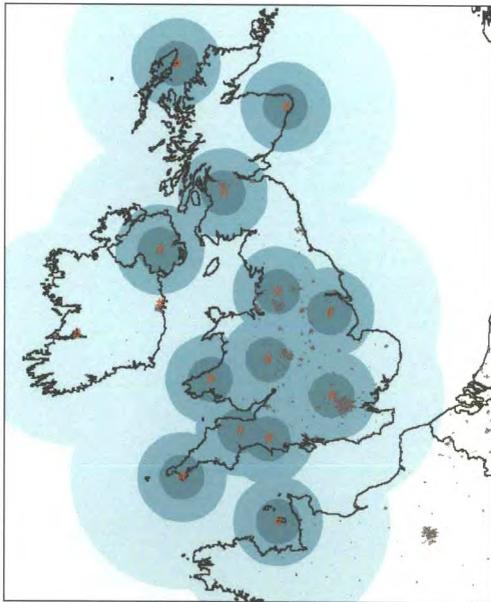


Figure 8. Projected radar network coverage as at June 2001.

in use, through consolidation of material. The new versions will address the issues associated with automated systems and be made available via the internet for ease of access and amendment.

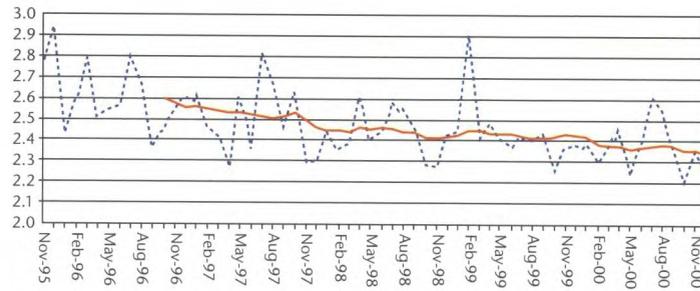


Figure 9. Time series of monthly r.m.s differences between hourly gauge and radar rainfall (blue dashed line). The red line is a running 12-month mean formed from the monthly values.



## Information Technology

### Managed massive data storage

The Met Office has an unusually demanding requirement to store and retrieve a vast and ever increasing amount of data — observational data from automatic sources, raw satellite and radar products, climatological archives, high-resolution numerical model data and output from the Climate Prediction Programme.

Hardware and a data management system, known as MASS (managed archive storage system), are being introduced to facilitate management of these data. In 2000, an initial investment was made in a FileTek StorHouse mass data storage system, and over subsequent months, work has continued on its development. When in full use in 2001, it will be one of the world's most sophisticated, leading-edge data storage systems, acting as the Met Office's strategic data repository. It will provide users with a standard access method to all of the Met Office data resources. MASS will allow significantly improved responsiveness and staff productivity compared with the current storage facilities. Business users and researchers will have access to powerful interactive facilities enabling access to any stored data. Currently under consideration are optional software products which enable the system to act as a transparent extension to an Oracle database, and also provide a relational file system, along Unix lines, for ad hoc data storage.

The MASS system has 16 high-performance StorageTek 9840 drives residing in a single StorageTek PowderHorn Automated Tape Library (ATL), and the system is scalable through the addition of further ATLs, see Fig. 10. MASS will cater for the projected Met Office data archiving requirement for at least the next five years — an anticipated data growth up to almost a petabyte (i.e.  $10^{15}$  bytes).

### Keeping IT working

The Met Office central computing service comprises mainframes, supercomputers, Unix servers, the MASS system and various associated systems. All these need continuous, 24-hour monitoring by IT Operations staff. During the year further development of the automated systems management software (Tivoli) has continued. The main purpose of the Tivoli software is to monitor and recover systems, thus providing a more consistent service, while reducing the overall costs of supporting these services. Where necessary, IT Operations staff are notified of the events and actions taken. Tivoli allows staff to



Figure 10. Inside MASS tape library, a grabber transfers one of over 2,500 cartridges.

concentrate on aspects of managing the system where their expertise will provide maximum benefit.

Based on a review of fault reporting, change management and change control procedures, a new system is being introduced to improve the handling of incidents reported to the Helpdesk and to provide fully integrated incident and change management. This system enables all changes to operational systems supported by the IT Operations Centre to be controlled and monitored by the change controller. The introduction of the system will improve the quality of service to customers, both internal and external.

### **Versatile and reduced-cost database management**

As well as new hardware to store data, the year 2000 saw the completion of the project to replace the corporate database management system (DBMS).

DBMS software provides the infrastructure and tools to facilitate the construction and management of collections of data. Typically, it hides from users the details of the computer operating system while providing access to the data through a standardised interface; it also incorporates facilities to control access.

For many years, we have used versions of the commercial product CA-IDMS from Computer Associates as our strategic DBMS. A project was initiated in 1998 to move to a DBMS that would be more versatile for our applications and cheaper to run. A world-leading product in the field, Oracle, was chosen following a comparative study.

Since the completion of the transfer, Oracle has easily shown its worth, as developers and users have gradually begun to exploit its greater range of facilities. As an example, the routine, twice-daily ingestion of data now typically takes half the time to complete, allowing data quality control processes and user applications using the data to begin half an hour earlier.

We maintain two complementary databases to store meteorological observations: the MetDB and MIDAS. The transfer of the main climatological database, MIDAS, to Oracle has also allowed the simplification of a great deal of user software, although some applications have needed radical rewriting to take full advantage of the versatility of Oracle.

The MetDB is the central system, storing incoming data in real time. It handles all types of observations, except for radar and satellite imagery, using the very efficient WMO standard code-system known as BUFR to store them. The database system was written

entirely in-house and is optimised for rapid and efficient retrieval of global fields of essentially simultaneous observations. It also incorporates facilities to allow storage of values interpolated from the operational NWP model analyses alongside the original observations.

The operational MetDB runs on the IBM mainframe (known as the GPCS), and is accessible from other computer platforms via an industry-standard tool called RPC. The implementation of this tool has proven less reliable than expected, and this is being resolved in close co-operation with IBM in the USA. Over the past year, components of the MetDB have been replaced to improve the throughput of observations and to cope with expected dramatic increases in the volume of incoming data.

MIDAS is the strategic climatological archive which provides flexible access to the data, including the ability to search over or extract from long time-periods. It also provides an excellent platform for the sophisticated quality control processes operated by the Observations Branch.

Other work has included the extension of the scope of MIDAS to include comprehensive information describing the observational data themselves — the 'Metadata' project — and to permit storage and automatic maintenance of a range of long-term statistics.

## **Reduced costs of computing**

The Met Office has run a central computing service since 1965 when it installed the English Electric KDF9. Since then the service has been provided by successive IBM (or equivalent) mainframes using IBM operating systems.

The requirements for this service have been reviewed taking account of the changing business needs of the Met Office, the increasing use of Unix workstations to present front-end graphics, supercomputers to perform numerical modelling and the MASS system to handle data storage.

Over the next few years the IBM S/390 system will be replaced by a large Unix server or cluster. This will provide the central general purpose computing facility at reduced cost.

This change of technology for the central computing service will result in easier interchange of information between systems, reduced development and support costs,

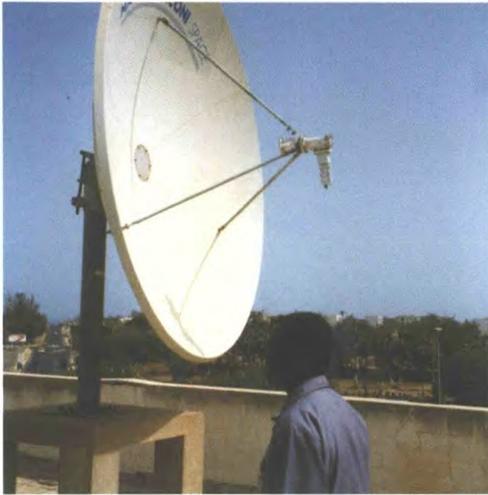


Figure 11. SADIS installation in Dakar, Senegal.

and allow the Met Office to be ready to exploit the computing technologies which are appearing on the horizon.

### Improved telecommunications

The Regional Meteorological Data Communications Network (RMDCN), a frame relay data exchange service spanning the majority of national meteorological centres in Europe, is now delivering the expected benefits. The improvements gained from RMDCN have been mirrored by migration to Internet Protocol (IP) in other message switching systems. A large number of customers of our main message switching system now exchange data using this protocol. Transfers of large data objects from a dedicated facility (NETLINK) to other national meteorological centres and to commercial customers have also been migrated to IP, greatly improving standardisation of delivery methods across various networks.

The Met Office has sites throughout the UK where forecasters have access to weather data and products from the central systems at Bracknell through a Wide Area Network (WAN) service. Existing 'legacy' X25-based networks are being migrated to a commercially managed IP network, the Met Office Remote Sites Network (MORSN). Once completed, considerable cost savings will be made as telecommunications are concentrated on one backbone service. The move of network hardware components to Met Office managed sites will increase reliability and reduce periods of downtime.

Collection of observations from automatic weather stations (AWS), auxiliary observers and marine systems has been updated to provide fully resilient facilities using file transfer methods over the standard WAN. A further stage of development will facilitate the collection of weather information from UK automated observing sites at ten-minute intervals into a central handling system.

### Satellite dissemination of information

As part of its commitment to civil aviation, the Met Office sends weather information from Bracknell to around 120 users via a system for satellite dissemination of aviation products (SADIS), see Fig. 11. Working with Astrium, this has been developed to improve reliability, increase data flow and to provide capacity for up to 21 users to use SADIS to transmit data to Bracknell.

As well as improving our own communications, the Met Office has implemented a satellite broadcast of regional data for Asia as part of our contribution to WMO. This was developed to use facilities shared with SADIS and enables national meteorological services within Asia to use existing equipment to access observational and forecast data in a simple and cost-effective manner. This is particularly useful in a region in which there are areas with limited telecommunications infrastructure.

## **Visualising the weather**

The Nimbus computer system is a PC-based system which supports both the storage and display of meteorological data (synoptic observations, satellite and radar imagery) and the creation and dissemination of forecast products to our customers.

Each Nimbus system is based on a local area network with attached PC file servers (running Microsoft Windows NT Server 4.0) and user PCs (running Microsoft Windows NT Workstation 4.0). Nimbus uses standard, off-the-shelf software wherever possible. Nimbus is replacing two older systems used at Met Office production units located on RAF and Army Air Corps airfields, civil centres located in the major cities, and other sites such as the BBC Weather Centre. In addition, Nimbus has been installed at a number of Royal Navy shore establishments.

Nimbus has now been installed at 54 locations. All Met Office forecasting sites in the UK now use Nimbus, and the system will be deployed to overseas sites in Germany and Cyprus, by Summer 2001.

## **Desktop facilities**

The desktop systems used by scientists now have standardised user management and access, a common standardised file system layout, and an improved central software distribution, management and ownership process. The standard configuration adopted will minimise the impact of, and facilitate faster recovery from, internal disk failures. An industry standard user interface has been introduced. Taken together, these changes have reduced the amount of effort needed to support the systems and, by introducing standards, they have reduced the time needed by users when transferring applications between teams. As part of the change, all 500 scientific desktop users now use the latest version of the HP Unix operating system.

Standardisation of the PC desktop has helped the us to achieve significant savings and performance benefits. In a recent independent benchmarking exercise, the desktop service was in the upper quartile in terms of performance and the cost was less than the average cost for comparable global public and private sector organisations.

The challenging objective of the Windows Application Server (WAS) project was to provide access to a standardised desktop for all users from any desktop platforms used in the Met Office. We had a specific need to allow Unix-based users access to corporate PC-based systems. Although aimed at the Unix community, this system has also been used to provide access to the climate database, our Human Resources database and the finance system from remote sites.



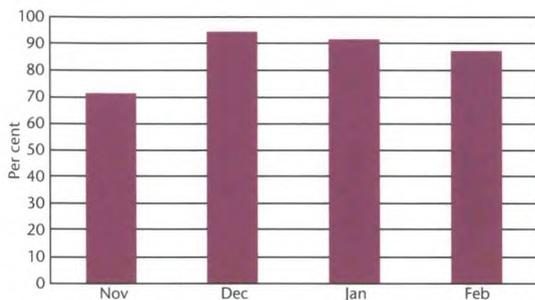


Figure 13. Hit rate for frost prediction, achieved by the OpenRoad automated first guess November 2000-February 2001, using the MORST model, corrected using the Kalman filter/MOS scheme.

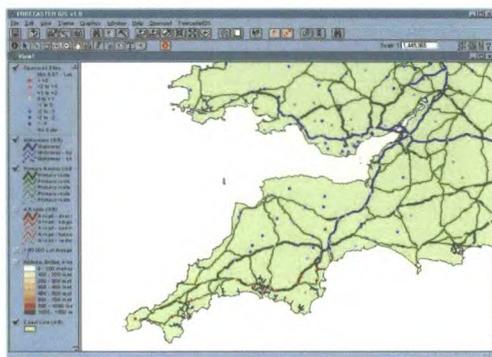


Figure 14. OpenRoad GIS display for the south-west UK, showing motorways and other primary routes and OpenRoad sites. Blue sites indicate that the previous night's minimum road surface temperature was below 0°C.

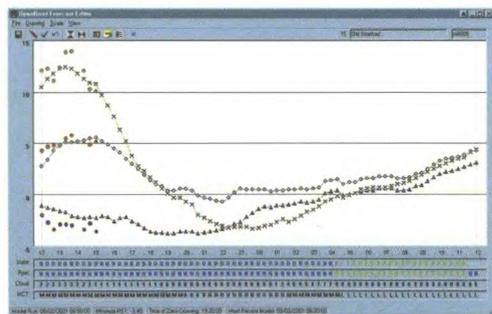


Figure 15. Forecast curves of air temperature (red), road surface temperature (green) and dew-point temperature (blue) and forecast values of road condition, precipitation, cloud cover and main cloud type for an individual OpenRoad site plotted against observations of the three temperature variables.

## OpenRoad 2000

A comprehensive upgrade of the OpenRoad production system was implemented in Autumn 2000 following a major development carried out over a short time to meet the timescale imposed by the regional office mergers.

The upgrade was developed in conjunction with Vaisala TMI who now carry out all sensor data collection and forecast dissemination. The data flow for the new system is shown in Fig. 12. Hourly sensor data are collected by Vaisala and fed into the Met Office central site-specific forecast database (FSSSI). From there they are fed into the new Met Office Road Surface Temperature (MORST) model along with atmospheric forcing data from the Site-specific Forecast model (SSFM) for each of some 500 OpenRoad forecast sites spread across the UK. The resulting first-guess road surface forecasts are adjusted by Kalman filter for sites with reliable observations before transmission to Nimbus systems at regional Met Offices.

MORST is a surface heat-balance model developed using similar physics to that incorporated in the Unified Model. It replaces the old locally run Road Surface Temperature (RST) model originally developed in the late 1970s. Automated results from the SSFM/MORST combination are substantially better than those from the old system with performance close to meeting the key service targets for OpenRoad without manual modification (Fig. 13).

In monitoring the situation for the sites in their region, the forecasters can view sensor data for the whole country using the Geographic Information System (GIS). The data can be displayed in a variety of formats against a range of map backgrounds from national to highly localised using 1:50,000 OS Landranger maps.

In checking the forecast graphs for the sites in their region, the forecaster can plot the nine forecast variables against available observations. If required, the graphs can be amended by the forecaster using a range of on-screen editing tools which can also maintain a level of consistency between forecast variables (Figs 14 and 15).

## Site-specific forecast services

Substantial progress was made in operational introduction of semi-automated site-specific forecast services. A preliminary version of a 5,000 global cities product was generated from the global model early in the year and a new service to the electricity

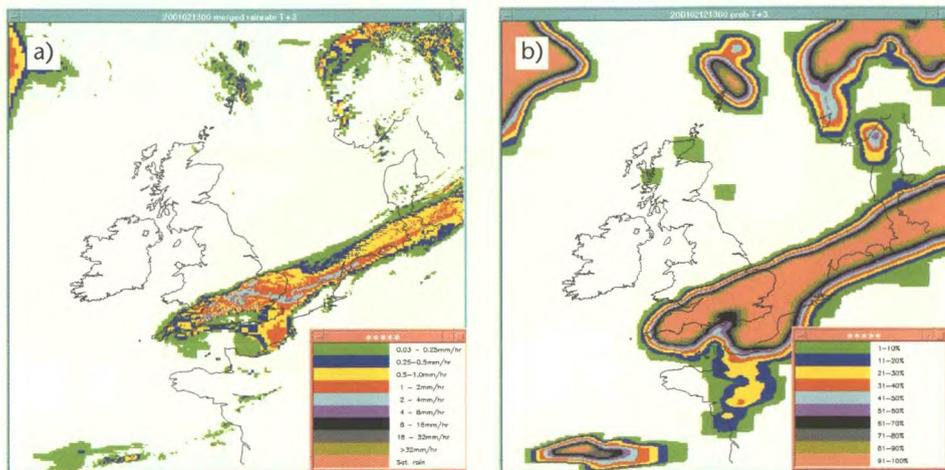


Figure 16. (a) Nimrod three-hour precipitation forecast from 13 UTC on 12 February 2001. (b) Equivalent three-hour probability of precipitation forecast used as input to the Time and Place service.

