The Met. Office

Scientific and Technical Review 1996/97

Excelling *in weather services*

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Scientific and Technical Review 1996/97

An Executive Agency of the Ministry of Defence

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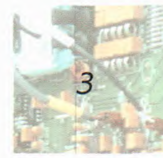


Chief Executive's review

Introduction

Highlights of performance

A technician at work on a laser cloud-base recorder.

Chief Executive's review (taken from Annual Report and Accounts 1996/97)

Introduction

While our administrative and financial structure changed on 1 April 1996 when we became a trading fund, The Met. Office remains a world-class, science-based organization working within the UK Government. We also continue to work with the intergovernmental organizations at the European Centre for Medium-range Weather Forecasts and EUMETSAT, the European meteorological satellite organization.

Our central aim is to develop capabilities in meteorological forecasting so as to deliver high-quality, cost-effective services to public and commercial customers in the UK, Europe and elsewhere.

It has been my privilege to lead the excellent and committed staff of The Met. Office since 1992. This, my last, Annual Report sets out the progress we have made during 1996/97.

Highlights of performance

Last year we were set key performance targets designed to stimulate improvement in our financial position, our efficiency and our quality of service. We recognized that these were challenging and that one or more might be missed. I can report that we met our financial targets and an administrative target to develop a new method for efficiency measurement. However, we missed our two 'quality of service' targets, one of which was to reach at least twelve of our fifteen, largely pass or fail, sub-targets defined in terms of levels of accuracy and timeliness of forecasts. In the event, we achieved ten. Work continued during the year to improve the bases on which we measure our performance and the measurement process itself. As a result, from 1997/98 onwards we are adopting targets based on an index approach which provides better average measures of performance.

Although we also did not reach the second of our quality targets, which was to improve the accuracy level of forecasts by 2% during the year, we maintained our performance relative to other centres. Indeed, our overall performance in forecasting for one to three days ahead continued to be among the best in the world, a result of our sustained research, focused on numerical weather prediction (NWP). We expect continued improvement as a result of the opportunities provided by our new supercomputer and also from research advances. Of particular note is our international research collaboration, such as the 15-nation study of weather fronts over the Atlantic undertaken with four research aircraft, including the Meteorological Research Flight's C-130, and the study programme on a new mathematical approach to NWP involving 200 specialists at the Isaac Newton Institute at Cambridge.

Our other planned programmes to develop our technological infrastructure – to improve efficiency and services to our customers – have delivered good results. In particular, some should lead to new opportunities for business through collaboration with other meteorological and environmental organizations. Forecasters in our National Meteorological Centre at Bracknell are now using our own unique display system to make more thorough use of computer-generated information, satellite data and other observations. The introduction of our Weather Information Network is enabling us to distribute data and centrally prepared guidance more quickly, accurately and conveniently to our staff around the UK and abroad. These developments underpinned the rationalization of our forecast production system and also our bid to

work with the Thailand Meteorological Department, along with other organizations, in the development of their service. We are proud to have been selected to carry out this programme and are working to ensure that this kind of collaboration will continue with them, and other meteorological services, in future.

The Observations Division of The Met. Office has a vital role in meeting our corporate efficiency and quality goals. Last year saw the progressive introduction of automated observing systems and the use of new techniques for upper-air soundings. It has been gratifying to hear from highway engineers and hydrologists how our weather radar data, delivered through the developing Nimrod system, are leading to better short-range forecasts.

The communication of observational data, collaboration in research and, increasingly, more-efficient sharing of infrastructure costs, are the primary outputs we expect from our international activities. We have continued to press in Europe for the initiation of the 17-nation European polar satellite programme to complement that of the USA, on which Europe continues to rely heavily. The Met. Office contributed to the programmes and initiatives of the World Meteorological Organization, ranging from meteorological services in urban environments, through TV training at the BBC Weather Centre, to the effective co-ordination within The Climate Agenda of the related activities of many UN agencies and scientific organizations.

The services provided to defence, aviation, the public service and commercial customers improved and were organized more tightly. Most required negotiation of new contracts. The Core Customer Group has worked well to ensure that the £70 million Core activities of The Met. Office are effective and will be funded at an appropriate level over the long term. We have greatly appreciated the efforts of the Group's members, representing the Civil Departments, MoD budget holders and the Civil Aviation Authority.

Thanks to our overall performance and much extra commitment by staff, our first year's income as a trading fund was in excess of £150 million. In particular, vigorous efforts by forecasting staff at all our locations led to the £5.3 million contribution, the largest yet, by the commercial arm of the Services and Business Division to the Core activities and central overheads of the Office. I am particularly pleased to be able to report that the trading fund has got off to such a satisfactory financial start. This is the sound foundation we needed in preparation for the very substantial capital investments we shall need to make in the future; equally good results should not be expected every year.

Looking ahead

But we start the next trading year from a strong position. Our tasks for 1997/98 are to strengthen relationships with our customers, to raise the quality of our services and to improve the value for money they represent. I am confident that my successor will ensure that these established expectations of The Met. Office are met.

C. Walker

Observations

A Severe Icing Environment Synoptic Automatic Weather Station (SIESAWS) on Cairnwell, Braemar, Scotland.

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

to provide input to Numerical Weather Prediction (NWP) and other forecasting methods;

to monitor the weather, e.g. to warn of hazardous conditions;

to verify the accuracy of forecasts;

to determine the variability of climate in space and time.

A variety of space, surface and airborne systems have to be used to make the necessary measurements. An important activity is improving understanding of the contribution of different types of observation to forecast accuracy.

Observing networks

Network studies

Impact studies have been carried out to determine the effect of surface observations on Nimrod (the fully automated short-range precipitation forecasting system) and the mesoscale model. The intention was to assess the extent to which the requirements for observations can be met by automatic observing systems to help when defining station networks.

For Nimrod, it was demonstrated that removing cloud observations has an increasingly detrimental impact on the analysis and prediction of low cloud. Visibility assessments indicated that observation distribution is more important than observation quality.

The mesoscale model cases showed that cloud and/or present weather reports can be expected to have a significant benefit on forecasts of rain in up to 5% of cases with widespread rainfall. Networks using either manual or automatic cloud observations gave similar skill.

Relationships between spacing of climate stations and the error of interpolating for temperature, sunshine and rainfall were studied. The method attempts to take account of topographical, coastal and urban influences.

Climate data

A climate archive is maintained containing observations from the land networks, marine platforms and upper-air stations. The data are subject to a wide range of quality checks, and estimates are provided where values are considered to be in error or are missing. A project to transfer the archive to a relational database is nearing completion.

As one of two Global Collecting Centres for marine climatological data established by the World Meteorological Organization (WMO), 1.8 million observations were received and processed in 1996 compared with 1.3 million in 1995.

Marine data

There are 600 ships, rigs and platforms in the UK Voluntary Observing Fleet. Port Meteorological Officers continued to liaise with this fleet, as well as visiting ships of other nationalities, to maintain observational standards. The Ocean Weather Ship *Cumulus* was withdrawn in June 1996, following studies which showed that the considerable expense could not be justified by the relatively few occasions when the forecast might be expected to benefit.

The Met. Office also operates 10 open-ocean buoy stations, and three inshore buoy stations. In early November, the open-ocean buoy on the K3 station, to the west of Ireland was lost, probably run down by a ship. As a result the location of this station is to be moved in Spring 1997 to 53.5° N, 19.5° W, to reduce the possibility of damage or loss.