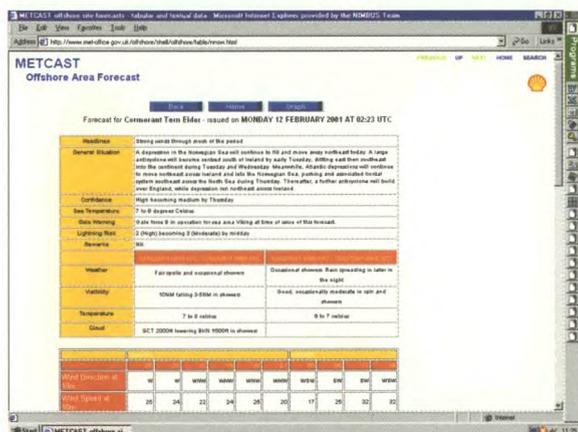


Figure 17. Part of the Met Office web site for Shell, showing a forecast for part of the North Sea issued on 12 February 2001.

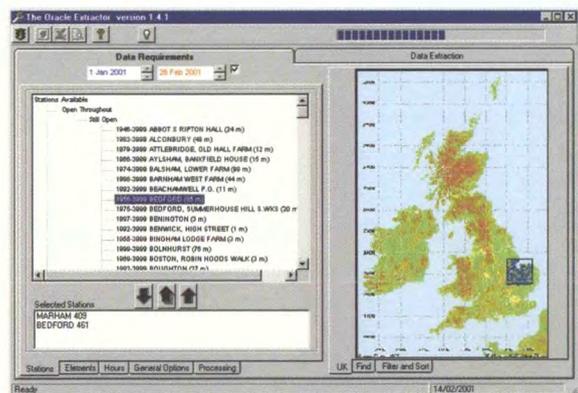


Figure 18. User Interface for the Extractor, showing site selection from the menu of available climate stations.

generation industry (NETA) was implemented. Medium-range atmospheric and wave data were added to the FSSSI database from the ECMWF ensemble, enabling new probability products to be generated, which are now being assessed by the offshore industry. The speed of FSSSI services was enhanced by re-engineering the datafeed to the site-specific forecast model, and by upgrading the database hardware. Good progress

was also made in developing an automated text generation procedure based on FSSSI data.

### Time and Place forecasts

Development of the *Time and Place* forecast provided a major new opportunity for delivering the high-resolution nowcasts generated in Nimrod. It provides very short-range forecasts for any UK location nominated by the user. Forecasts are hourly updated around half past the hour. A simple text message is provided containing temperature, wind, cloud, visibility and the risk of precipitation. The latter is derived from the Nimrod forecast, assuming that errors are due to uncertainty in the advection vector. An example of the relation between the deterministic and risk forecasts is given in Fig. 16.

### Marine forecast services

Work was undertaken to generate new data files and graphics from the Aberdeen Met Office's current Offshore Production System (OPS), and to allow their transmission via FTP to Bracknell. Here they form components of new web sites dedicated to specific offshore customers, including Shell, Total Fina Elf and Marathon (Fig. 17).

A new Marine Production System (MPS) has been developed to replace the OPS. As well as generating improved versions of the products currently available, it will produce a wide range of new products. It is better integrated with the available Nimbus framework, allowing increased automation. Development of the MPS is at an advanced stage, with user testing planned at Aberdeen in mid-March.

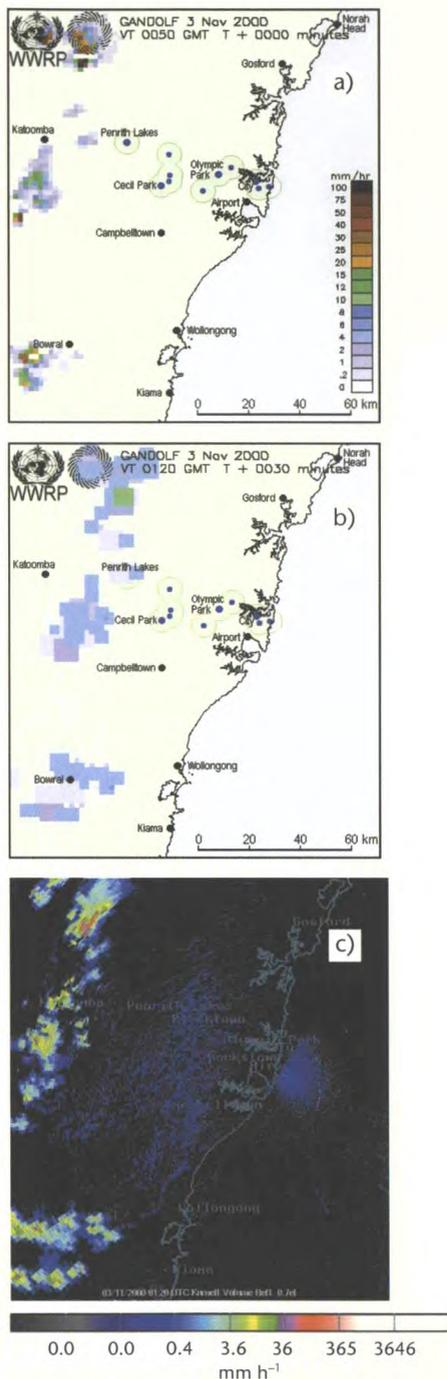


Figure 19. (a) GANDOLF rain analysis for 0050 UTC on 3 November 2000, and (b) T+30 minute GANDOLF rain-rate forecast (c) validating reflectivity image from the Australian Bureau of Meteorology's Kurnell radar.

## Climate data services

The Extractor is a PC application developed to allow Met Office staff easy interactive access to our climatological database (MIDAS). Climate Unit staff, forecasters in Bracknell, London, Belfast and Glasgow as well as staff in the Press Office and ADAS Wolverhampton are currently using the system. The application was developed using Visual Basic and MS Access, and connects to MIDAS using ODBC through the Oracle client (Fig. 18).

## Supercomputer production

Development of the capability to run the operational NWP suite on the second T3E supercomputer was completed and implemented, dramatically reducing the number of missed forecast runs. A large number of upgrades to the operational suites were implemented, including introduction of the UK waters wave model and the Atlantic Ocean model. A major review of downstream product generation was undertaken which identified the need for a more consistent and flexible fields database. Work started on developing an implementation plan based on the existing Horace infrastructure and incorporating the change to the New Dynamics NWP model.

## Hydrology

Effort was focused on applications of our existing state-of-the-art Nimrod and GANDOLF nowcasting systems during the year. Both took part in the WMO World Weather Research Programme (WWRP) Forecast Demonstration Project in Sydney from September to November 2000. An example of GANDOLF performance is shown in Fig. 19 for an occasion when thunderstorms developed over the Blue Mountains to the west of Sydney. Later in the day some of these produced heavy rain, large hail (>7 cm) and three tornadoes in Sydney. The area of New South Wales shown, corresponds to the Severe Weather Warning Area used by the Australian Bureau of Meteorology during the Olympic Games.

Several other opportunities for overseas use of Nimrod were discussed and work started on delivery of the precipitation component of Nimrod to Gematronik for installation at the Polish met. service.

Further enhancements to Nimrod quality were developed, including the use of radars from the near continent, improved quality control of the advection process to prevent occasional reverse vectors resulting from aliasing, an improved rain-gauge adjustment

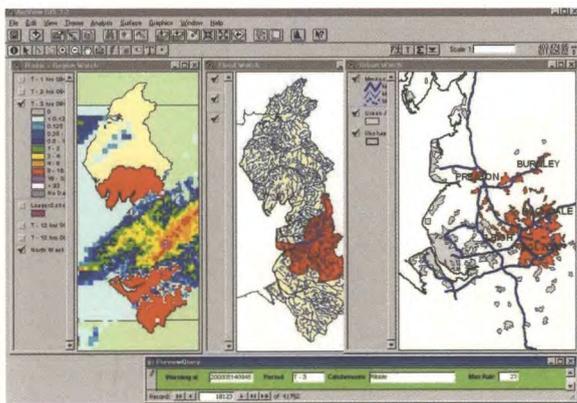


Figure 20. Example of rainfall display from the ENVIROMET system.

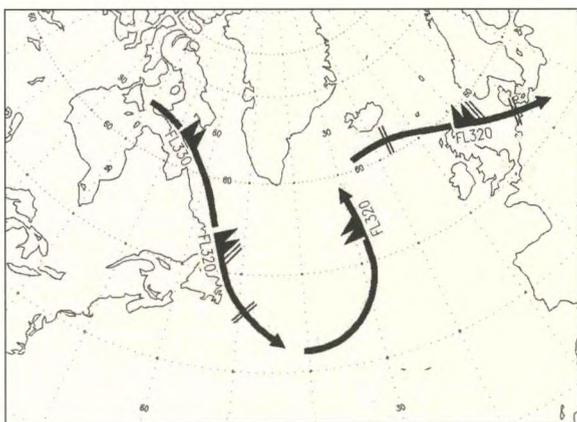


Figure 21. Jet streams derived from model forecast fields using the generic Horace feature identification facility.

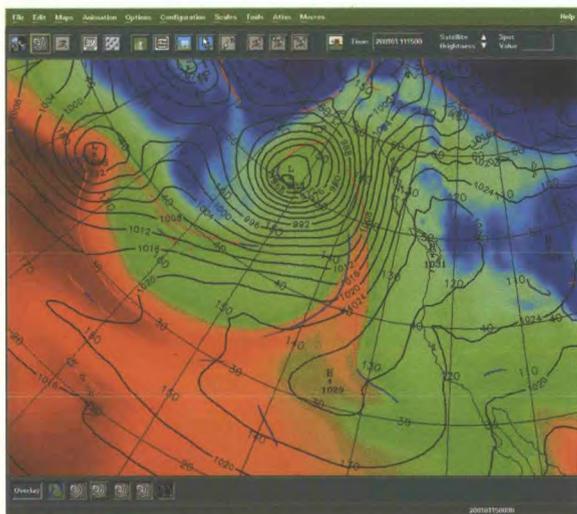


Figure 22. Fronts derived from model forecast fields using the generic Horace feature identification facility.

scheme, and a promising analysis of the scope for predicting the occurrence of severe weather associated with thunderstorms.

The formal opening of the Joint Centre for Hydro-Meteorology at Wallingford focused attention on our links with hydrological research, and several joint funding bids with CEH (Wallingford) were progressed. An existing collaboration in developing a soil moisture model reached the implementation stage following successful trials.

Presentation of the results is particularly important for very short-range forecasts and warnings. We introduced a new automated catchment warnings service based on Nimrod for both internal and external use, making use of user-defined rainfall accumulation thresholds for each catchment. We developed a new display system for hydrological data, to meet Environment Agency requirements, under the name ENVIROMET, using a commercial Geographical Information System (Fig. 20).

## Meteosat Second Generation (MSG)

The announcement of a delay of more than a year in the launch of the first Meteosat Second Generation satellite was a great disappointment. However, good progress was made in developing the new processing system. It is now being developed with a dual capability and is planned for implementation in 2001. Initially the advantages of the new system will be in efficiency and flexibility. New processing modules to make use of the additional capabilities of MSG will be integrated following post-launch trials.

## Forecaster support systems

### Nimbus

Nimbus replaced ODS as the main support system for outstation forecasters during late 1999 and 2000. Following its initial release in Autumn 1999 to meet Year 2000 requirements, we identified many areas for improvement. A major upgrade was carried out in July 2000 to address these concerns. The visualisation component of this upgrade, together with some additional enhancements, were issued as NAMIS Release 3. Considerable interest has been expressed in Nimbus overseas, and a version was installed in Latvia early in the year. More extensive

modifications are in preparation for another version destined for Belgocontrol, the Belgian air traffic control agency.

### ***Horace***

Two upgrades of Horace were released in April and November. We developed and delivered a version of Horace for onboard use by the Royal Navy as part of their EDS system. A version of Horace was also delivered to the Australian Bureau of Meteorology.

While numerical model data are always provided in grid-point formats, forecasters still have to convert these data to a more object-style presentation. For instance, jet streams and frontal systems are represented on forecast products using standard symbols. Now that the tools exist to provide users with the ability to 'draw' these features on-screen, it is a natural step to provide them with automatically created representations that can be modified. The intention is that the forecaster accepts a large proportion of the features and only modifies those that are significantly different from current thinking.

To provide 'automated jet streams', the forecaster now has the ability to run a tool on Horace that scans specified NWP data fields for scalar and gradient information that exceeds user-defined thresholds. Once filtered, the data are further refined to meet presentation quality criteria (e.g. depending on the scale of the chart, jets must exceed a certain physical length to avoid clutter). The final set of points can then be displayed in standard format and modified further using the same tools as for user-drawn features (Fig. 21). A similar technique applied to thermal fields provides the location of fronts (Fig. 22).

## **Support for warning services**

### ***Dispersion of toxic material***

We completed implementation of a new system supporting the nuclear accident service during the year after extensive testing with the DETR. The new system is based on a dedicated Unix platform connected to a user interface in the Met Office's environment monitoring and response centre. This guarantees a quick response within the demanding timescales required.



Figure 23. Example of automated first-guess early warning message based on the ECMWF ensemble.

### First-guess early warnings

We are using ensemble data from ECMWF to provide the forecaster with improved notice of possible synoptic development that might require warnings (of gales, heavy rain or snow events) to be issued to the public. A scanning system has been developed that searches the ensemble set for forecasts that meet warning criteria and raises a message to alert the forecaster. This message is similar to the one already used for operational issue, allowing the forecaster to amend the suggested probabilities associated with the event and add supplementary text, before being passed electronically to the main dissemination system.

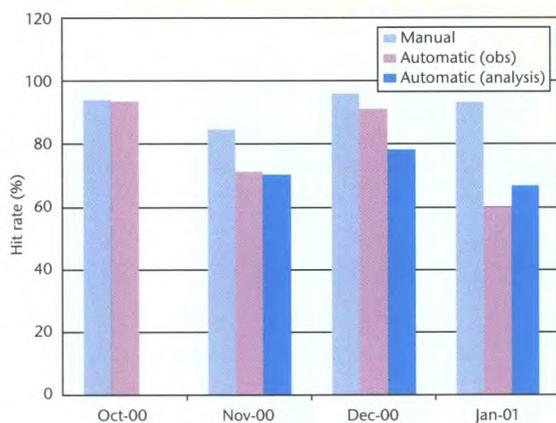


Figure 24. Gale warning verification: comparison of hit rates obtained using subjective verification (manual), and using objective verification against observations only or against analyses.

Currently, we issue warnings if the likely occurrence of the event exceeds 60% anywhere in the UK. Initial investigations suggest that, at lead times of 72 hours or more, it is unlikely that 60% of the ensemble members will produce such a strong signal of an event occurring. Nevertheless introduction of the first-guess messages has been associated with a significant increase in the lead time at which warnings are first issued (Fig. 23).

### Gale warning verification

Reliable measures of forecast accuracy are increasingly important, both for automated and manual forecasts. During the past year, substantial effort has been put into developing objective techniques for verifying warnings. While the basis for verification must be the actual weather reports, account must be taken of likely variations between reporting stations, especially over the sea. This is done implicitly by the reviewer, in a subjective verification scheme, but must be built in explicitly, in an automated scheme.

Figure 24 shows preliminary results from a new automated gale warning verification scheme. The automated scheme using observations relies entirely on the representativity of the coastal reporting stations and a small number of marine reports. The scheme using analyses should mimic the subjective scheme more closely, but depends on other forecast information to judge how winds will vary across the shipping areas. As can be seen, these preliminary results vary considerably. Our aim is to tune the automatic scheme using analyses to reproduce the subjective scheme as closely as possible.

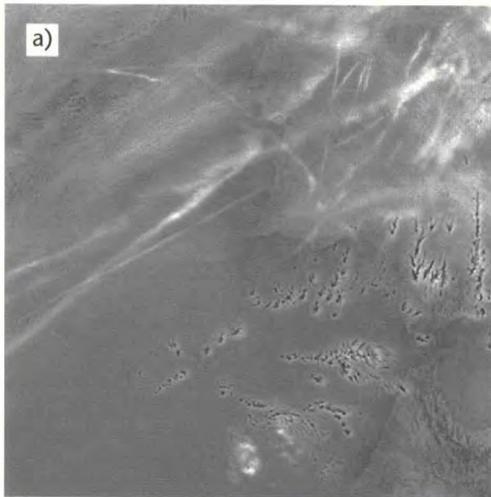


Figure 25. (a) NOAA 14 polar-orbiting satellite image of Spain and Portugal in the late afternoon of 4 October 2000 showing the brightness temperature difference between channels 4 and 5 of the AVHRR instrument. (b) Contrails diagnosed by the detection algorithm.

## Defence

### *Trafficability*

A new soil moisture model developed under contract at CEH (Wallingford) was integrated into the Computerised Met. System (CMetS) battlefield forecasting facility. Indices of the ability of the ground to support vehicles have been calculated and new forms of presentation added to the system. The soil moisture model has undergone extensive validation this year, both directly using in situ measurements, and also indirectly using river flow.