Discussions are now taking place to maximize the usefulness of open-ocean buoy data by automatically selecting the hourly synoptic observation from the data provided by duplicated sensors. Code changes will also be necessary to ensure that hourly, rather than six-hourly, observations will be available for use in the NWP models. A feasibility study is in progress to obtain spectral-wave data from the buoys. It is hoped that these data will be available operationally within two years.

Upper-air data

Eight upper-air stations continued to operate during the year making six-hourly soundings of pressure, temperature and humidity with winds determined by Navigation Aid (NAVAID). The sites are multi-functional with other commitments including ozone measurements, equipment trials, surface observing, and services to military and civil aviation. In early 1997 the UK network was the main land-based sounding contributor to the Fronts and Atlantic Storm Track Experiment (FASTEX). Sounding co-ordination for the 10 countries involved was also our responsibility. The Met. Office is engaged in the test and evaluation of commercial sondes. With the demise of the Omega tracking system in Autumn 1997, special effort has been devoted to testing and evaluating Global Positioning System wind-finding sondes to meet the requirement in the Falkland Islands, St Helena and Gibraltar. Increased effort has been required for negotiations to retain much of the current radio-frequency spectrum for radiosonde use both in Europe and worldwide as commercial pressure increases.

Ozone data

Ozone sondes were flown to measure vertical profiles of ozone at Lerwick and total ozone was measured at Camborne and Lerwick on behalf of the DoE. As part of a European study, Lerwick made additional flights during the winter from which ozone depletion could be calculated. A marked decrease in total ozone was observed in early March associated with the movement of a major cold trough in the stratospheric circulation and probably some ozone depletion (Fig. 1). Weekly bulletins were issued from January to April during the period of maximum ozone depletion.

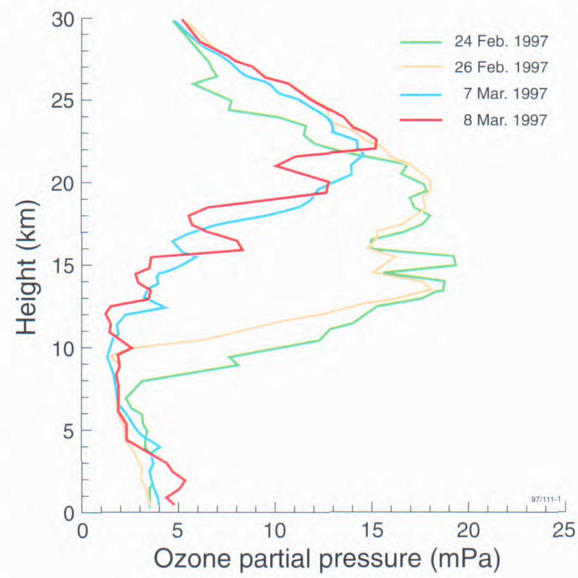


Figure 1. Lerwick ozone-sonde ascents.

New technology

Automation

The programme of automation has continued to deliver improvements in cost effectiveness. There are now 80 operational Semi-Automatic Met. Observing System (SAMOS) stations, with 11 new installations and one equipment move completed during the year. Twenty-eight of these SAMOS provide reports out-of-hours from stations which are not fully manned, and 17 of them operate as automatic stations with no manual input to the observations.

The laser cloud-base recorder (LCBR) and visiometer installation programmes have continued with the UK network totals now 95 LCBRs and 90 visiometers. The number of sites where the LCBR and visiometer outputs are integrated into SAMOS, enabling automatic readings of cloud and visibility to be incorporated into synoptic reports, has risen to 39.

Software has been developed to enable a commercial present-weather sensor to be interfaced with SAMOS, and an algorithm is being developed to integrate all available sensor information into automatic present-weather reports. Trials of remote-controlled closed-circuit television are taking place at five operational sites, from Devon to the Highlands. This technology has significant potential for remote weather observation, and these trials will assess its impact on both forecasting and observing.

A full aviation version of the Computer-Aided Meteorological Observing System (CAMOS), the commercial variant of SAMOS, was purchased by Lithuania for use at Siauliai airport. The Irish Meteorological Service also expanded their network with the purchase of two more systems.

Aircraft observations

The Met. Office continued to support the WMO Aircraft to Satellite Data Relay (ASDAR) system. Out of 19 units supplying data to Bracknell, 10 are installed on British Airways aircraft. Two of the UK ASDARs were supplied to the Mauritius Met. Service under the WMO Voluntary Co-operation Programme and are now fitted in Air Mauritius aircraft. The requirement to receive 90% of reports from 15 aircraft within 115 minutes of observation time was met. KLM airlines in collaboration with the Dutch Met. Service, KNMI, has developed a new potentially cheaper solution known as AMDAR (Aircraft Meteorological Data And Reporting). This is a software system which simulates ASDAR reports but is downloaded via VHF communication links rather than via satellite. The UK Met. Office is currently liaising with British Airways and KNMI/KLM to install an AMDAR system for evaluation.

Wind profiler

The Met. Office is investigating the use of wind profiler radars to improve the coverage and cost-effectiveness of operational wind measurements in the troposphere. During 1997 an international experiment (CWINDE-97) enabled wind measurements by various European radars to be exchanged for the first time and displayed centrally for access by users. The observations will be used to examine their usefulness for operational meteorology. The Met. Office provided the management for the project, developed the real-time data displays and supervised the initial archiving of data.

The Aberystwyth Mesosphere-Stratosphere-Troposphere radar operated jointly by the Natural Environment Research Council, the University of Wales and the Daresbury Rutherford Appleton Laboratory, and supported by The Met. Office, provided measurements throughout the experiment. In addition, an ultra-high frequency (UHF) wind profiler was installed at Camborne, Cornwall in February 1997 for further evaluation of measurements in the lower layers of the troposphere. Shortly after the UHF wind profiler operations commenced, serious flooding occurred on the Lizard peninsula. The wind measurements by the radar during this period can be seen in Fig. 2.

Weather radar

The 15 weather radars reliably provided raw rainfall data throughout the year. The only exception has been the radar at Shannon, operated by Met. Éireann, which was off the air for a substantial part of the year while it was being replaced.

Continuing demands for improvements in radar-rainfall estimates, and a consistency in performance, have led to increased monitoring and verification of the radar's performance and data quality. Higher standards of routine maintenance are being devised utilizing more-sophisticated test and calibration equipment.