### *Ballistics*

Assessment of the meteorological component of the artillery error budget continued with a detailed study of the relative benefits of using balloon soundings, model predictions and a combination of the two, as provided by CMetS.

### *Contrails*

Contrails are ice condensation trails that form behind aircraft under certain meteorological conditions. They are of military interest because their presence can expose covert air operations.

Contrail forecasts covering the North Atlantic flight routes have been calculated from NWP temperature and humidity data for a number of days in the period September to December 2000. The forecasts are being verified against actual contrails in high-resolution satellite imagery using a contrail detection algorithm developed by Deutsches Zentrum für Luft- und Raumfahrt (DLR), see Fig. 25. The presence of aircraft is confirmed using flight data from National Air Traffic Services (NATS).

### *Defence climate database*

A new global climate database has been developed to give our defence customers easy access to a wide range of climatological statistics for hundreds of overseas observing stations. The whole application, containing both data and access routines, is contained on a single CD. This allows the data to be used anywhere there is a PC. Currently the CD only contains land climatologies but it is planned to add upper-air and marine data shortly. The application was developed using Visual Basic and the climatologies developed from data stored in the Met Office's climate database MIDAS.

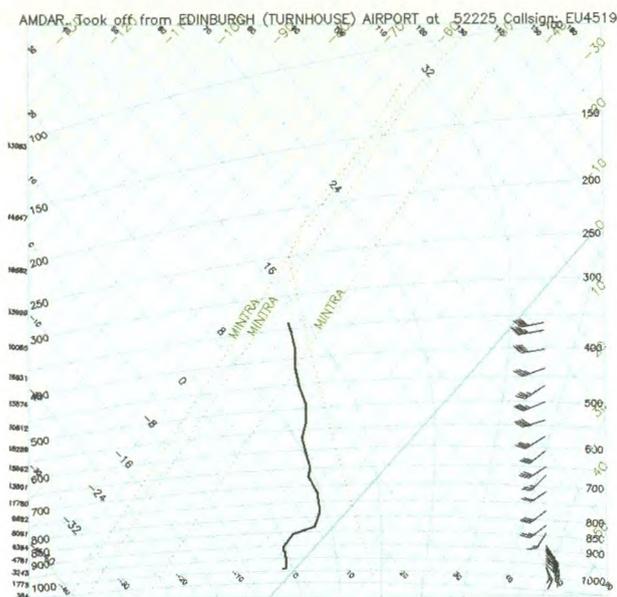


Figure 26. Horace display of the wind and temperature profile observed by an aircraft taking off from Edinburgh during a very cold spell in February 2001.

### **Defence semi-automation**

Good progress was made in developing the capability to generate automated first-guess versions of standard military aerodrome forecasts for subsequent modification by the forecaster. Trials of early prototypes were under way at the end of the year.

### **MOMIDS**

We implemented a trial connection of MOMIDS through MoD networks at Brize Norton, providing substantially improved speed and reliability. Using the same technology, a connection to the Joint Mission Planner was also demonstrated.

### **Civil aviation**

#### **Automated significant weather charts**

Generation of an automated first-guess upper-level WAFS significant weather chart was completed and put on trial during the year, though problems remained with the jet stream component. Work started on the additional elements required for the medium-level chart.

#### **AMDARs**

We are receiving a growing number of automated aircraft reports (AMDARs). As well as providing increased data coverage over the data-sparse oceans they also provide wind and temperature observations at high temporal resolution on ascent from, and descent to, airports. Software is currently under development on Horace to visualise these data in the same format as traditional vertical profiles obtained from radiosondes (Fig. 26).

#### **Nowcasting for aviation**

We have made considerable progress in demonstrating the capability to nowcast for civil aviation. This includes a demonstration of the benefit of using the WAFTAGE nowcasting model with AMDAR data, to predict winds in the Heathrow approach area, and a demonstration of uplinking a nowcast to an aircraft in flight.

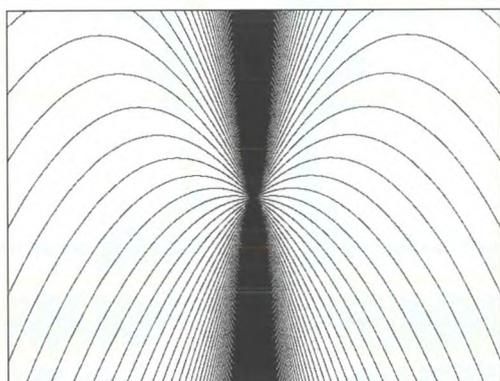


Figure 27. Sound propagation, from a source in the centre of the picture, in the presence of an inversion, computed by the ray model.

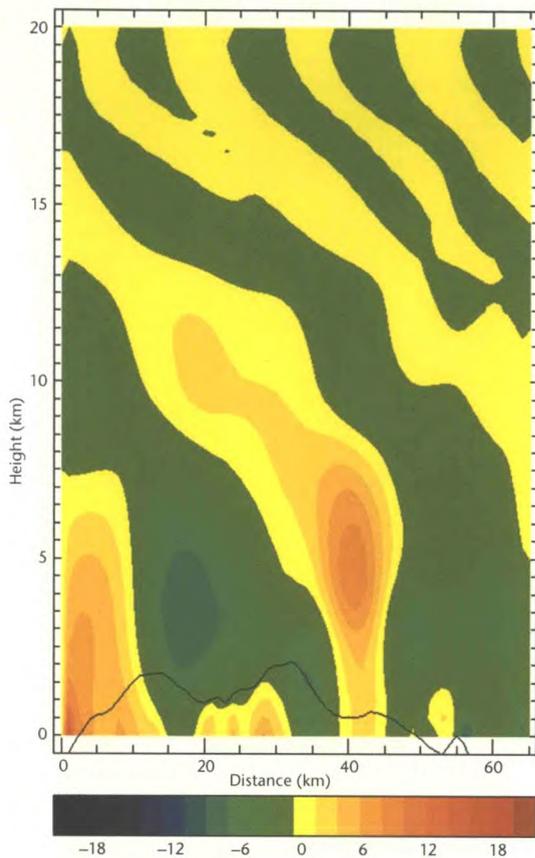


Figure 28. Contours of vertical velocity ( $m s^{-1}$ ) for a vertical cross-section through the Alps near Monte Rosa derived from the equilibrium model. Downraughts are represented by negative values.

### ***Aircraft sound propagation***

The environmental impact of aircraft noise near airports is considerable, so operators have a strong interest in finding ways to minimise disturbance. Sound propagation in the atmosphere is strongly influenced by temperature and wind speed gradients. As a result, the intensity of sound reaching the ground varies with location relative to the aircraft trajectory. We want to quantify the effect of meteorology on noise exposure in the vicinity of aircraft take-off and approach routes.

A rigorous calculation of the acoustic field around an aircraft in an atmosphere with varying wind speeds and temperatures would require a numerical solution of the 3D wave equation. A simpler approach, since the changes in the speed of sound occur gradually, is to use a ray-based model of sound propagation. Calculations have shown that this approximate treatment is valid for a wide range of meteorological conditions (Fig. 27).

### ***Mountain downdraughts***

Increasing air traffic movements over Europe are generating increasing pressure for more airspace capacity and hence for a reduction in the minimum vertical separation between aircraft. There is concern that strong downdraughts generated over mountains could result in a loss of vertical separation.

The problem is being studied using numerical simulations of flow near the Alps obtained from the equilibrium model of Vosper and Mobbs.

Figure 28 shows a simulation for part of the Alps. Upstream conditions, from a station near Munich, are for 0600 UTC 8 November 1999, during the Mesoscale Alpine Programme, when downdraughts were observed. The wind was from the north, blowing from left to right in the diagram. Height is shown relative to the linearisation reference level of 2 km. The greatest vertical velocity amplitudes occur immediately above the mountains. At the heights at which vertical separations are to be reduced (8.5 km to 12.5 km), the maximum downdraught obtained in the entire computational domain was  $9.5 m s^{-1}$ .

EGCC 130007Z 130110 30006KT 5000 – BKN005 BECMG 0104 9999 NSW SCT012  
 BKN050 PROB30 TEMPO 0409 3000 BR SCT003

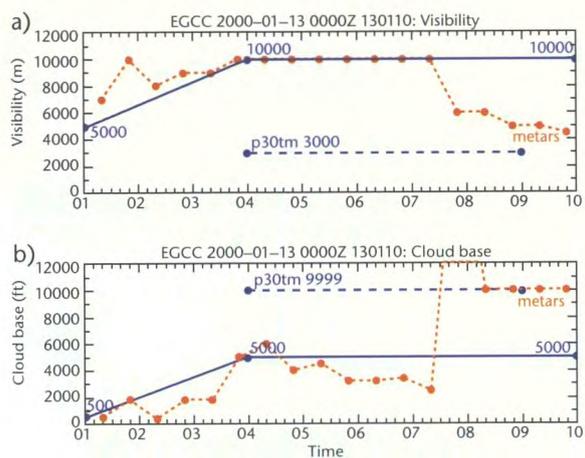


Figure 29. TAF (text at top), its objective interpretation (blue dashed lines for probs), and verifying METARs (red dots) for Manchester Airport, issued 13 January 2000, valid from 0100 to 1000 UTC showing the probabilistic interpretation of the visibility (a) and cloud (b) elements of the TAF as used by the objective verification scheme.

## TAFs

Once a TAF has been issued, the forecaster monitors it against incoming observations to make sure it is still valid. A system has been developed, as part of a European-wide collaborative project, to carry out this task automatically on Horace. If the latest airfield observation is outside the range of the forecast in the TAF, the forecaster is alerted so that an amendment can be issued if required.

Maintaining the quality of TAFs depends on easy availability of verification figures. We now use an objective verification scheme, which measures quality using an objective interpretation of the qualitative components of the message, such as BECMG and TEMPO. An example comparison of a TAF and METARs using this fixed interpretation is shown in Fig. 29. The initial gradual change in forecast from 01 UTC to 04 UTC represents the BECMG groups in the TAF, while the alternative forecast, represented by the dashed lines from 04 UTC to 09 UTC, corresponds to the PROB30 TEMPO groups.





## Numerical Weather Prediction

Numerical Weather Prediction (NWP) underpins nearly all of the forecasting services provided by the Met Office, ranging from predictions of the weather over the UK for a few hours ahead, to forecasts for the whole globe for several days ahead. The numerical models used to produce these forecasts are developed within the Unified Model (UM) system, which provides the computational and scientific framework necessary for both climate prediction and NWP. We maintain and routinely run both a global and a UK ‘mesoscale’ version of the UM in the operational suite of computer programs.

We undertake research and development in all aspects of the NWP system with the aim of improving the accuracy of the operational forecast models. Particular emphasis is placed on improving the forecasting of the occurrence and timing of major changes to the weather; significant weather elements, such as cloud, precipitation and visibility; and extreme surface weather events.

The work aims to:

- reflect improved knowledge and representation of atmospheric behaviour in the formulation of the UM;
- utilise information from new data sources, particularly those from satellite-based instruments;
- improve the techniques for the assimilation and quality control of the observational data;
- validate forecasts and diagnose the source of forecast errors.

## Improvements in operational forecast models

### *Enhancements to global data assimilation and forecasting system*

The operational global model has been upgraded to use the new Met Office Surface Exchange Scheme (MOSES). The previous land-surface scheme had a single-layer soil moisture store and made no allowance for the energy involved in the phase changes of the water within the soil. MOSES addresses both of these deficiencies by introducing four soil layers for both temperature and moisture, and includes a treatment of the energy associated with the phase change of the water. In addition, MOSES also explicitly parametrizes the influence of atmospheric variables, such as temperature,

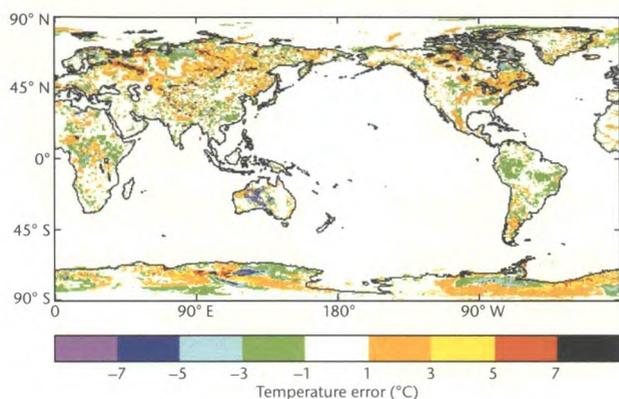


Figure 30. Changes in temperature error (°C) from using MOSES in a six-day forecast from 7 March 1998, with the global model. Positive values represent an improvement.

humidity and radiation, on the stomatal resistance of vegetation. The previous scheme had geographically varying stomatal resistance, but no temporal variation. Figure 30 shows the improvement in screen-level temperature using MOSES, as compared with the previous surface scheme, when verified against the model analysis. It clearly shows there is a beneficial impact from representing the effects of soil freezing at high latitudes during the northern hemisphere winter.

This upgrade to the global model temporarily unified the treatment of the land surface within the operational models, until the UK mesoscale model had a further upgrade to the MOSES 2, ‘tiled’ surface scheme (see later).

We are continually working to improve our global three-dimensional variational (3DVAR) assimilation system. 3DVAR has been our operational data assimilation system since March 1999. Following successful forecast trials, a package of changes was introduced into operations in Spring 2000.

- Use of observed rather than retrieved radiance from infrared and microwave sounding instruments on NOAA 13 (TOVS) and NOAA 15 (ATOVS) satellites — While primarily a technical change, the impact was to allow the radiance information to fully influence the 3DVAR analysis.
- Revised background error covariance model — The background error covariances control how closely the analysis fits the observations and how the information is spread in the gaps between observations. Experiments have shown that the use of longer horizontal correlation scales is beneficial.
- Use of model background at correct observation time — The previous operational system used the model background at the main synoptic hour to compute the observation increments, irrespective of the time at which the observation was made. We have introduced a time interpolation, so that the background is obtained at the observation time by linearly interpolating between model fields.

These changes gave improvements in forecast verification during the trial (Fig. 31) and subsequently in the NWP index following their operational implementation. In addition the ‘Danish Storm’ of 3 December was better predicted, being 7 hPa deeper than the operational forecast which was 25 hPa too shallow compared to reality.

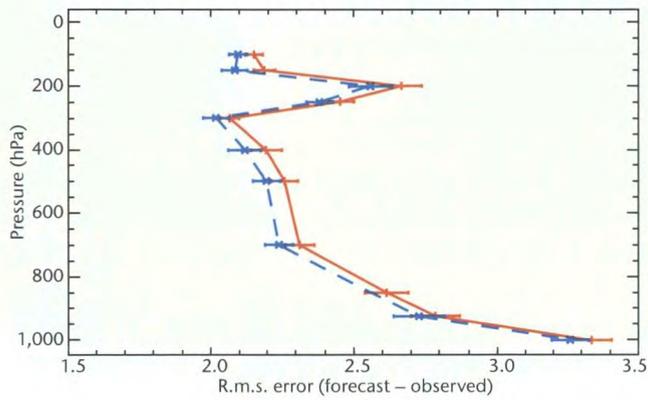


Figure 31. T+72 r.m.s. errors against radiosonde temperatures (as a function of height (pressure)) in the northern hemisphere during a December forecast trial of assimilation upgrades (operational (red solid), assimilation upgrades (blue dashed)). The assimilation upgrades show a reduction in r.m.s. errors throughout the troposphere.

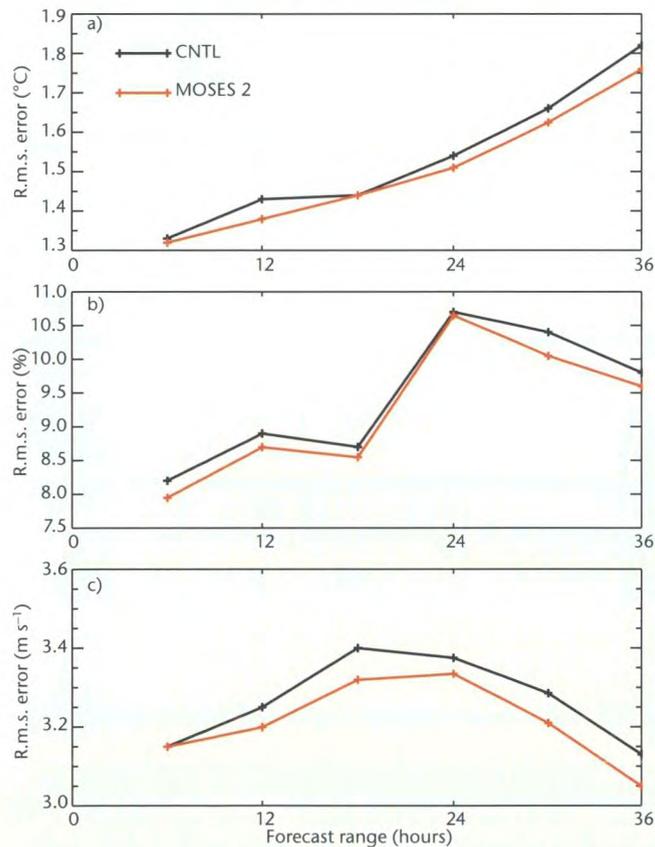


Figure 32. R.m.s. errors for the primary variables from the upgrade trial of MOSES 2 in the UK mesoscale model, (a) temperature, (b) relative humidity and (c) wind speed.