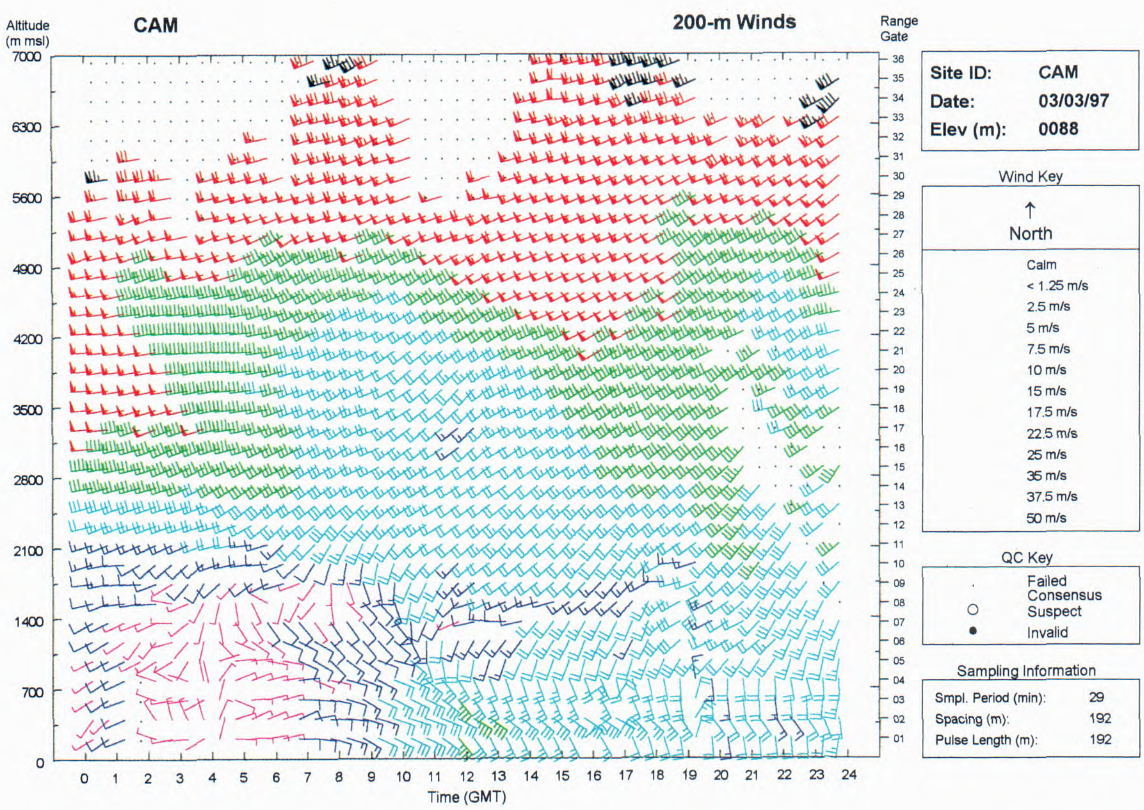


Figure 2. The wind measurements by radar during 3 March 1997.

A programme of tasks has been identified for the future maintenance and planned development of the radar network. These have been devised in collaboration with the Environment Agency, our major partners in England and Wales, with a view to establishing a Memorandum of Understanding in 1997 on commitment and potential joint funding over the next 10 years.

The Met. Office is a partner in the DARTH project (Development of Advanced Radar Technology for application to Hydrometeorology), which is funded by the Commission of the European Community and co-ordinated by the University of Essex. The role of The Met. Office is to assess the potential benefits of new radar measurement techniques, such as Doppler and polarization-diversity, to operational C-band radar.

An automated radar-based forecast system for thunderstorm warnings, the GANDOLF system (Generating Advanced Nowcasts for Deployment in Operational Land-surface Flood forecasting) is being developed in partnership with the Thames Region of the Environment Agency. GANDOLF uses a conceptual model of a thunderstorm and combines this with real-time radar data to provide high spatial and temporal rainfall warnings direct to the Thames flood-control centre. This work is due to be completed in 1997. Fig. 3 gives an example of the GANDOLF classification of development within a thunderstorm.

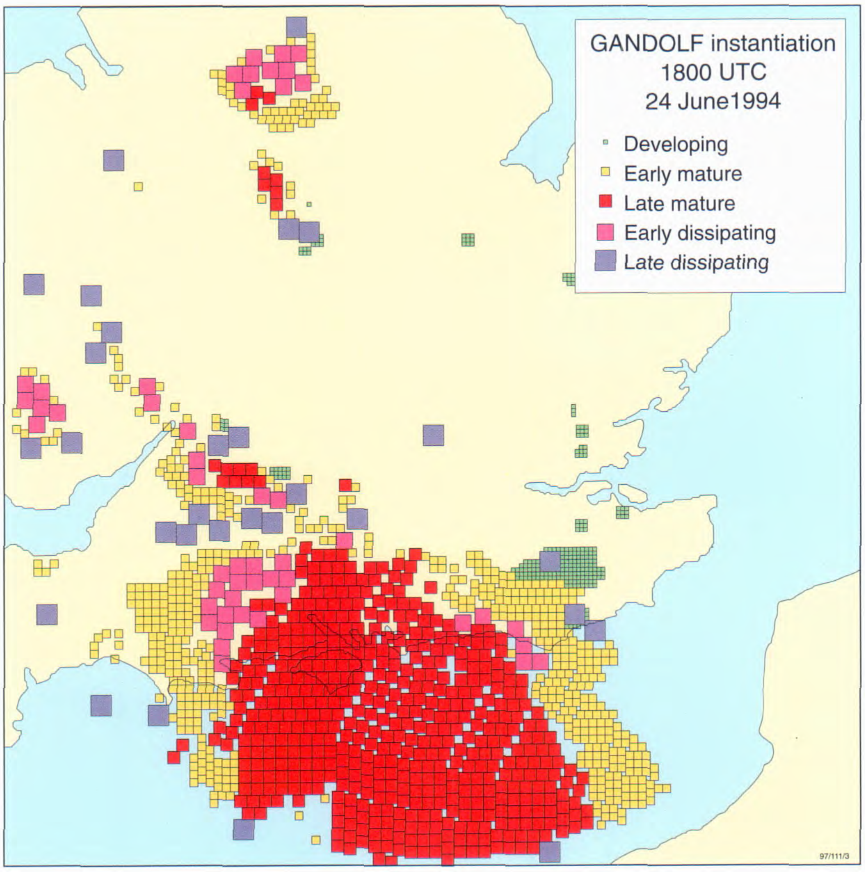


Figure 3. GANDOLF classification of development within a thunderstorm.

Space-based observing

The Met. Office increasingly relies on the assimilation of space-based observations into the NWP models. These observations, which are of particular importance in otherwise data-sparse regions, provide a consistent source of global data with a horizontal resolution commensurate with the model.

New satellites

EUMETSAT is the focus for operational meteorological satellites within Europe and currently operates the Meteosat programme. The Meteosat Second Generation (MSG) programme continues in its final design and build phase. Industrial MSG studies had predicted noise levels of up to twice the specification for certain critical MSG channels. However, under contract to EUMETSAT, the Met. Office demonstrated the feasibility of improving noise on these channels by factors of 1.4–1.7, while simultaneously enhancing the value of the information for end-user applications. As a result, the infrared IR 3.8 channel was changed, despite the well developed status of the programme – a considerable achievement. MSG will provide data at 15-minute intervals from 12 spectral channels. One will be a high-resolution (1 km) broadband visible channel, the others will include imagery in the visible, IR, water vapour, CO_2 and ozone bands with a 3 km resolution.

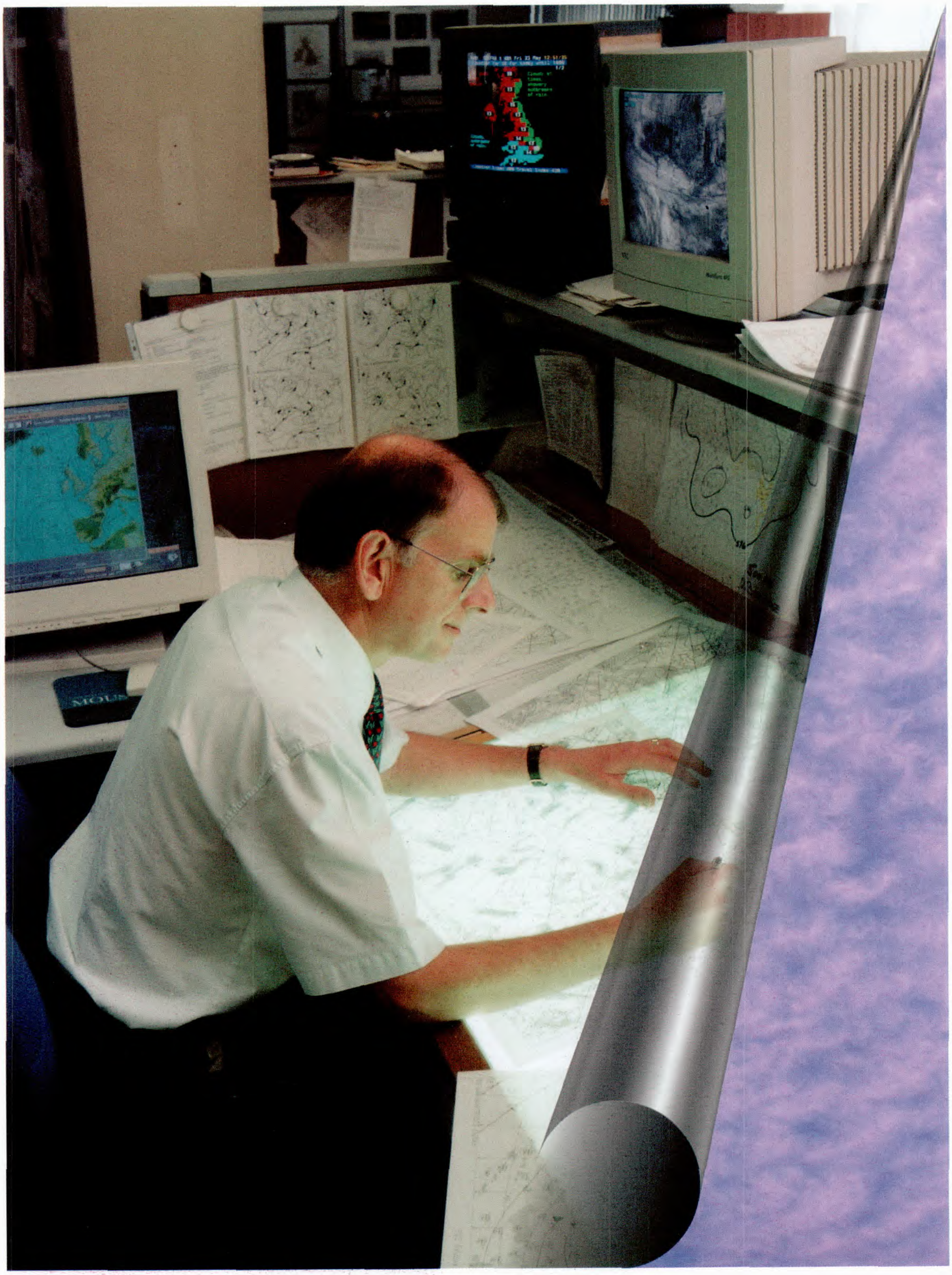
The planning of the programme for the EUMETSAT Polar System continued in both EUMETSAT and the European Space Agency. This is to provide, in conjunction with the USA, polar orbit data from 2002 to 2016.

New instruments

The Met. Office has been playing an important role in the development of the new Infrared Atmospheric Sounding Interferometer (IASI). This has included the development of a simulator instrument, the Airborne Research Interferometer Evaluation System, which has been flying on the Met. Research Flight C-130 aircraft during the year. Assessment of the IASI information content has also been studied. This has demonstrated how certain specifications can be relaxed, and end-user data-volume reduced, without affecting the utility of IASI data.

The Met. Office has provided microwave humidity sounding instruments (AMSU-B) for installation on polar-orbiting satellites NOAA-K and NOAA-L. A further AMSU-B is in storage ready for integration with NOAA-M. NASA has signed a contract with The Met. Office for the upgrade of the AMSU-B engineering model to flight-worthy status. This refurbishment is due to be completed by February 1998.

Development of the supporting science for the AMSU instruments has continued, using a pair of microwave radiometers fitted to the C-130 aircraft. These radiometers operate in the atmospheric windows corresponding to the channels used by the AMSU instruments. Field measurements have included a series of campaigns to characterize the microwave properties of various soil types, under differing soil moisture conditions.



Met. Office Photographic Services

Operational Services

The Chief Forecaster in the National Meteorological Centre, Bracknell.

Information technology

The Cray T3E supercomputer

In 1995 a requirement was identified for additional computing power to run large-scale numerical models in support of The Met. Office's forecasting and research activities. After a competitive procurement, a contract was awarded in April 1996 to Cray Research for the supply of a T3E supercomputer, to replace the existing Cray C90 machine. The new computer will provide at least a fivefold increase in computing power over the C90.

Previous Met. Office supercomputers have used a parallel vector processor architecture. In contrast, the T3E uses a massively parallel processor design that uses hundreds of processor elements (PE), each consisting of small, relatively cheap but fast CPUs and local memory.

The new machine has been delivered and will be installed in phases. Initial stages were planned to enable the transfer of The Met. Office's application codes; this allows the early transfer of the Unified Model (UM) which is used for weather forecasting and climate research purposes. The later phases with a 696 PE configuration will provide the capacity to run the required workload.

The first set of equipment was installed in October 1996. Good progress has subsequently been made with transfer of the UM and by the end of the year, routine tests of the models were under way. After The Met. Office has taken delivery of the final parts of the T3E in April 1997, the whole workload will be transferred to the T3E. Significant efforts were made, working with the supplier, to ensure that the T3E provides the facilities and reliability that The Met. Office requires as a foundation to many of its operational services.

IT review

A strategic review of information technology (IT) in The Met. Office was completed in August 1996. The Management Board recognized the progress made in recent years but agreed that some rationalization of IT provision would be beneficial for the business. Study groups were set up to look at the proposals and make detailed recommendations. Some aspects of computer support and maintenance are already well organized and managed. As an example, the Single Source Maintenance contract that started in late 1993 provides substantial savings compared with the many smaller contracts it replaced. However, help desks in The Met. Office are fragmented and poorly co-ordinated with the result that many of the common problems are not identified or captured.

The review concluded that no single approach to the provision of IT services in The Met. Office can meet the full requirement cost-effectively. To maximize the benefits to the organization, different approaches are required for different aspects. A common theme is the need for better definition of responsibilities and relationships between different areas of The Met. Office, and a clearer identification of costs. A study to identify the requirement for the help desks has been completed. This information will be used in implementing a more responsive and cost-effective process for managing calls from both the external and internal users of Met. Office services.

As a result of this review, many aspects of IT services and their management will be adjusted during 1997. This will ensure a sharper focus on serving the needs of customers and users, and will improve productivity throughout the organization. The review also stressed the importance of some aspects of technical strategy. For example, it is essential to continue to reduce the diversity of types of IT equipment and to improve the robustness of systems, since both lead to reduced support costs. Some of these technical changes will take several years to complete but the result will be to provide IT services more efficiently and effectively, consistent with business needs.

Networks

- *Weather Information Network (WIN)* The Met. Office uses telecommunications networks for collecting observations and transferring data between sites; this network also plays a part in delivering services to customers. The WIN will replace a number of existing analogue and digital networks with a single, resilient, high-speed digital network.

  The WIN has three main components: the main network store-and-forward nodes, which allow identical streams of data to be moved to many locations without overloading the network; the general network capacity provided by the Defence Packet Switched Network; and network nodes. The network nodes, known as Outstation Communications Processors (OCPs), are provided at most outstation sites. The major part of WIN was installed and commissioned during the year, including all the main nodes, plus around 75% of the nodes requiring OCPs. Installation of the remaining equipment, including overseas locations, and overall acceptance of the network, is planned for 1997.