### Enhancements to UK data assimilation and forecasting system

The UK mesoscale model was further upgraded to the next generation of MOSES. MOSES 2 introduces a ‘tiled’ surface approach, whereby the surface exchange is calculated for up to nine different surface types (or tiles) before averaging the results. This enables the fluxes of heat, moisture and in particular momentum, to be modelled in a more physically realistic way. Figure 32 shows the r.m.s. errors for temperature, humidity and wind speed against all synoptic observations in the UK mesoscale model domain. The results are the average for 16 case studies that were used to assess the upgrade. This figure shows that MOSES 2 reduces the errors for all of the primary variables.

Following on from the land-surface physics improvements, the assimilation of near-surface temperature observations has been improved by inclusion of a soil temperature increment equal to the analysed atmospheric temperature increment at the lowest model level. This refinement led to noticeable improvement in screen temperature forecasts during trials (Fig. 33).

The prediction of visibility has been improved. The parametrization has been extended to account for the reduced visibility with snow and rain. The new scheme takes into account separately the large-scale and convective, liquid and frozen precipitation, with scattering coefficients estimated from Marshall-Palmer distributions of droplet size and the precipitation rates. The diagnosis of visibility is also dependent upon relative humidity and aerosol. These relationships have been retuned and, for aerosol, a better diurnal cycle and relaxation to climatological values introduced. In tests the objective verification of the forecasts improved for visibility less than 5 km (Fig. 34).

### Development of the NWP system

#### Applications of satellite data

As reported in recent years, satellite-sounding data now play an important role in NWP. Radiance data from the Advanced TIROS Operational Vertical Sounder (ATOVS) instruments on the NOAA polar-orbiting satellites are assimilated directly into the NWP model to improve the analysis of temperature and humidity. In addition to their use in NWP, products derived from ATOVS data

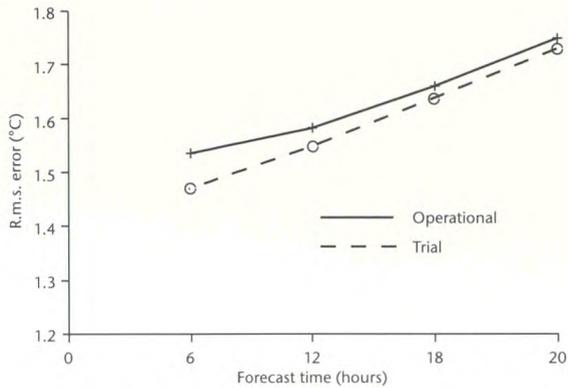


Figure 33. R.m.s. error in screen temperature as a function of forecast time for an enhanced UK mesoscale assimilation system. The enhanced system includes a soil temperature increment. The verification results are against observations and are averaged over 80 forecasts in a three-week period in December 2000 and January 2001.

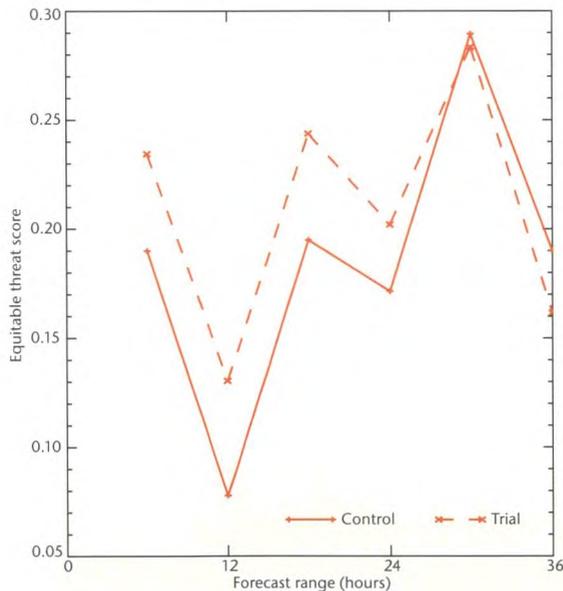


Figure 34. Verification of visibility forecasts of less than 5 km (equitable threat scores) for the improved visibility diagnosis (trial) and previous formulation (control). A larger score indicates more skilful forecasts. The new scheme is more skilful up to 24 hours ahead.

are now made available directly to forecasters. Quality control of ATOVS data is a vital step in the assimilation of radiances into the NWP model. Radiances from the Advanced Microwave Sounding Unit (AMSU) undergo a number of tests to detect observations that are contaminated by clouds and precipitation. These quality control indicators also provide useful imagery, showing areas of significant liquid water cloud and precipitation over regions of the ocean not covered by surface radar. Composite imagery comprising AMSU cloud and precipitation products from NOAA 15 and 16, overlaid on Meteosat infrared imagery, is now provided operationally to forecasters (Fig. 35).

In operational NWP we make use of information on wind from three satellite sources:

- ‘atmospheric motion vectors’ derived by tracking cloud features in consecutive geostationary images, to give estimates of upper-level winds;
- scatterometer data, which provide information on ocean surface wind speed and direction;
- microwave imagery, which provides information on ocean surface wind speed.

When wind (and other) observations are assimilated, the weight they are given depends on the expected errors — both of the observations and of the NWP fields into which they are being assimilated. A good understanding of these error characteristics is therefore very important. To help in this process, we have started to generate and publish an ‘integrated satellite winds monitoring report’ which presents monthly statistics of differences between atmospheric motion vectors and NWP-predicted winds, both for the Met Office global model and for the ECMWF model. By observing the similarities and differences, we expect to make deductions about the sources of those differences. Broadly speaking, features that appear different from the two centres suggest the NWP models are the main source of error, whereas common features point to the satellite winds as the main source of error (see Fig. 36). This monitoring report has been developed in collaboration with ECMWF as part of the work of EUMETSAT’s Satellite Applications Facility (SAF) for NWP, which the Met Office leads.

A scatterometer is a satellite instrument that emits radar pulses towards the sea surface and then measures the intensity of the backscattered radiation. Estimates of the surface wind can then be retrieved from the measured backscatter. However, there is normally an upwind/downwind ambiguity in the retrieved wind direction, which needs to be

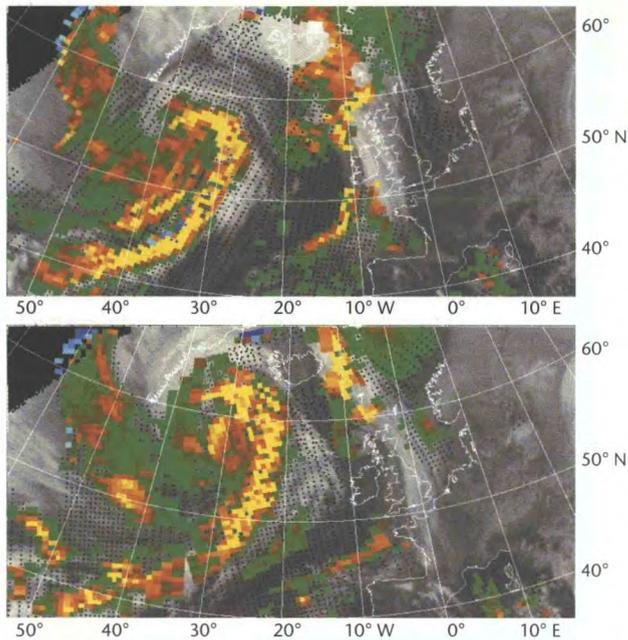


Figure 35. Composite imagery from AMSU on NOAA 15 from 1 February 2001. The upper image was generated from the morning overpasses, the lower from the afternoon overpasses. The eastward progression of an active frontal band can clearly be seen between the two images.

resolved. With the introduction of the 3DVAR data assimilation scheme at the Met Office, we can now perform the ambiguity removal on each wind pair within the assimilation scheme itself. Global impact studies confirm the expected positive impact of using scatterometer data in the model, especially in the tropics and southern hemisphere. In particular, the data are useful in helping to specify developing tropical cyclones. Figure 37(a) shows the analysis of a tropical cyclone with the aid of scatterometer observations from ERS-2. The importance of these data is highlighted when a second analysis is formed without the data (Fig. 37(b)), resulting in a much shallower feature.

### Verification of NWP models

An important component in the continuing development of the NWP models is the process of evaluating model performance. During 2000/1 we have been investigating new techniques for verification. This has involved a move away from performing verification over all weather situations to considering how the model is performing in particular weather situations of interest to users, such as extreme events.

One aspect has been to verify our precipitation forecasts from the UK area model against radar measurements based on the Nimrod quality-controlled radar rainfall analysis product. Current practice is to verify six-hour precipitation

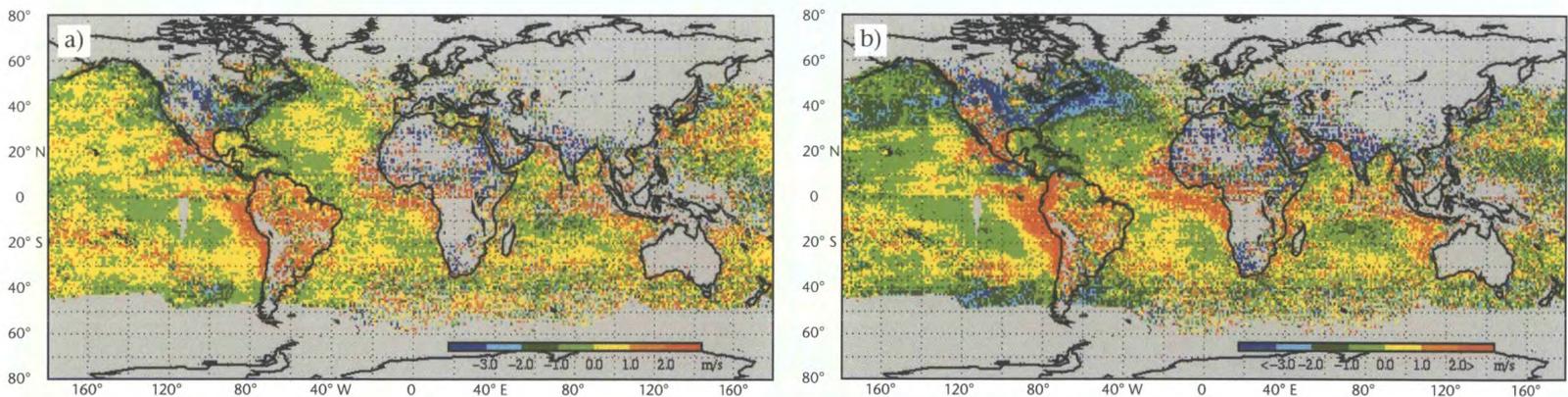


Figure 36. An example of the Integrated Satellite Winds Monitoring Report, which plots the difference between 'atmospheric motion vectors' and NWP field wind speed ( $m s^{-1}$ ) for December 2000. The 'atmospheric motion vectors' apply to the 1,000–700 hPa layer and are derived from infrared satellite images. (a) Based on Met Office NWP data, and (b) similarly based on ECMWF NWP data.

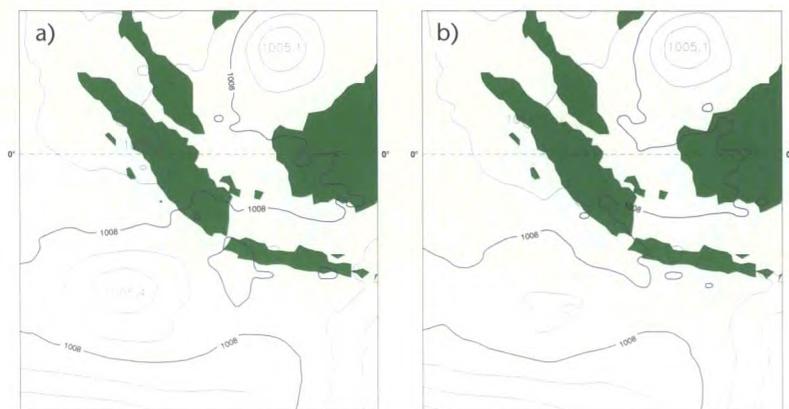


Figure 37. Analysis of a tropical cyclone at 12 UTC, 10 December 1999, (a) with and (b) without ERS-2 scatterometer data.

accumulations against the rain-gauge data at 42 sites around the UK. In comparison the radar precipitation data provide information for verifying our forecasts at much higher spatial (5 km) and temporal (hourly) resolutions. Measures of errors in timing and maximum precipitation accumulations are being developed. In the severe flooding event that hit Sussex and Kent during 10–11 October 2000, the UK model forecasts at 25–30 hours lead-time gave a good indication of the maximum precipitation accumulations in the region and of the time variation of extreme precipitation events during this period (Fig. 38).

### Development of New Dynamics

The UM uses finite difference techniques to solve the set of equations that describe the motions and thermodynamics of the atmosphere. Alternative methods for solving these equations, which provide the potential for more-robust and accurate solutions, have been under investigation for a number of years and a new integration scheme has now been developed. The immediate benefits will be improved forecasts, particularly of extremes, but the new formulation also provides the scientific foundation for very high-resolution modelling that is the long-term key to improving the accuracy of weather forecasts over the UK.

The new scheme has required substantial changes to the UM programs due to changes in the underlying structure of the model grids and the variables used. Everything required for pre-operational trials of the new scheme is now in place. This includes coupling with the 3DVAR data assimilation and development of the capability to run the UK area mesoscale configuration. Although further development work remains, the trials so far have been encouraging, with better forecasts being obtained for several events involving deep depressions and associated severe weather in the vicinity of the UK.

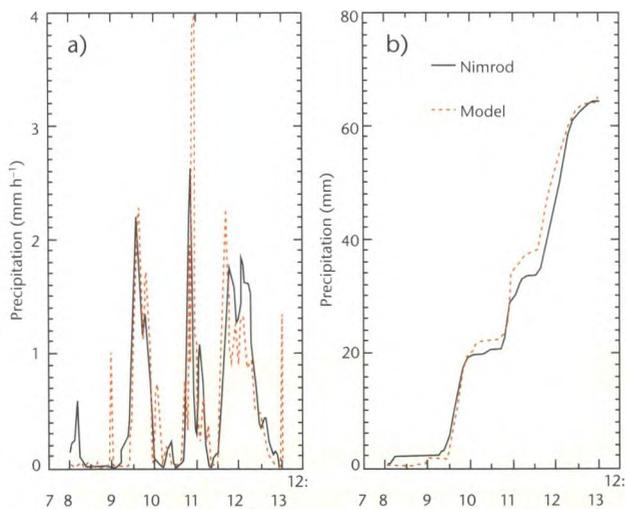


Figure 38. Time-series of (a) hourly precipitation accumulation and (b) cumulative precipitation for the UK model 25- to 30-hour forecasts and the radar (Nimrod) from 7–13 October 2000.



## Atmospheric Processes Research

Atmospheric Processes Research work is concerned with conducting well-constrained observational or modelling experiments, with the aim of ensuring that physical processes in the atmosphere can be represented in weather and climate models in the most appropriate and consistent way. Often, high-resolution models are first validated against whatever detailed observations are available. The models are then used as a proxy for real observations to investigate the sensitivity of a process to the conditions or the way it is represented in the model. To illustrate this approach, four examples of our work are presented.

The scientific effort in modelling is roughly matched by an equal effort in analysing data collected by the Meteorological Research Flight (MRF) C-130 aircraft and by a range of surface-based instruments operated by the Meteorological Research Unit (MRU) at Cardington.

### Modelling the diurnal cycle of marine stratocumulus

Important to the development of an accurate parametrization of turbulent mixing in stratocumulus clouds is an understanding of their diurnal cycle. Observations of marine stratocumulus, for example during the First ISCCP Regional Experiment (FIRE), indicate a marked thinning during the daytime. This international experiment was supported by both MRF C-130 and the tethered balloon of the MRU.

These clouds persist largely due to the turbulent transport of moisture from the sea surface and, in general, this is driven by long-wave radiative cooling at cloud top. Therefore daytime warming of the cloud not only evaporates cloud water directly but also, by raising the buoyancy of the cloud layer, makes this turbulent mixing between the cloud layer and the surface harder to sustain. This can lead to the cloud layer becoming decoupled from the sea surface, cutting off its moisture supply and causing the cloud to thin further. As the sun sets, continued long-wave cooling at cloud top can recouple the cloud layer to the surface, re-establishing the moisture supply and thus causing the cloud to thicken again.