  The new network is designed to improve both reliability and capacity, while substantially reducing overall costs. The benefits of increased capacity have been seen for those parts of the network currently installed but there has been some initial disappointment about the levels of reliability achieved. Substantial effort was necessary to ensure that the equipment (both hardware and software), procedures and staff training were able to provide the required level of reliability.

- *Global Satellite Data Network* Many national meteorological services (NMSs) operate satellite ground stations that are able to receive broadcasts from their nearest geostationary satellite. Such 'local' reception delivers timely images of their own geographic area, which is sufficient for the majority of NMSs. For those with wider or global interests, some form of communications relay is required so that data from other satellites can be obtained. In the past such relay systems have been built on an ad hoc basis.

  The Met. Office has taken a lead in defining and developing a global computer communications network; allowing access to satellite-image data from all the openly available geostationary weather satellites. The system allows data to be exchanged between partners, for example GOES-E and GOES-W data received in Montreal, Meteosat data received in Bracknell or Lannion (France), and data from Japanese Geostationary Meteorological Satellite (GMS) received in Melbourne. Current participants are the UK Met. Office, the Canadian Meteorological Centre, the Australian Bureau of Meteorology, the Japanese Meteorological Agency, Météo-France, the European Centre for Medium-range Weather Forecasts and EUMETSAT.

The network uses the same standard Transmission Control Protocol/Internet Protocol (TCP/IP) as the global Internet, but over a private network. The private network allows the traffic to be controlled so that all the partners are provided with a pre-defined level of performance; this could not be guaranteed on the open Internet. By sharing the costs of bilateral links among the partners, it was possible to build a cost-effective satellite-image delivery system.

The network is being used to help characterize the next generation of networks, as well as serving a valuable purpose for satellite-image data exchange. New generations of networks will be required to provide a greater range of functions than the existing GTS.

Satellite data processing – Autosat-3

The commissioning of Autosat-3 was completed. This is the central system which is responsible for the reception of raw satellite data and the generation of image-based products. Autosat-3 processes locally received data from Meteosat and the NOAA polar-orbiting series of satellites, together with remotely received data from the GOES-E, GOES-W and GMS satellites.

The system is based around four standard UNIX workstations and is much simpler and cheaper to operate and maintain than its predecessor which was based on mini-computer technology of the 1980s. The system is also more modular and takes full advantage of new computer technology. For example the system state is monitored using Web technology.

The National Meteorological Centre

The Central Forecasting Office (CFO) at Bracknell has historically been a global analysis centre, a guidance centre for outstations such as Weather Centres, and a provider of forecasting services and warnings to ensure safety on land, sea and air.

On 2 December 1996, the CFO became the National Meteorological Centre (NMC), in line with the ideas contained in an internal Forecasting Rationalization report. This report recommended which forecasting products should be produced centrally and which are more suitable for producing locally.

This name change after more than 50 years is part of the move towards a more-efficient and up-to-date working environment, with a complete refurbishment now under way. The Met. Office is now focusing the resources of outfield offices to the commercial and military work best done locally, i.e. Local and Regional Production Units, and the resources of the NMC to the work best done centrally. There will soon be three main Central Production Units (CPUs) in the NMC (Fig. 4).

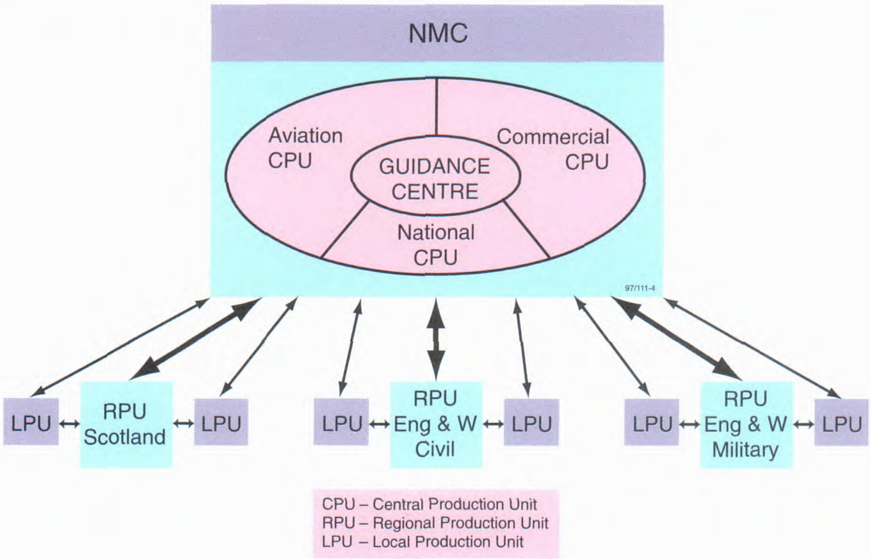


Figure 4. The three main Central Production Units (CPUs) in the NMC.

Aviation CPU

This unit will be responsible for all aviation-related products, ranging from local forecasts in southern England to near-global high-level significant weather charts. It will also produce the main guidance and warnings for aviation. The production of aviation forecast charts (AIRMETs) and warnings of hazardous weather (SIGMETs) has moved to this unit from Glasgow and Manchester, and the responsibilities of Frankfurt and Toulouse Regional Area Forecast Centres also now form part of this CPU. See under **WAFC responsibility** in the **Forecasting Systems and Forecasting Products** section.

National CPU

This unit will be involved with UK forecasting including some Public Met. Service (PMS) scripts and other media work. This unit will also take over the current responsibility for co-ordinating severe weather warning messages.

Commercial CPU

This unit provides forecast services to order for any part of the world (including some UK work) – both onshore and offshore – for up to 10 days ahead. Ship routeing and marine forecasts with professional nautical advisory services will also be provided.

These production units will liaise closely with the Guidance Centre which will lie at the heart of the NMC. The Guidance Centre, staffed by the Chief and Deputy Chief Forecasters will become responsible for all guidance to all UK outstations in textual, graphical and verbal form. The NMC will be responsible for other PMS work such as the Storm Tide Warning Service, sea swell and emergency response warnings.

The output from the NMC is also under review following a customer satisfaction survey of all its internal customers, such as Weather Centres and Defence outstations.

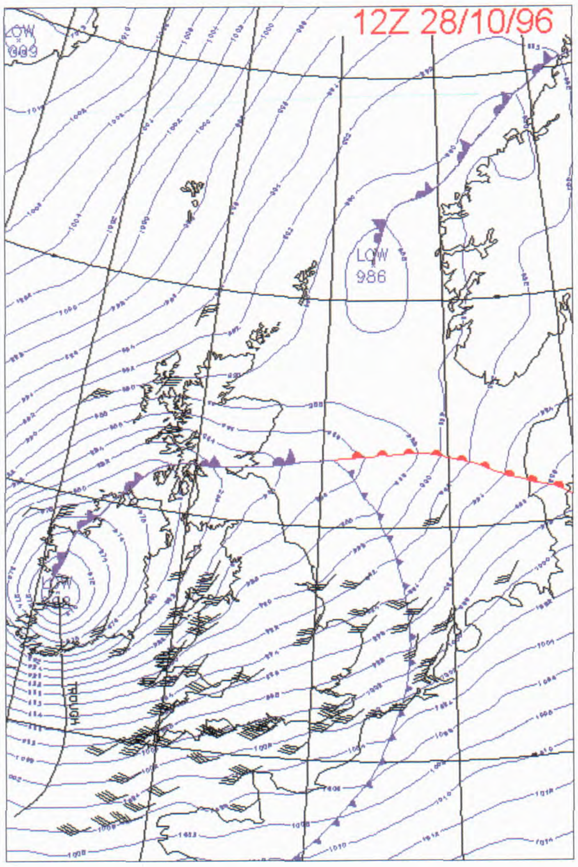


Figure 5. The position of Lili on 28 October 1996.

Medium-range guidance

A fundamental rethink of the medium-range guidance (forecast period from about two to 10 days) to outstations is under way as part of a project to promote the use of probability forecasting. This will enhance the existing guidance with new additional products created for days four and five. These will show for example the probabilities of alternative large-scale solutions, a range of tracks and intensities of low pressure areas, including a most likely solution and point probabilities for specific weather elements.

Workshops

NMC workshops are a forum where forecasters and model developers work together on 'post-mortems' of interesting weather events and they continue to provide important lessons for both the forecasters and the Numerical Weather Prediction (NWP) Division research and development staff. During the autumn a study was made into the severe gales of Monday 28 October 1996, caused by the remnants of hurricane 'Lili'. The workshop studied the forecasts related to the movement of Lili across the British Isles on this date (Fig. 5). The former hurricane produced severe gales across Ireland, Wales and southern England, with gusts to over 60 m.p.h. in many places and to over 70 m.p.h. in upland and coastal regions, with many reports of damage to trees and to property close to the coast. Although the event was successfully forecast in the short term, it was poorly forecast by most model runs in the medium and longer term and several lessons were learnt that may be of benefit in the future. It also showed that automatic bogusing of tropical storms (insertion of 'pseudo-observations' to locate the storm) is beneficial and can be very important in data-sparse regions.

NMC workstation system

To enable the CPUs and Guidance Centre to operate efficiently and to their full potential, a whole range of new analysis and production software is being developed for use on Horace, the operational NMC workstation system. This will enable many tasks, for example the creation of the analysis, forecast charts and many aviation products, to be done entirely on screen with the more routine elements done automatically for the forecaster. An example of this 'on-screen analysis' is shown in Fig. 5 for the 'Lili' storm. This chart has been quality controlled and smoothed to allow for erroneous data and can be compared with the chart before quality control occurred, as shown in Fig. 6. The 'bull's-eyes' represent erroneous observations of pressure and the lack of smoothing (to accommodate minor adjustments) results in an unrealistic looking pressure field. Seeing also **Horace** in the **Forecasting Systems and Forecasting Products** section.

OPUS

In addition the Outstation Production Unified System (OPUS) will be installed for the first time within the NMC, initially going into the National and Commercial CPUs. This system will allow the NMC to be more flexible in its dissemination of forecasting products.

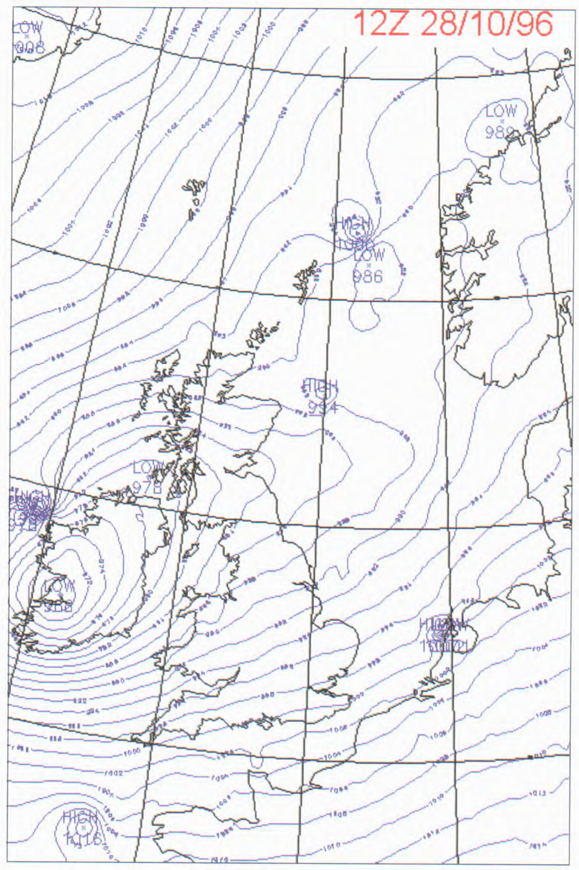


Figure 6. The pre-quality control checked chart.

Forecasting Systems and Forecasting Products

The operational NWP system

Most of The Met. Office's forecasting processes are based on its operational numerical weather prediction system. There has been a continued improvement in the quality of the products generated. This improvement was helped by refinements in the scientific formulation of the models, and by better use of the observational data in defining the initial state of the atmosphere in those predictions.

Work is now under way to migrate the operational NWP suite to the recently acquired Cray T3E supercomputer. By the end of the period the global model was running reasonably reliably, and the trial suite is now running with observation processing, continuous global model assimilation and verification. This work is a necessary step towards the implementation of more-accurate operational NWP models later in 1997.

Nimrod

Nimrod is the very-short-range forecasting system which has been operational since November 1995. Its forecasts cover the UK and immediate area; fully automated forecasts are produced every 30 minutes for six hours ahead.

The rainfall forecasting component has continued in operational use with a high level of reliability. Improvements were made in the removal of spurious echoes, to the tracking of embedded showers within broader rain areas, and in the retention of rainfall structure in the later part of the six-hour forecast. Diagnosis of hail was improved for the precipitation-type product by separating soft hail from true hail. Melting of soft hail is then diagnosed if the temperature is high enough. Related algorithms were used to diagnose lightning and thunderstorm-initiated wind gusts.

The cloud analysis and forecast cycle has been run throughout the year. Routine assessments show significant predictive skill, but the results fall short of current manual forecasting capabilities. A weakness in the use of Meteosat imagery has been the poor height assignment of thin cirrus cloud. A technique for dealing with this was developed using images from the water vapour channel. A trial of the technique showed useful improvements in height assignment, provided the cloud was not too thin.

After several years' development, a fog nowcasting system was implemented in October. The analysis uses Meteosat images by day and NOAA–AVHRR (Advanced Very High-Resolution Radiometer) images by night, to diagnose potential fog areas; it then calibrates the visibility within these areas using the nearest available surface reports. The forecast makes use of local trends of heating and moistening from the mesoscale model, and also uses the model aerosol prediction.

An assessment of the skill of TREND forecasts for Heathrow and Gatwick, prepared from Nimrod low-cloud and visibility forecasts, was carried out in the NMC during March. This showed that Nimrod produced good forecasts on most days, but made about twice the number of errors as a human forecaster.

Tropical cyclone forecasting

The use of advisory messages received from tropical cyclone warning centres on the location of individual cyclones was automated into the NWP system. The quality of the resulting predictions is commendably high. Following a request from the National Hurricane Center in Miami, advisory messages produced by The Met. Office's forecasting system are now being issued for predicted 12-hourly positions of tropical cyclones.

Ensemble predictions

The operational production of ensemble forecasts by the European Centre for Medium-range Weather Forecasts (ECMWF) was extended from a 33- to a 51-member scheme during the year. The necessary revisions of the products provided to the NMC were successfully achieved within a few days. The enhanced service is designed to provide more-accurate guidance for medium-range forecasting, in both the accuracy of individual predictions and in the confidence to be placed in the 51 differing atmospheric evolutions which are predicted. Additionally, two workstations were commissioned to process the ECMWF products more efficiently and reliably.