In addition to solar radiation, a number of other processes can play a role in the process of decoupling. These include long-wave radiative warming of cloud base, turbulent mixing of relatively warm dry air across cloud-top and drizzle (which acts both to warm the cloud layer and cool the sub-cloud layer). The situation is further complicated over land by the possibility of a feedback whereby any sunshine that penetrates the cloud

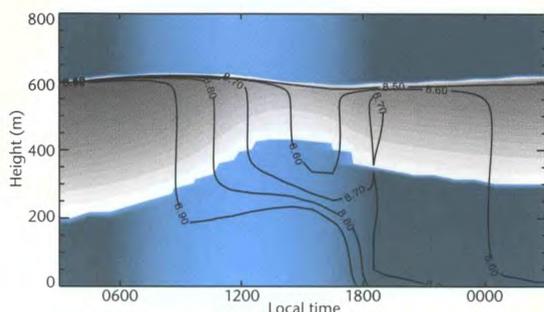


Figure 39. Time-height contour plots of liquid water mixing ratio (grey-scale contours ranging from 0, white, to  $0.8 \text{ g kg}^{-1}$ , darkest grey) and  $q_t$  (line contours, increments  $0.1 \text{ g kg}^{-1}$ ). The variation of net solar radiation is illustrated by the shades of blue in the background.

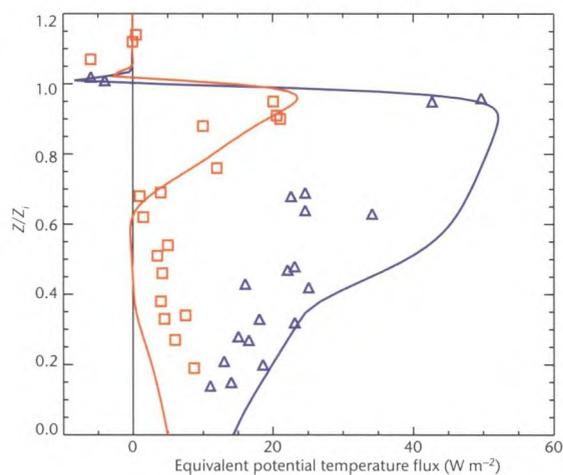


Figure 40. Turbulent fluxes of equivalent potential temperature against height scaled by the height of the capping inversion ( $z_i$ ) at midday (red) and midnight (blue).

can rapidly warm the ground, thus warming the boundary layer as a whole and so evaporating the cloud still further.

This study uses high-resolution 3D large-eddy simulations (LES) to both investigate the interactions between these processes and also provide a detailed data set for comparison with the single-column version of the Unified Model (UM). The simulation shown here is compared with observations made during FIRE in 1987 using the MRU's tethered balloon on San Nicolas Island off the coast of California.

Figure 39 shows the variation across the day of the domain-averaged mixing ratios taken from the LES, both liquid water and total water ( $q_t$ ). The marked thinning of the cloud layer during the daytime is well reproduced, as are the changes between a well-mixed boundary layer (with uniform  $q_t$ ) at night and a decoupled cloud layer (with  $q_t$  smaller in the cloud layer compared to the sub-cloud layer) during the day. The reduction in turbulent transport between the cloud and sub-cloud layers during daytime can be seen by comparing the observations of equivalent potential temperature flux made at midnight and midday shown in Fig. 40; the lines from the LES demonstrate good quantitative agreement with the symbols from the observations.

## The timing of deep convection

The timing of convective precipitation is often difficult to model but important in many practical applications. Several Cloud Resolving Models (CRMs) from around the world are being used in an intercomparison project to investigate the diurnal cycle of deep convection over land. One major aim of this project is for the CRMs to provide information for the improvement of convective parametrization schemes in large-scale models. The Met Office Large Eddy Model (LEM) is one of the CRMs taking part in this project organised jointly by ARM (Atmospheric Radiation Measurement) and GCSS (GEWEX Cloud System Study). The CRMs are forced using data derived from a 300 km square network of observations taken over the southern Great Plains of the USA, centred on Lamont, Oklahoma. Surface fluxes and profiles of tendencies of temperature and moisture are used to force the CRMs. Results are compared with observations of precipitation, temperature, moisture and various cloud data taken using profilers, satellite and radar.

Initial results from this intercomparison showed that although the CRMs could capture many features of the observed convection, they all had problems capturing the

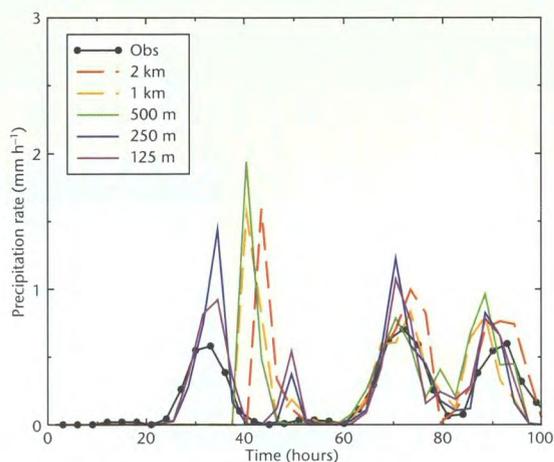


Figure 41. Time-series of precipitation from observations and the LEM using a range of horizontal resolutions.

timing of convective events. Typically the onset of precipitation in the CRMs lagged the observed precipitation by six hours or more and tended to rain too strongly when they did begin to precipitate. A delay of over six hours is a serious problem when investigating the diurnal cycle of convection, so several experiments have been carried out using the Met Office LEM to investigate this problem.

One set of experiments focused on the horizontal resolution of the model. The standard grid length for all the CRMs in the intercomparison was chosen to be 2 km, typical of many CRM studies of deep convection. To investigate the impact of this, the intercomparison experiments were repeated with the LEM using grid lengths of 1 km, 500 m, 250 m and 125 m. Figure 41 shows the time-series of precipitation produced by the LEM and includes the observed values from a network of rain gauges. The standard 2 km run was severely delayed in its production of precipitation. However, as resolution was increased the delay in precipitation was reduced, and with a horizontal grid length of 250 m or 125 m, there was a much closer match to the observed rainfall. Further investigation of the model behaviour showed that it was the improved representation of transport of moisture out of the boundary layer which leads to the improvements at higher resolution.

## Representing orography in the forecasting model

An accurate representation of flow over orography using numerical simulation techniques such as the UM is clearly dependent on the resolution of the model used. Flow over well-resolved hills can be expected to be well represented, while features close to the model grid scale are likely to be poorly described. As a result, some numerical weather prediction (NWP) models apply a smoothing to their resolved orography fields. The most appropriate smoothing method is, however, not well established.

With this in mind, a study to investigate which scales of topography can credibly be represented in numerical models has been performed. Since the results obtained are potentially sensitive to the flow regime, a wide range of cases was examined, including neutral flow over small hills embedded in the boundary layer and highly stable flow over and around large mountains. In each case, a series of simulations was undertaken in which the horizontal resolution of a numerical model was decreased. In none of these cases do simulations with only two grid points per hill show any appreciable skill. Furthermore, many undesirable features exist in these results, indicating that hills or mountains with these scales should be removed from the resolved topography field.

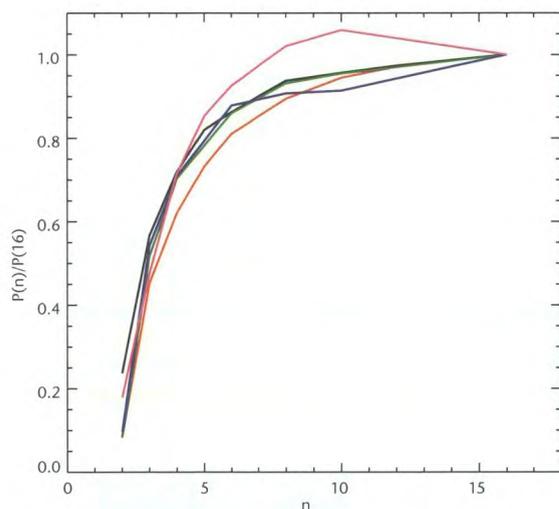


Figure 42. Ratio of pressure drag obtained from a simulation with  $n$  grid points per hill  $P(n)$  to the value obtained for a well-resolved hill with 16 grid points  $P(16)$ . The different colours correspond to series of simulations performed with a particular set of flow parameters, ranging from stable flow over a low two-dimensional ridge to flow over and around a three-dimensional high elongated mountain.

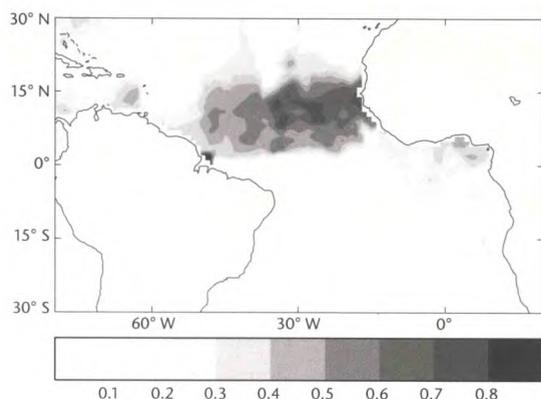


Figure 43. Aerosol optical depth at  $0.63 \mu\text{m}$  derived from AVHRR data obtained from the NOAA web site <http://las.saa.noaa.gov>. The optical depth shown here is a composite derived from eight days of aerosol data including 27 April 1999.

This is consistent with results obtained with the UM where smoothing of topography with scales of twice the model grid length decreases the occurrence of grid point storms (which are a signature of numerical noise).

When four or six points are used to resolve the hill, the results are qualitatively reasonable, but the values of drag are smaller than those obtained in the best resolved simulations, see Fig. 42. As the resolution of the numerical model increases, the quality of the results improves and the values of drag converge. Thus, any smoothing technique used in large-scale NWP models must be suitably scale-selective, removing the damaging small scales but not affecting scales greater than six grid lengths, which provide a valuable amount of information to the model solution.

### The radiative properties of Saharan dust

While the radiative effects of Saharan dust are important in determining the energy balance of the Earth and atmosphere, they are highly uncertain owing to the competing nature of the scattering and absorption of solar and terrestrial radiation. The radiative effects of Saharan dust have been studied by the MRF on two transit flights between Tenerife and Ascension Island on 27 April 1999 and 8 May 1999. Figure 43 shows a composite image of aerosol optical depth from AVHRR data during this period.

Measurements of the Saharan dust aerosol size distribution reveal significantly larger particles than typical industrial pollution. Optical properties derived from the size distribution were found to agree with in situ measurements performed by the aircraft, and independently inferred from Sun-photometer data collected nearby on the Cape Verde Islands.

Measurements were also performed with the aircraft's broad-band radiometers that measure the irradiance in various wavebands through a horizontal surface. The solid lines in Fig. 44(a) and (b) show the measured upwelling irradiance in cloud-free areas as a function of latitude on each of the transits for the clear-domed radiometer ( $0.3\text{--}3.0 \mu\text{m}$ ) the red-domed radiometer ( $0.7\text{--}3.0 \mu\text{m}$ ), and the derived visible irradiance ( $0.3\text{--}0.7 \mu\text{m}$ ). The upwelling irradiances in the absence of aerosols are modelled using the flexible radiative transfer code developed by the Hadley Centre and are shown by the dashed curves. The difference between the dashed and solid curves represents the perturbation to the upwelling irradiance caused by the presence of Saharan dust aerosol, which reaches approximately  $-60 \text{ W m}^{-2}$  and represents a more than doubling of planetary albedo. These measurements have been used to derive aerosol optical depth, and compared

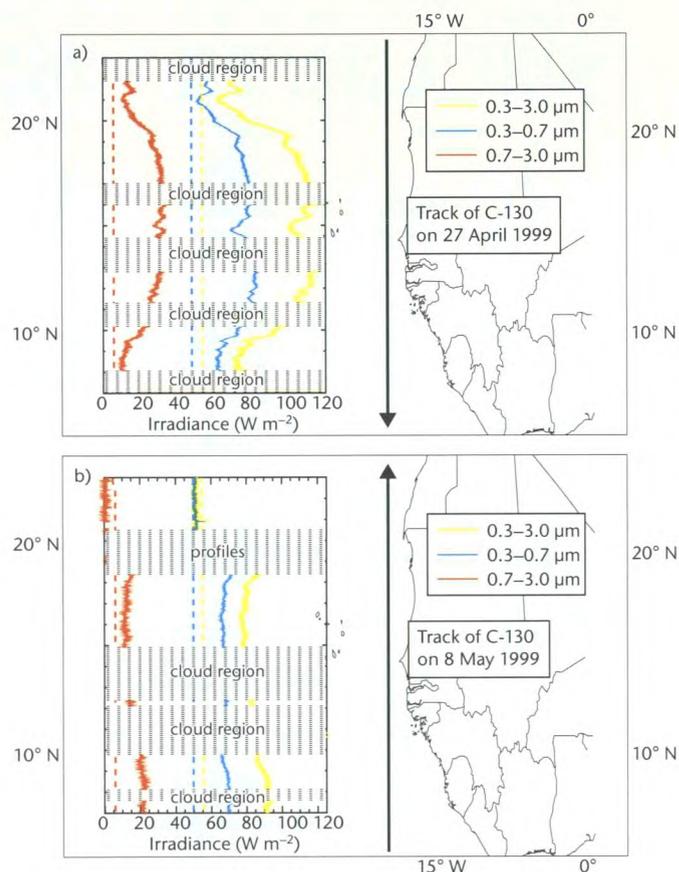


Figure 44. The measured (solid) and modelled (dashed) upward solar irradiances as a function of latitude (longitude fixed at 18° W) for: (a) 27 April 1999 and (b) 8 May 1999. The areas denoted 'cloud region' are where cloud was detected using the downward facing video camera and 'profiles' represents an area where the aircraft sampled the aerosol size distribution and optical properties. The yellow colours represent the 0.3–3.0  $\mu\text{m}$  spectral region covered by the clear-dome pyranometer, the red colours represent the 0.7–3.0  $\mu\text{m}$  covered by the red-dome pyranometer, and the blue colours represent the 0.3–0.7  $\mu\text{m}$  spectral region obtained from the other two spectral regions. Error bars of  $\pm 5 \text{ W m}^{-2}$  are assigned to the solar measurements.

against a new satellite-derived aerosol optical depth retrieval algorithm from NASA, the results of which are very encouraging.

The success of these measurements led to an intensive measurement campaign based in the Cape Verde Islands in September 2000, where a perturbation to the upwelling irradiance of  $-130 \text{ W m}^{-2}$  was measured during an intense dust storm. These results are currently being analysed and compared against satellite measurements and the dust model developed by the Hadley Centre. The detachment of the aircraft to Africa during August–September 2000 was funded through a variety of customer interests. Both scientifically and logistically, the detachment was extremely successful and much useful data have been gathered.





## Climate Research

### Climate change predictions

A series of HadCM3 climate model experiments has been conducted to investigate new emissions scenarios prepared as reference cases for the IPCC Third Assessment Report. The starting point for the 'Special Report on Emission Scenarios' (SRES) is a number of 'storylines' describing the way that the world (population, economies, etc.) will evolve over the next 100 years. In general, these envisage a more prosperous and technologically advanced world than the present day, leading to a wide range of greenhouse gas emissions. The emissions of sulphur dioxide, which produce sulphate aerosols known to have an important cooling effect on climate, are substantially fewer than in the IS92 scenarios.

Figure 45 shows the predicted changes in global mean surface air temperature in these scenarios, with a control run as a reference, and Fig. 46 shows the corresponding changes in global mean sea level.

The A1FI scenario produces particularly dramatic and accelerating warming in the second half of the 21st century, with roughly a factor of two difference in global warming between the highest and lowest scenarios by 2100. Land warms at approximately 1.8 times the rate that the ocean warms. Trajectories of global sea-level rise appear to remain rather more tightly bunched than global warming based on our current calculations, but at the moment there are large uncertainties in modelling of sea-level response.

The resolution of the global model is limited by computing resources to 300 km. In order to obtain increased detail over Europe, simulations using a regional model with 50 km grid are driven by the global model. This leads to a considerable improvement in the simulation of extreme rainfall events over the United Kingdom.

One of the potentially most damaging impacts of increases in greenhouse gases is a possible increase in the frequency and extent of tropical storms (Fig. 47). The current coupled model barely resolves tropical storm, so we have analysed changes in tropical storm tracks in a high-resolution ( $0.83^\circ$  latitude by  $1.25^\circ$  longitude) version of the atmospheric model. The control experiment was forced with observed sea-ice and sea-surface temperatures. In the anomaly experiment sea-ice, sea-surface temperatures and greenhouse gas forcing were changed to mimic the mean changes which occurred in

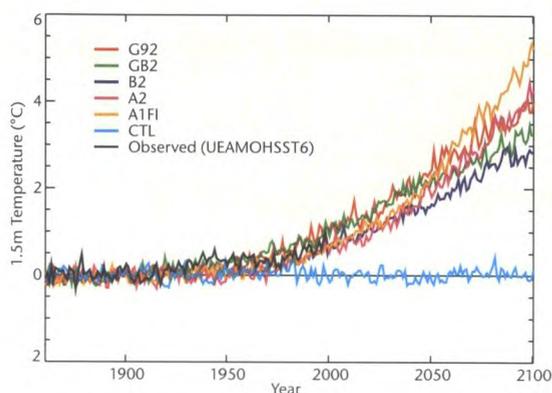


Figure 45. Time-series of annual global mean temperature (°C) in HadCM3 scenario experiments SRES, A2, B2, A1FI and the control run (CTL) for the period 1859–2100, each relative to their average over the period 1880–1920. Observed global mean temperature anomalies from the MOHSST6-UEA data set are also shown. GB2 and G92 are based on the SRES B2 and old IS92a scenarios respectively, run with changes in greenhouse gases only.