WAFC responsibility

The provision of World Area Forecast System (WAFS) products, global, regional, and national, comes from three sources: World Area Forecast Centres (WAFCs); Regional Area Forecast Centres (RAFCs) and National Forecast Centres within each International Civil Aviation Organization (ICAO) state. ICAO has embarked on a long-term streamlining of this process and has now implemented an integrated distribution system which combines both terrestrial and satellite communications. The two WAFCs are Bracknell ('London') and Washington DC; they communicate with each other, and with the RAFCs and National Forecast Centres, via the Global Telecommunication System (GTS) and by satellite.

The long-term aim of the WAFCs is to provide and distribute global data, in the form of upper wind and temperature grid-point data, and charts and global Significant Weather (SIGWX) charts in a digital format, for flight planning purposes. This aim has not yet been fully achieved. The WAFCs provide and distribute global grid-point data, and wind, temperature and SIGWX charts for those RAFCs which have already handed over their responsibilities to WAFCs. The remaining RAFCs continue to provide regional upper wind and temperature charts plus regional SIGWX charts, while the National Forecast Centres provide much of the low-level information required within a national boundary for flight safety purposes.

For WAFC London, the formal responsibilities were expanded during the year so that they now include the previous responsibilities of RAFCs Frankfurt, Toulouse and Moscow. The on-screen computer-based production process is more efficient than its predecessor, and the graphical quality of output is also better.

SADIS

Aviation forecast products are disseminated through many communication channels. At an international level, two 'official' types of the Aeronautical Fixed Service (AFS) exist: terrestrial and satellite. The terrestrial channels, known as the Aeronautical Fixed Telecommunication Network (AFTN), link the regions of ICAO together through designated 'gateways'. The standards, line speeds and other ICAO requirements are controlled by regional communication groups. One important method of satellite communication is SADIS (Satellite Distribution), which became operational in 1995.

SADIS was developed on behalf of the ICAO European region for the satellite distribution of WAFS data. The contract has been arranged and signed by The Met. Office although the overall system is an ICAO one. SADIS uses the Intelsat satellite to provide a global beam footprint extending across the whole of Europe, Africa, the Middle East and Asia extending from 20° W to 140° E. Its successful development continued during the year.

Horace

The role of the operational workstation system Horace has been successfully extended during the year. It now provides the main IT platform for forecasters in the NMC and at RAF Headquarters Strike Command and Royal Navy sites. New functions are delivered through regular software releases; hardware capability during the year has also been improved. The Horace system is a major feature of the contract won during the year to supply meteorological facilities to the Thailand Meteorological Department.

Forecasters are now able to view most of the required meteorological data, satellite imagery and NWP forecast products on-screen, including Nimrod products. The SIGWX production is also integrated into the Horace system, using common support and database facilities.

A system is being developed for trials later in 1997 which will produce the NMC's main guidance charts on-screen instead of on hard copy. This will include both the initial analysis of observational data and the main forecast charts for the days ahead. This will be one of the most radical changes in production seen in the NMC for many years. See under **NMC workstation system** in the **National Meteorological Centre** section.

These new systems are expected to make savings in production, and provide 'machineable' products which can be easily integrated into other products

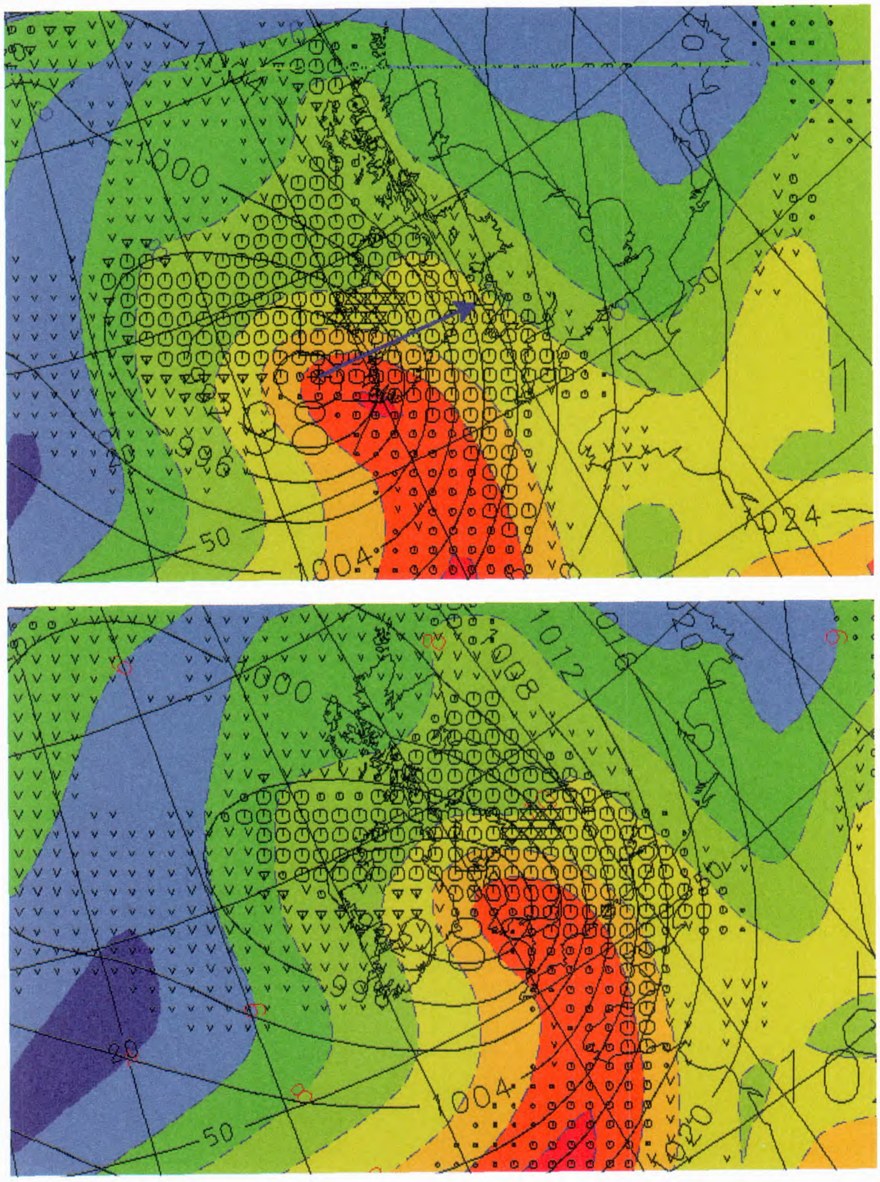


Figure. 7. On-screen field modification via potential vorticity. Top, raw model forecast from the limited area model showing 850 hPa wet-bulb potential temperature (colours), mean sea-level pressure and precipitation. The arrow shows movement vector applied on-screen to the potential vorticity. Bottom, resulting modified fields retrieved from inversion of the new potential vorticity distribution.

downstream from the NMC. They will also allow an improved evaluation of the value added by the forecaster to the basic NWP forecast.

Operational production costs

New capabilities have allowed various forecast production processes to be transferred from the IBM 9672 mainframe computer to local workstation systems. Other changes have eliminated old technology which in turn removed the need for a substantial volume of routine chart production work on the mainframe. As a consequence, the loading of operational production on the mainframe computer has been reduced. This will be translated into a real saving when the next replacement of the front-end computer system is required.

Site-specific forecast model

A deficiency of current NWP is that the results relate to large areas, squares of about 17 km side in the mesoscale model. Many forecasting requirements are for specific locations: airports, road sites, oil rigs, etc. Work has therefore started on an adaptation of the UM for site-specific forecasting. Like any 'limited area' model, coupling to a large-scale model is crucial, and this has been the main focus of development this year. During the autumn, a trial at fifteen locations showed that this had been achieved, and the predictions were realistic when vertical resolution and specification of the surface characteristics were enhanced.