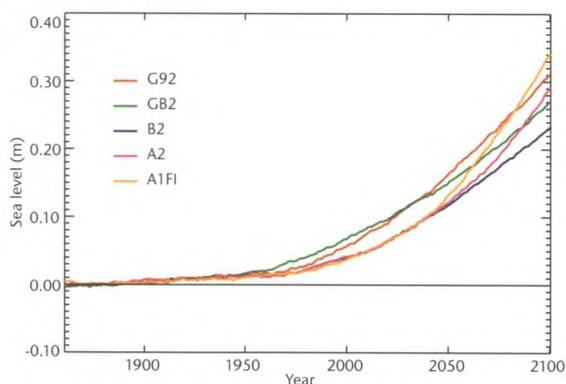


Figure 46. Time-series of annual mean sea-level rise (m) due to thermal expansion in HadCM3 scenario experiments G92, GB2, B2, A2 and A1FI relative to a control run with no change in forcing.

the coupled model when greenhouse gases were increased (period 2080–2100 of the IPCC IS92a scenario) while maintaining the natural variability of the control experiment.

In the anomaly experiment, there are more tropical storms in the north-east Pacific and in the Indian Ocean basins and fewer in the North Atlantic, north-west Pacific and south-west Pacific regions. The reduction in east-to-west sea-surface temperatures in the equatorial Pacific is similar to that observed during El Niño. The pattern of changes in cyclone genesis in the North Atlantic and north-west Pacific is also qualitatively similar to that observed during El Niño.

One test of a climate model is to compare simulations of the recent past with the instrumental temperature record. When only natural factors (e.g. changes in solar irradiance, dust from major volcanic eruptions) are included, then the model fails to produce the warming in recent decades. When only anthropogenic factors (e.g. increases in greenhouse gases and sulphate aerosols) are included, the trend is reproduced poorly. The best fit to observations is obtained when both natural and anthropogenic factors are taken into account.

Another test of a climate model is to compare simulated past climates with reconstructions of past climates based on palaeoclimatic data. The most recent marked climate change occurred during the last glacial maximum, 21,000 years ago. A simulation in which the ice age continental ice-sheets and carbon dioxide concentrations were prescribed has been run over 700 years. Many of the features of the large-scale temperature response (Fig. 48) agree with palaeoclimatic reconstructions. The most interesting aspect of the response is the small SST changes in the North Atlantic, which result from a strengthening of the thermohaline circulation. This increases the oceanic heat transports in the North Atlantic which limit the cooling in this region.

### **Intergovernmental Panel on Climate Change (IPCC)**

The IPCC was set up in 1988 to provide periodic assessments of current scientific consensus concerning climate change, its potential impacts and the range of possible response strategies. The focus of the IPCC's Working Group I (WGI), co-ordinated by a Met Office technical support unit, is the physical climate system. IPCC 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

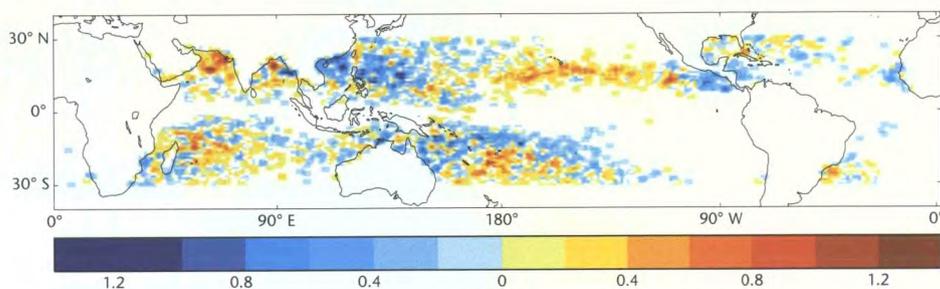


Figure 47. Change in tropical storm genesis (2083–97 mean minus 1980–94 mean) in a high-resolution atmospheric model with sea-surface temperature changes prescribed from a lower-resolution coupled model experiment. The units are numbers of tropical storms which develop in each  $0.8^\circ$  latitude  $\times$   $1.25^\circ$  longitude area in a 15-year period.

played a major role in the negotiation and implementation of the UN Framework Convention on Climate Change (FCCC).

This year IPCC Working Group I completed its Third Assessment Report. This report was compiled between July 1998 and January 2001, by 122 lead authors, supported by 516 contributing authors. The draft report was reviewed by many hundreds of experts and by governments.

### Climate variability

#### Global climate trends

We have produced the first analysis of global and hemispheric surface temperature variations that explicitly quantifies the major sources of uncertainty. One of the largest uncertainties relates to corrections to SSTs for serious biases before 1942. Climate model simulations show that, on the annual average and on large space scales, these complex corrections are likely to be fairly accurate. We have calculated annual temperature anomalies by combining land- and ocean-based observations using an optimal averaging technique (RSOA), modified for a changing climate. This allows estimates to be made of uncertainties in the annual anomalies resulting from data gaps and random errors and provides a better estimate of the mean than does a simple average. It also

permits the addition of dependent uncertainties associated with the SST bias-corrections, urbanisation effects on land, and changes in the exposure of land thermometers (Fig. 49).

This research gives a global mean temperature increase since the late nineteenth or early twentieth centuries of  $0.6^\circ\text{C} \pm 0.2^\circ\text{C}$  (95% confidence limits).

Provisional estimates suggest that 2000 is likely to be the seventh warmest year in the record, slightly cooler than 1999. Our new global temperature anomaly forecasting system produced a forecast for 2000 about  $0.1^\circ\text{C}$  warmer than observed.

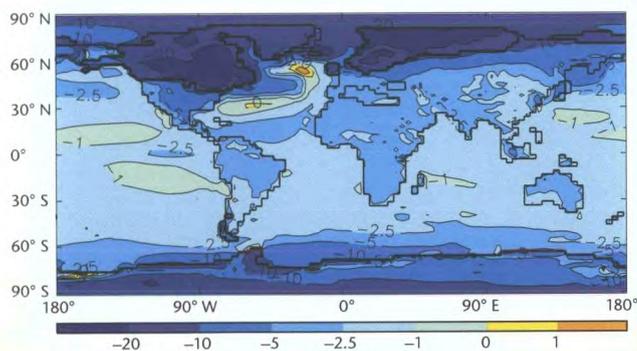


Figure 48. Change in surface temperature from present in a simulation of a coupled ocean–atmosphere model driven by ice-age boundary conditions. Contours at  $=1.0, -1.0, -2.5, -5, -10$  and  $-20^\circ\text{C}$ .

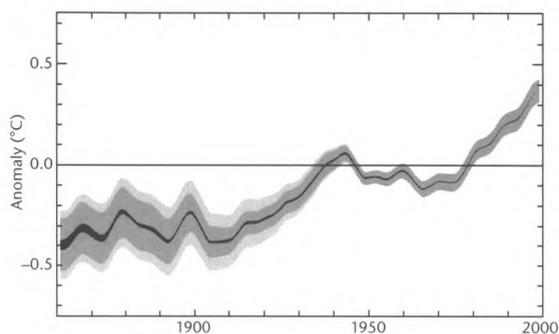


Figure 49. Global surface temperature anomalies, 1861–1999 and their uncertainties. Dark shading represents uncertainties from data gaps and random errors alone; intermediate shading represents added SST bias-correction and urbanisation uncertainties; light shading represents all uncertainties.

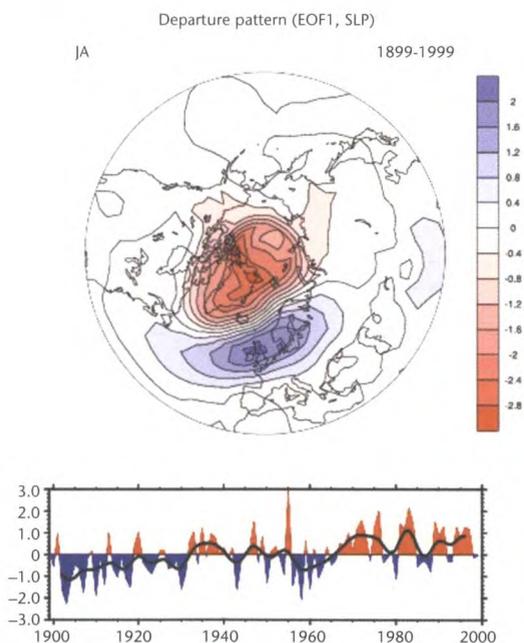


Figure 50. Structure and time-series of the leading pattern of July and August mean sea-level pressure in the extra-tropical northern hemisphere. The pattern has a centre near UK and shows multidecadal variability.

## Changes in extremes

International collaboration has resulted in new data sets that can describe how the frequency or severity of climatic extremes have changed during the second half of the 20th century. Ten indicators (five temperature and five precipitation) were created, applicable to a wide variety of climates. These range from the number of days per year below 0 °C to the fraction of annual precipitation falling in extreme daily rainfall events. Of particular interest is whether heavy rainfall events are increasing in a warming world. Despite substantial regional variability, there is an overall significant trend towards increased heavy rainfall events. Large land areas of the globe have still to be analysed, particularly Africa and South America.

England and Wales Precipitation (EWP) and other UK regional precipitation series are now automatically updated in real time consistent with historical data. This has provided a more detailed and accurate Met Office capability for monitoring rainfall. The autumn (September to November) of 2000 was the wettest in the 235-year series, and October to December was the wettest three-month period. The year 2000 was the wettest since 1872, and the third wettest in the series. The precipitation regions covering England and Wales have seen a significant decrease in summer precipitation totals over the record period since 1873, with most also showing an increase in winter precipitation.

## Decadal and multidecadal climatic variability

The clearest pattern of temperature variation over the last century is the one which reflects warming of the globe. However, there is growing evidence that the global climate system also contains several modes of climatic variability operating on decadal to multidecadal timescales involving temperature and atmospheric circulation. One seems to involve multidecadal variations in UK high summer (mainly July and August) anticyclonicity and cyclonicity and therefore rainfall. It appears to be part of a large-scale mode of summer atmospheric variability (Fig. 50). These long timescale UK climate variations are likely to be linked to summer rainfall variations in the Sahel of west Africa.

## Interannual to interdecadal predictability

Further observational support has been found for the influence of North Atlantic sea-surface temperatures on the winter North Atlantic Oscillation (NAO). If the SST patterns were known in advance, the correlation skill of a forecast of the winter NAO

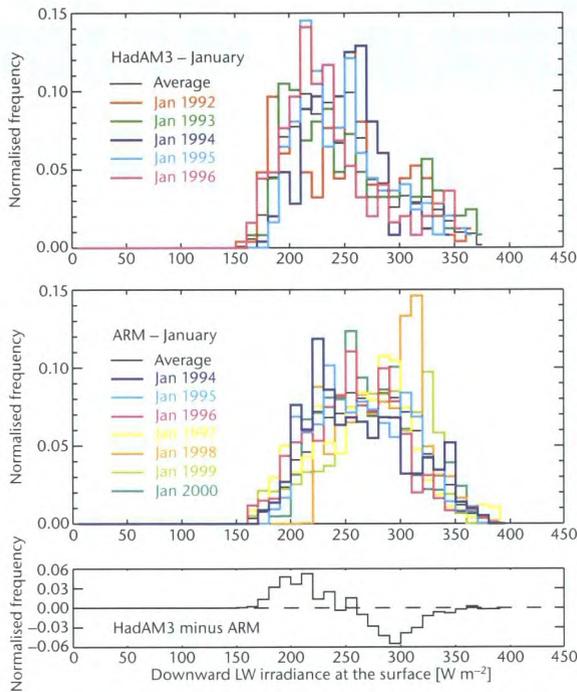


Figure 51. The difference (bottom) between model (a) and observations (b) histograms of the normalised frequency of occurrence of downward terrestrial radiation at the surface for January from a multi-year simulation using HadAM3 and observations from Oklahoma.

in this period is likely to be in the range 0.45 to 0.63 based on data in the last half century. For the first half of the 20th century, however, observational and atmospheric model results agree, showing very little predictability of the winter NAO. This suggests that there is multidecadal variability in the predictability of the winter NAO. However, the coupled ocean-atmosphere GCM, which incorporates the HadAM3 atmospheric model, fails to show a causal link from north Atlantic temperatures to the atmosphere. Whether this is due to model error or multidecadal variability in predictability is unclear. This model does, however, represent well the opposite forcing of SSTs by the NAO through the action of surface heat fluxes.

## Model development and parametrizations

New surface observational techniques and opportunities are providing fresh insights into the cloud simulations of the NWP and climate configurations of the Unified Model. The Atmospheric Radiation Measurement (ARM) programme was initiated over 10 years ago by the US Department of Energy to collect observations of radiation and clouds in order to enhance understanding of processes and enable the development of parametrizations for atmospheric models. Data from the longest running ARM site in Oklahoma, USA, have been compared against climate simulations for the 1990s using HadAM3, the current standard version of the Hadley Centre climate model. Comparing measurements of downward solar and terrestrial radiation from the site with the simulation shows that the model over-predicts the occurrence of low downward terrestrial/high solar radiation events (Fig. 51). This suggests that either the frequency of low cloud cover events is too high or that clouds are too thin when they do occur. The use of cloud occurrence data obtained from lidar measurements at the site will assist in clarifying the cause of the error. Similar comparisons using a version of the Unified Model (UM) with an updated representation of clouds (HadAM4) suggests that the model bias is substantially reduced, supporting previous indications of improved performance from comparison with satellite observations.

Surface-based cloud radars (Fig. 52) provide a detailed view of cloud systems indicating regions of ice, supercooled water and embedded convection. Although only presently available at a few locations around the world, in the near future similar radars will be flown on satellites, providing a global view of the vertical structure of cloud systems. The surface observations are being used to validate cloud fields in the mesoscale version of the UM, which uses a mixed-phase microphysics scheme.

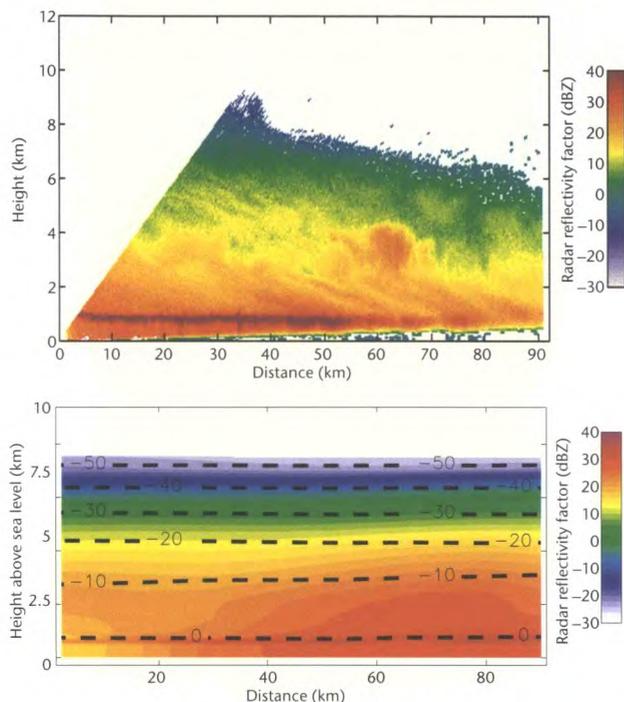


Figure 52. (a) Cross-section of observed radar reflectivity from the Chilbolton radar for a frontal system on 21 November 2000. (b) Calculated reflectivity from the mesoscale version of the Unified Model for the same cross-section as (a). Isotherms are shown dashed.

Satellite data provide important information for evaluating models. A direct comparison involves using the model to simulate the radiances that are actually observed by the instrument. A version of the climate model radiation code has been developed to enable this to be done. This work will be extended in 2002 with the launch of Meteosat Second Generation, which will carry an enhanced imager and the Geostationary Earth Radiation Budget (GERB) instrument.

## Atmospheric chemistry modelling

As a result of human activities, atmospheric concentrations of a number of greenhouse gases are anticipated to build up further during this century. To predict the rises in the global concentrations of methane, ozone and sulphate aerosols from their pre-industrial baseline levels, we use a global three-dimensional Lagrangian chemistry-transport model, STOCHEM, which is fully integrated within the coupled atmosphere-ocean climate model, HadCM3.

We have performed two 110-year fully coupled model integrations from 1990 through to 2100 with HadCM3/STOCHEM using ‘control’ and ‘climate change’ climatologies, both with increasing man-made trace gas emissions from the IPCC SRES A2 scenario. The global mean ozone increases between the 1990s and the 2090s (Fig. 53) are dramatically reduced when feedback between climate change and tropospheric chemistry is introduced. A corresponding reduction in the build-up of future methane concentrations is also noted. These reductions are significant for climate change prediction and are driven by increases in tropospheric temperatures and water vapour concentrations.

## Stratospheric processes research

Understanding the interaction between climate change and ozone amounts continues to be a major component of the research programme. In the past, trends in ozone and temperature have been simulated for the period 1980–2000, taking into account the increases in greenhouse gases and CFCs. Increases in computer resources and improvements in modelling capability now enable continuous, multidecadal length integrations to be performed with UMETRAC (Unified Model with Eulerian Transport and Chemistry).

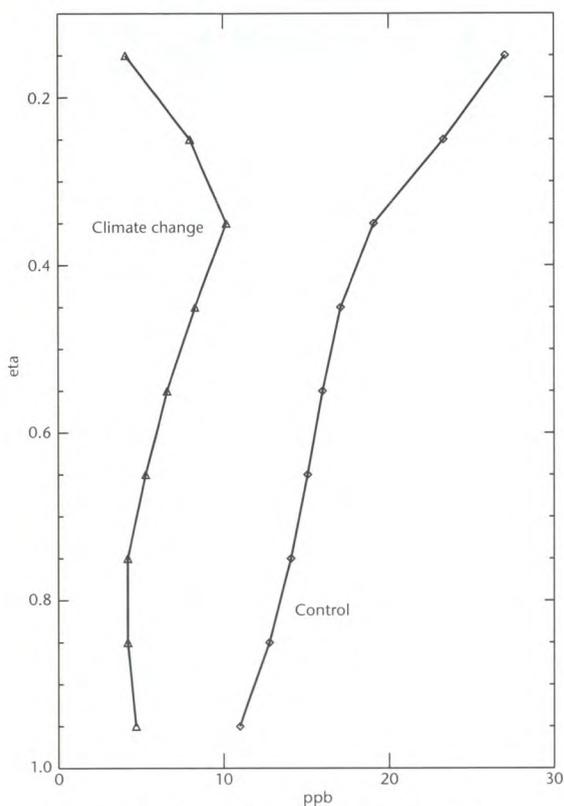


Figure 53. Global mean change in ozone for July, 2000-90

The impact of solar changes on climate has received much attention in the scientific community since it is necessary to understand natural processes which may be contributing to climate change. Figure 54 shows the ozone difference, solar maximum minus solar minimum, for the 11-year solar cycle.

In the lower stratosphere, the perturbation is several per cent and this could have an important climate signal. The model simulations also show increased ascent of tropical air during the solar maximum and this could have important implications for the transport of radiatively and chemically active gases.

Further investigations are in progress to understand why the upper stratospheric signal is somewhat smaller than observed, and the lower stratospheric signal is large but in much closer agreement with observations.

### Cross-tropopause transport

Chlorofluorocarbons (CFCs), along with bromine compounds, have been unequivocally identified as being responsible for most of the anthropogenic destruction of stratospheric ozone. With curbs on emissions of these substances, the recovery of the ozone layer will depend on their removal from the atmosphere. Since CFCs have no significant tropospheric removal process, but are rapidly photolysed above the lower stratosphere, the timescale for their removal is set mainly by the rate at which air is transported from the troposphere into the stratosphere. Using a global climate model we predict that, in response to the projected changes in greenhouse gas concentrations during the first half of the 21st century, this rate of mass exchange will increase by 3% per decade, due to more vigorous extra-tropical planetary waves emanating from the troposphere. We estimate that this will accelerate the removal of CFCs with recovery to levels currently predicted for 2050 and 2080 occurring five and 10 years earlier, respectively.

### Atmospheric dispersion

Understanding and predicting the processes by which airborne pollutants are transported in the atmosphere remain important for a range of atmospheric pollution problems. These include forecasting the spread of materials from major atmospheric releases, such as those from nuclear accidents, chemical spills or volcanic eruptions; and understanding and forecasting air quality.

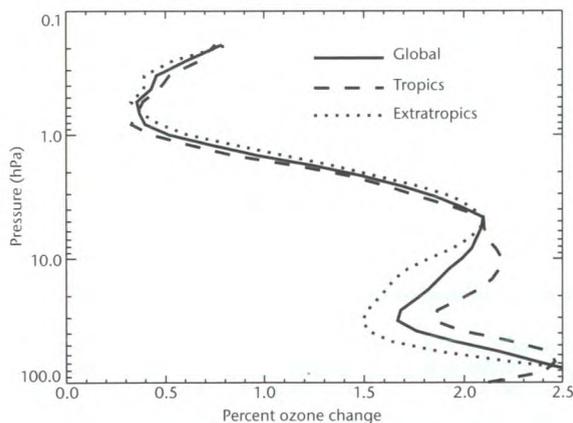


Figure 54. Difference in ozone values in % for solar maximum minus solar minimum for the 11-year solar cycle.

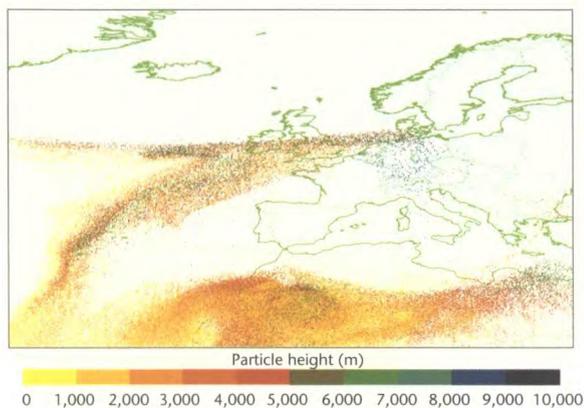


Figure 55. NAME predicted Saharan dust plume over the UK, 3 March 2000. Colours represent height, with lighter colours being in the lower atmosphere.

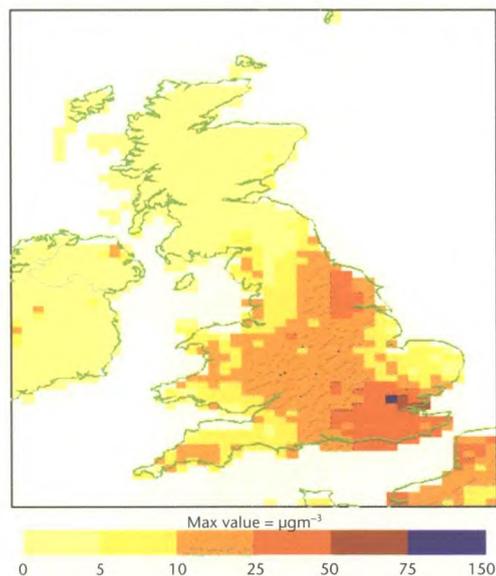


Figure 56. Forecast particulates (PM10) over the UK, 1 February 2001. Slack winds from the south-east resulted in poor air quality.

### The NAME model

The NAME dispersion model, is used to simulate the transport and fate of pollutants over ranges of a few kilometres to several thousands of kilometres. It has been improved this year by the development of a new plume rise scheme. Many plumes, such as those emitted from power stations or from forest fires are initially buoyant until they have cooled due to mixing with ambient air. Correctly predicting this plume rise is critical for predicting downwind pollutant concentrations. The new scheme uses conservation equations of mass, momentum and heat and has the advantage of being suitable for a far wider range of meteorological conditions than the previous empirical scheme. Results are encouraging, showing that the NAME model produces similar skill to other established short-range models.

The development of chemistry in NAME has continued with the addition of nitrogen chemistry. The aims are to improve our ability to predict concentrations of NO<sub>2</sub>, a key atmospheric pollutant, and to improve our understanding of the formation and transport of nitrate aerosols. The scheme has been tested against measurements made during two recent measurement campaigns in Birmingham as part of the PUMA project. We are now adding hydrocarbon chemistry, to enable the model to produce ozone forecasts.

### NAME-PPM

We have developed a new model, NAME-PPM, which will integrate both short- and long-range capabilities, to provide a 'unified' dispersion model. Pollution levels in a city are due to a combination of local emissions and the import of pollutants from a few to several hundreds of kilometres upwind. Progress is being made in developing a buildings effect module for NAME-PPM.

### Saharan dust episode

NAME has been used to help analyse and understand a number of pollution events through the year. This included a study of exceptionally high particulate (PM10) levels and 'dirty' rain over widespread parts of the UK in early March 2000. At first it was suspected that volcanic ash from a recent eruption of Mount Hekla in Iceland had reached the UK. Subsequent analyses of the observations and satellite imagery, combined with NAME modelling, showed that the episode was due to the transport of

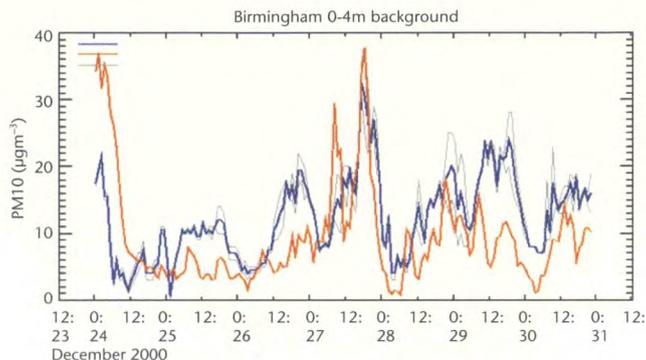


Figure 57. Model versus observed PM10 at Birmingham. The model clearly picks out the high pollution events.

dust from the Sahara. A follow-up study has identified several more episodes of Saharan dust transport resulting in elevated PM10 measurements over the UK. Figure 55 shows the simulated dust plume reaching the UK on the night of 2/3 March 2000.

### **Air quality**

The NAME model is used to generate routine air quality forecasts for the atmospheric pollutants NO<sub>2</sub>, SO<sub>2</sub>, CO and PM10. Forecasts are generated twice daily, producing hourly forecasts up to three days ahead. Both UK and European emissions are included, with UK emissions based on 1998 data at 1 km resolution from NETCEN (National Environmental Technology Centre). European emissions are of particular importance for predicting particulate (PM10) levels, as a significant component of particulates can be sulphate aerosol, formed during long-range transport. A range of rolling statistics comparing model predictions with routine observations is generated to indicate model skill at a range of locations. A key limitation to generating better air quality forecasts is the need for accurate emission data. For example, emissions are generally only available as annual totals, with actual emissions varying widely during the day and between seasons. An example forecast map for PM10 is shown in Fig. 56, showing high levels over much of England. Figure 57 shows modelled and measured PM10 over Birmingham during the last week of December 2000.





## Ocean Applications

Ocean Applications develops, and brings to implementation, the ocean modelling systems required to meet Met Office customer needs. This includes operational ocean models for wave forecasting; our Forecasting Ocean–Atmosphere Model (FOAM), a global and basin-scale real-time ocean analysis and forecast system; and regional modelling of the shelf-seas around the UK. We also support seasonal forecasting and climate research, providing the ocean component of the Hadley Centre’s coupled ocean–atmosphere models, and have begun the UK’s contribution to Argo.

### Operational ocean modelling

#### *Wave modelling*

An important requirement is for forecasting low frequency swells (~18 seconds period); these can cause significant disruption to offshore operations. Such swells can be generated by local storms or hurricanes, and propagate great distances across the oceans. The Synthetic Aperture Radar (SAR) aboard the satellite ERS-2 is the first instrument to provide near real-time global observations of low frequency wave energy. These can be used to give the power spectrum of the energy of ocean waves. However, the processing assumes that the waves do not move while the satellite passes over. Hence the direction of propagation of the waves relative to the satellite track is ambiguous (Fig. 58(a)). To resolve this ambiguity an iterative inversion technique (first developed at MPI Hamburg, and now under development at DLR) is applied to retrieve the wave energy spectrum by combining the SAR spectrum with a first-guess spectrum (Fig. 58(b)) taken from the wave model (see Fig. 58(c)).

Further assessment of the retrieval technique is still needed, as it is possible the scheme over-estimates the long-period wave energy. New techniques are also being developed to assimilate the SAR observations into the global wave model to produce better forecasts of low frequency swell.

#### *Forecasting Ocean–Atmosphere Model (FOAM)*

A global version of FOAM with 1° resolution is run daily, to provide forecasts out to five days ahead for ocean temperature, salinity, currents and sea-ice cover. This year, a second version with 1/3° (~30 km) resolution was introduced into the operational

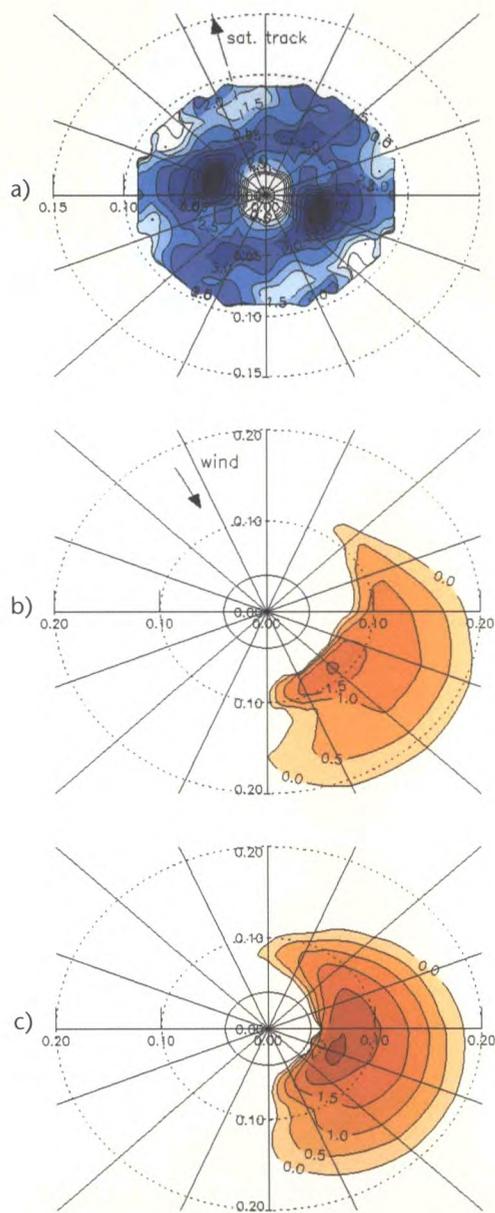


Figure 58. Polar plots of wave energy spectrum versus direction and frequency at 36.2° N, 41.3° W at 1303 UTC on 14 January 2001. (a) SAR spectrum, (b) model wave energy spectrum and (c) observed wave energy spectrum. The latter is retrieved from the first two spectra.

suite. This version covers the Atlantic and Arctic Oceans and is nested within the global model.

A set of experiments was performed with these two models and a third, nested within the 1/3° model, covering the Gulf of Mexico and the Caribbean Sea at 1/9° resolution. The models were all driven from the Met Office's NWP system and run for three years from 1 January 1997. Some integrations assimilated no observations, others assimilated only thermal data and the remainder assimilated thermal data and sea-surface height data from satellite altimeters. The results show that the 1/9° model gives the better simulation.

Figure 59 compares the sea-surface temperature (SST) in the Gulf of Mexico for 14–19 March 1998 from the 1/9° model assimilating (a) just thermal data, and (b) surface height and thermal data. Figure 59(c) shows the corresponding seven-day mean SST derived from satellite AVHRR data. Only coarse-resolution SST data were assimilated in the model and the altimeter data clearly improve the representation of mesoscale eddies as shown by the variations in the model's SST.

### Shelf-seas modelling

The operational shelf-seas model predicts the evolution of temperature, salinity and current profile over the continental shelf and shelf break. Comparison with AVHRR SST observations for August 2000 (Fig. 60) shows general agreement over the shallower waters of the southern North Sea, although the water off the Dutch coast is warmer than in the model. Also, the model is much cooler in the deeper waters to the north-west of Scotland and Ireland. This is partly because the model surface layer is 5% of the water depth, therefore in deeper waters the model SST represents a depth of several tens of metres. To improve surface layer representation in deeper water, the model has been adapted to use a hybrid vertical coordinate. This retains the advantages of terrain following co-ordinates near the sea bed, but gives better resolution over the near-surface layers in deeper water. The improved model will be implemented during 2001.

The shelf-seas model produces daily-averaged SST. However, there can be considerable variability on timescales of less than one day, particularly in coastal waters where solar heating and tides can be important. There are variations arising from tides, the daily cycle of heating and changes in weather. The relative importance of each depends on the specific location.

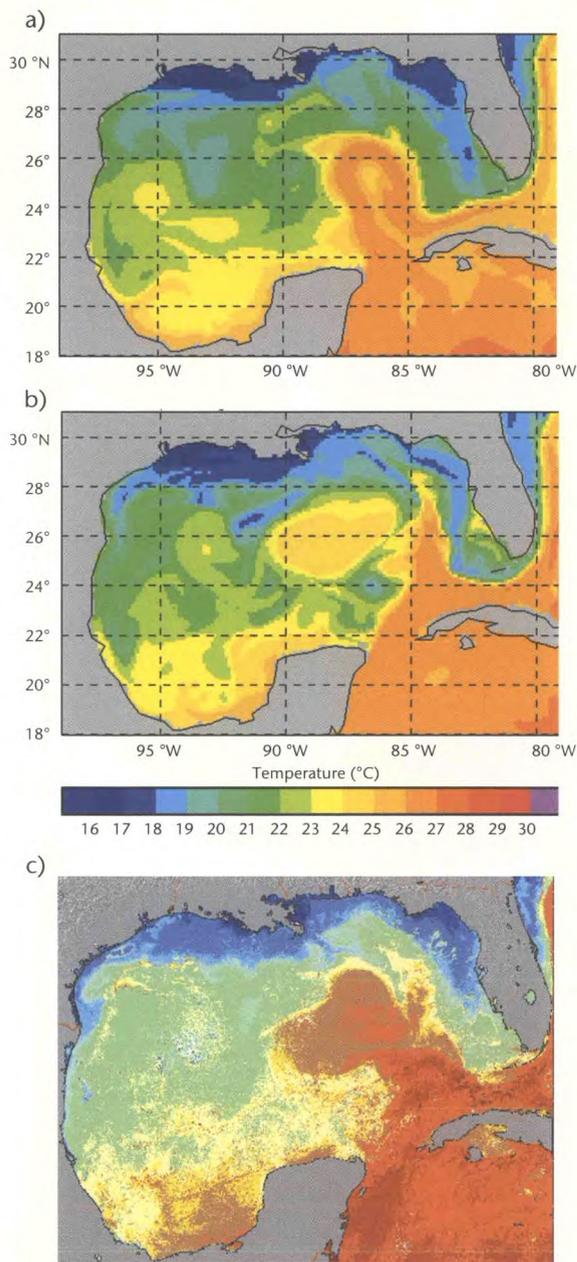


Figure 59. SST ( $^{\circ}\text{C}$ ) for 14–19 March 1998 in the Gulf of Mexico; (a)  $1/9^{\circ}$  FOAM assimilating in situ thermal profiles and coarse-resolution SST data, (b) as in (a) but with assimilation of altimeter data, (c) the corresponding seven-day AVHRR composite.

## Seasonal climate modelling and prediction

Research and development into seasonal forecasting methods are carried out using dynamical models, together with statistical relationships based on historical data. The main source of predictive skill is SST, which changes relatively slowly and can be predicted on a seasonal timescale. A variety of regional and global forecasts is produced and issued.

### Experimental global seasonal forecasts

A quasi-operational seasonal prediction system is run to generate experimental seasonal predictions for all areas of the globe. The forecasts are made available to UN organisations and to over 130 national meteorological services. Predictions are also supplied to the Drought Monitoring Centres of Africa to provide four-month-ahead outlooks for Africa's rainy seasons (Fig. 61). New developments include predictions for the Indian summer monsoon for the Crisis and Humanitarian Affairs Department of DfID, and exploration of forecast applications through participation in the DTI Foresight Initiative 'Seasonal Forecasting for the Food Chain'.

The real-time predictions are produced using a 'two-tier' representation of the atmosphere–ocean system. The atmosphere component (HadAM3) of the Hadley Centre climate prediction model is integrated forward from current atmospheric conditions out to four months in a nine-member ensemble. The expected global SST evolution is supplied using an independent prediction of SST and sea-ice based on persistence of observed SST anomalies.

### Ocean–atmosphere interaction

More-complex prediction models have a dynamical ocean coupled to the atmospheric component, to represent air–sea interactions and feedback. Good initialisation of the equatorial oceans is important for coupled model seasonal predictions. Unfortunately assimilation of data near the equator in most ocean models tends to drive unrealistic overturning motions which return the models towards their own climatologies early in the forecast. In collaboration with the University of Reading, a new pressure correction technique for generating more dynamically balanced states has been developed. Figure 62 shows how the method changes the currents in the equatorial Pacific. The weakening of the core of the undercurrent, its increased eastward penetration and the increase in the westward surface currents are all improvements.

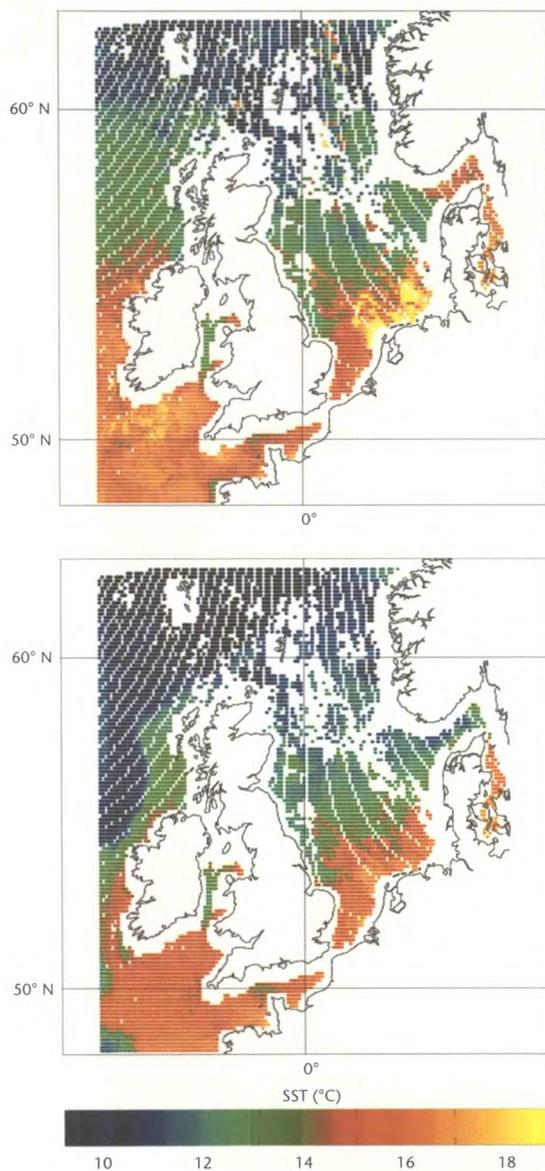


Figure 60. Monthly mean SSTs for August 2000, (top) AVHRR satellite observations and (bottom) mean model values for the same time and place as the satellite observations.

A new global coupled model has been developed for producing seasonal forecasts out to six months and beyond. In particular, this type of model is suitable for predicting the onset and evolution of the ENSO events that are a prime source of interannual climate variability.

## Ocean modelling for climate studies

### *Ocean and sea-ice model development*

Many important processes in the ocean occur at spatial scales which cannot be resolved by current climate models (e.g. eddies, boundary currents, sill overflows). To test the impact of better resolution, we have developed a climate model incorporating a  $1/3^\circ$  resolution ocean model coupled to the Hadley Centre atmospheric model HadAM3. Early results show improved simulation of important current systems, e.g. flow through the Indonesian region and the dense overflow from the Nordic Seas into the North Atlantic. The better ocean resolution also results in changes to the large-scale heat balance of the atmosphere, emphasising the complex, coupled nature of the climate system.

A new version of the ocean climate model (HadGOM) is being developed, as part of the new coupled climate model HadGEM1 (see Climate Research). Compared with the present coupled model (HadCM3), this has improved horizontal resolution (particularly in the tropics), twice the number of vertical levels and a more realistic coastline. It also has a more comprehensive sea-ice model, including the dynamical effects of ice rheology and improved representation of ice thermodynamics.

### *The role of the ocean in climate*

Experiments with HadCM3 have investigated the impacts that a collapse of the thermohaline circulation (THC) of the Atlantic Ocean would have on climate. These are global in extent and include changes to temperature, precipitation, atmospheric circulation and probably the carbon cycle. The experiments have shown that both oceanic and atmospheric feedback is crucial in determining the stability of the THC. An important factor is the interplay between changes in the atmosphere hydrological cycle and the subtropical gyre in the Atlantic Ocean.

The results emphasise the importance of good representation of hydrological processes in climate models. In HadCM3, the North Atlantic develops a salty bias over time.

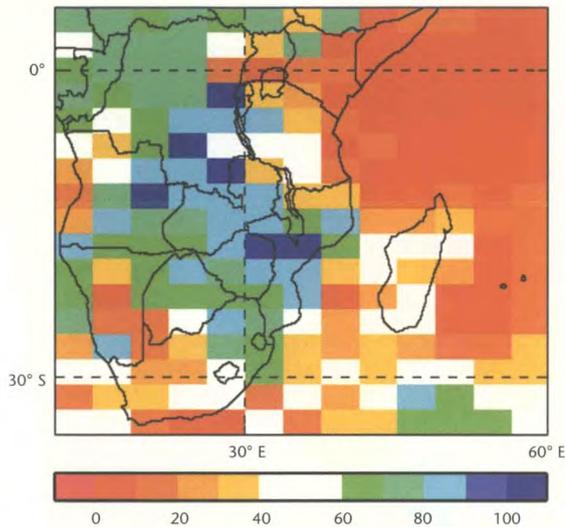


Figure 61. Probability forecast issued in December 2000 for above-normal rainfall for the January to March 2001 rainy season in southern Africa. Forecast probabilities favour above-normal rainfall over much of the central and eastern parts of the continent.

A 'sensitivity test' was run where the surface flux of fresh water into the tropical and subtropical Atlantic (approximately 30° N to 30° S) was increased. This significantly reduced the salinity drift in the North Atlantic, even to the north of the region where the fluxes were changed. This, along with comparison against observational estimates of the hydrological cycle, indicates that excessive evaporation in the model's tropical and subtropical Atlantic is largely responsible for the salinity drift in HadCM3.

The North Atlantic Oscillation Index (NAOI) is an indicator of European climate and has increased over the past 40 years. In a 1,000-year control run of the HadCM3 coupled model, we see periods of interdecadal variations in the simulated NAOI, similar to those observed. One such period has been studied. A small ensemble of century-timescale simulations was run in which the variability in the deeper ocean (below 500 m) was suppressed. In each case the simulated NAOI shows reduced interdecadal variance compared to the control suggesting the deeper ocean exerts a significant influence on atmospheric variability on these timescales. As the ocean has longer natural timescales than the atmosphere, this is an encouraging result regarding the potential for decadal climate forecasts.

We are using the coupled model to investigate ocean monitoring strategies to enable early detection of climate change in the ocean. Early results suggest that sub-surface temperature and salinity are useful quantities to monitor, particularly in the southern Indian Ocean, but other quantities such as heat transports and the thermohaline circulation may be less useful because of poor signal-to-noise ratio.

### ***The ocean carbon cycle***

The release of dimethylsulphide (DMS) by plankton has been suggested as part of an important feedback mechanism on climate. DMS released from the ocean produces sulphate aerosol in the atmosphere which modifies the properties of clouds; this changes the amount of solar radiation reaching the ocean and affects plankton growth. The HadCM3 model has been adapted, using the Hadley Centre Ocean Carbon Cycle Model (HadOCC), to include a representation of these processes. Results from simulations (Fig. 63) suggest that climate is sensitive to DMS emissions.

## Ocean observations — Argo

We have begun the UK contribution to Argo, an international programme to establish a global array of profiling floats to measure the temperature and salinity of the upper 2,000 m of the oceans. The work is being funded by the Department for Environment, Food and Rural Affairs, the Ministry of Defence and the Natural Environment Research Council. Southampton Oceanography Centre, the British Oceanographic Data Centre and the UK Hydrographic Office are also participating.

The observations from Argo will provide improved data for assimilation into FOAM and our coupled seasonal prediction models. During the spring, eight floats were deployed in the North Atlantic (five in the Irminger Basin, one in the Iceland Basin and two in the Rockall Trough). Argo measurements of sub-surface temperature and salinity will assist in early detection of climate change in the ocean, and plans include deployment of floats in the southern Indian Ocean, where a freshening of the intermediate waters is believed to be a signal of man-made climate change.

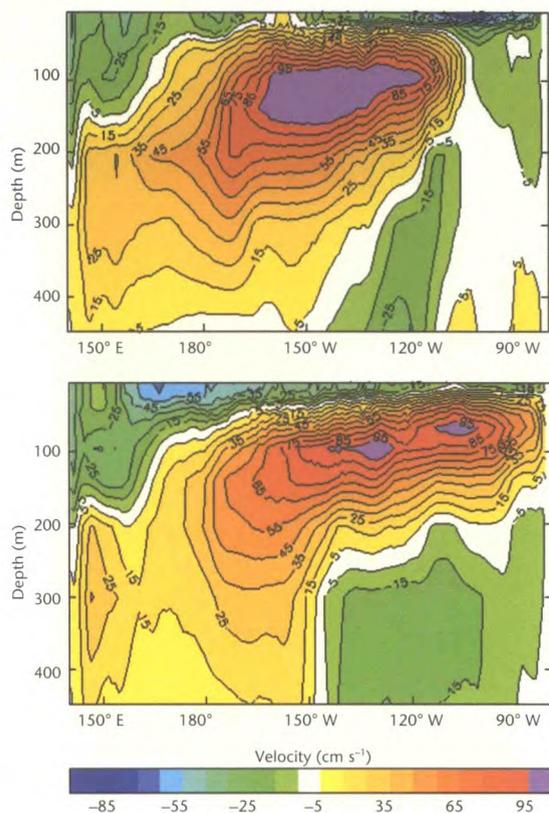


Figure 62. Zonal currents in the equatorial Pacific from analyses that assimilate ocean temperature observations using (a) the standard method and (b) the new pressure correction technique.

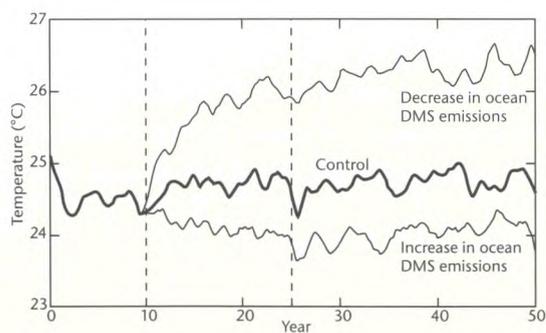


Figure 63. Average SST (°C) between 30° N and 70° N in the North Atlantic. The thick line shows the control run, the thin lines two experiments in which emissions of DMS were adjusted. The temperature takes around 15 years to settle to a new state after the DMS change is initiated.

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## Acronyms

ADAS	Agricultural Development and Advisory Service	METAR	Meteorological Airfield Report
AMDAR	Aircraft Meteorological Data and Reporting	METOP	Meteorological Operations Satellite
AMSU	Advanced Microwave Sounding Unit	MIDAS	Met Office Integrated Data Archive System
ARIES	Airborne Research Interferometer Evaluation System	MOMIDS	Met Office Military Information Distribution System
ARM	Atmospheric Radiation Measurement (USA)	MORSN	Met Office Remote Sites Network
ASAP	Automated Shipboard Aerological Programme	MORST	Met Office Road Surface Temperature
ATL	Automated Tape Library	MOSES	Met Office Soil Evaporation Scheme
ATOVS	Advanced TIROS Operational Vertical Sounder	MPI	Max Planck Institute (Germany)
AVHRR	Advanced Very High Resolution Radiometer	MPS	Marine Production System
BECMG	'Becoming' code on TAF	MSG	Meteosat Second Generation
BUFR	Binary Universal Form for the Representation of meteorological data	NAME	Nuclear Accident Model
CEH	Centre for Ecology and Hydrology	NAMIS	NATO Automated Meteorological Information System
CFC	Chlorofluorocarbon	NAO	North Atlantic Oscillation
CRM	Cloud-resolving Model	NATS	National Air Traffic Services
DBMS	Database management system	NETA	New Electricity Trading Arrangements
DfiD	Department for International Development	NETCEN	National Environmental Technology Centre
DLR	Deutsches Zentrum für Luft- und Raumfahrt (Germany)	ODBC	Open Database Connectivity
DTI	Department of Trade and Industry	OPS	Offshore Production System
ECMWF	European Centre for Medium-range Weather Forecasts	RMDCN	Regional Meteorological Data Communications Network
ENSO	El Niño Southern Oscillation	RPC	Remote procedure call
ERS	European Remote-sensing Satellite	RSOA	An optimal averaging technique
EWP	England and Wales Precipitation	RST	Road surface temperature
FCCC	Framework Convention on Climate Change	SADIS	Satellite Distribution
FIRE	First ISCCP Regional Experiment	SAF	Satellite Application Facility
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-based flood Forecasts	SAMOS	Semi-automatic Meteorological Observing System
GCM	General Circulation Model	SAR	Synthetic Aperture Radar
GCSS	GEWEX Cloud System Study	SRES	Special report on emissions scenarios
GERB	Geostationary Earth Radiation Budget	SSFM	Site-specific Forecast Model
GEWEX	Global Energy and Water Cycle Experiment	SST	Sea-surface temperature
GOOS	Global Ocean Observing System	TAF	Terminal Aerodrome Forecast
GRAS	GNSS Receiver for Atmospheric Sounding	TEMPO	'Temporary' code on TAF
IASI	Infrared Atmospheric Sounding Interferometer	UMETRAC	Unified Model with Eulerian Transport and Chemistry
IPCC	Intergovernmental Panel on Climate Change	UTC	Universal Time Co-ordinated
ISCCP	International Satellite Cloud Climatology Project	WAFS	World Area Forecast System
LEM	Large Eddy Model	WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe
LES	Large eddy simulation	WAN	Wide Area Network
MASS	Managed massive data storage	WGI	Working Group I (of IPCC)
		WWRP	World Weather Research Programme



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