Development of aviation products

Work has continued on improving forecasts of a variety of phenomena which relate to aircraft operations. A new technique for enhancing high-level wind predictions was trialled, and further use was made of the wind nowcasting system, WAFTAGE (Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe), to investigate the benefit of improved winds in the approach to landing. New work was started on aspects of turbulence, including clear air turbulence, mountain waves and wake vortices. Work on icing has increasingly focused on the threat from supercooled drizzle drops, large droplets which sometimes form in thick unglaciated cloud near the freezing level.

A project on aviation forecasting was undertaken with EU sponsorship in collaboration with Météo-France and other French organizations. A major part of the work was the investigation of forecasts for landing and take-off, their value and accuracy, as well as new forecasting techniques.

Computerized Meteorological System (CMETS)

NWP products form an important part of the information available to meteorologists supporting UK armed forces on the battlefield. Work started on nowcasting system which will automatically update this remote guidance using local observations. Components from Nimrod are being used together with the WAFTAGE system and a boundary layer airflow model.

Performance measurement

Demand for rigorous evaluation of The Met. Office's performance has increased markedly, including the quality of forecasts, to the satisfaction of external auditors. A new composite index has been put in place for the coming financial year which will more properly measure the quality of the operational NWP forecasts. A new 'partial' UK NWP Index of forecast performance has also been devised; it is based on verification of mesoscale model forecasts of temperature, wind and precipitation against station observations. This will be used as an important measure of The Met. Office's performance starting with effect from 1 April 1997.

International meeting

The seventh annual meeting of the European Group on Operational Workstation Systems was hosted at The Met. Office College, Shinfield, 3–6 June 1996, which was attended by 19 representatives from 17 European countries. During the meeting there were demonstrations of the systems being developed in France, Germany, Hungary and the Netherlands, as well as those from The Met. Office.

Met. Office Photographic Services

A technician installs a closed-circuit TV camera for remote weather forecasting trials at S&B sites.

The Services and Business (S&B) Division acts as The Met. Office's interface to its customers. There are four main customer groupings: the Ministry of Defence, the Civil Aviation Authority, commercial customers and the Public Met. Service. Science and technology have important roles to play in helping generate and deliver services to this diverse customer base.

Delivery to customers

Internet

The Met. Office's World Wide Web site continues to deliver up to 25,000 pages a day to a wide range of UK and overseas users. A survey of site users was conducted to find out views and ideas for development. In July a trial commercial service (MetWEB) was launched. During the period of the trial over 3,500 users visited the site. Accessed using a payment mechanism, based on credit card purchased virtual tickets, the site contains detailed UK marine and aviation products similar to those on MetFAX. Following the trial and some development, MetWEB is now an established service and continues to attract customers.

Mobile phones

Mobile communication is now an established technology and offers opportunities for new services. Met. Office weather forecasts can now be obtained for the caller's location on the Vodafone 2222 Infoline Service, as part of a package of services developed by the Automobile Association.

Fax

The MetFAX dial-up fax service has grown significantly and now receives nearly one million calls per year.

MIST

- *Service update* The Meteorological Information Self-briefing Terminal (MIST) system has been in operation since 1992. It gives customers interactive access, via their PC and telephone lines, to a database of products and services held on a host computer at Bracknell. A new host system, based on Pentium technology and using mirrored servers for reliability, was brought on-line in early June 1996, with the old host being decommissioned in August 1996. The change to the new host was accompanied by a move away from use of the M5000 packet switching network and the public switched telephone network (PSTN) to PSTN only.

- *Capacity* A second modem bank was installed early in 1997, which increased the capacity for dial-in customers. The modems have also been upgraded from V32 (9,600 bps) to V34 (28,800 bps). This has decreased customer on-line time, helping to cut costs and increase host resource availability. The two MIST dial-in numbers, one per bank of modems, now allow up to ten concurrent accesses. Two modems are used for dialling out data to customers. An Integrated Services Digital Network (ISDN) link is also available for either dial-in or dial-out, supporting faster transfer speeds.

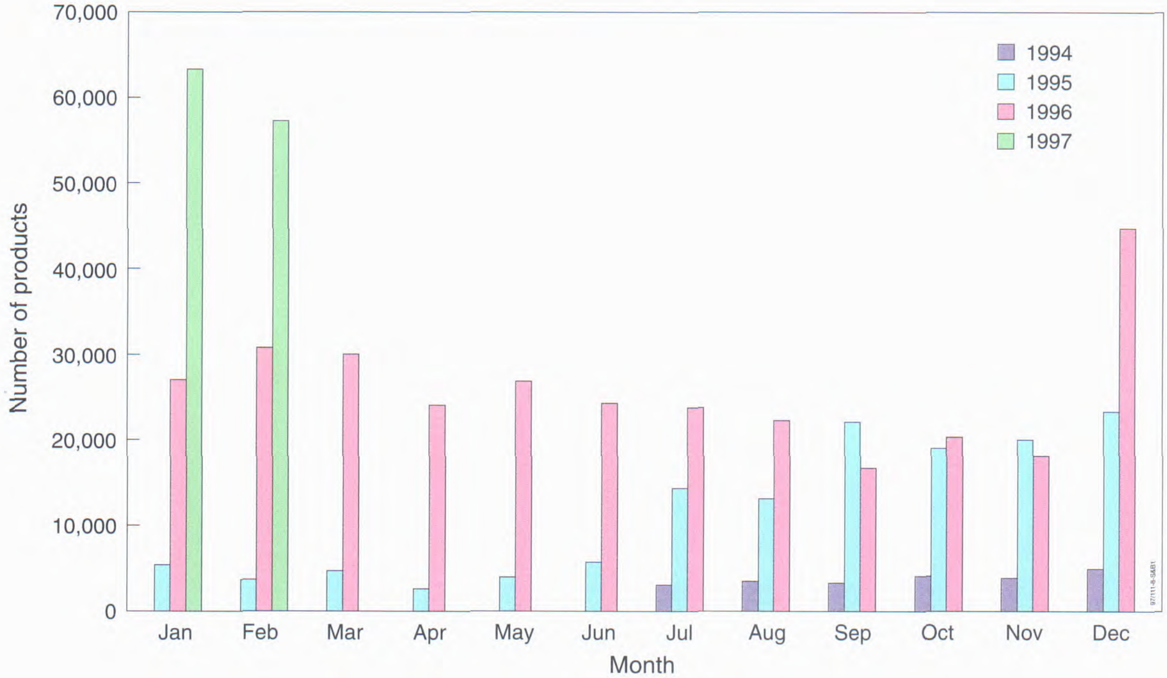


Figure 8. The number of products downloaded from MIST by dial-in customers, comparing annual changes by month.

Increased capacity is necessary because use of MIST has grown. Fig. 8 shows the increase in the number of products downloaded by dial-in customers since comparable records began. The chart shows both the large increase in data requested by customers and the seasonal nature of the monthly data volumes.

The number of dial-out customers – customers who are dialled regularly from the MIST host with fixed sets of products – has increased from five to ten since March 1996. The frequency of dial-outs to customers varies ranging from four times an hour to once a day.

♦ *New developments* During 1997 The Met. Office will release a new version of MIST for Windows. One of the main enhancements over the present DOS-based version, is the ability to tile and animate several products at the same time, so that different weather types may be compared on screen. The new version runs on the latest Microsoft Windows 95/Windows NT platforms, and requires a Pentium processor to utilize the new features. These include: a higher-resolution map background to the displays; the ability to customize colours and threshold settings for plotted parameters such as wind, temperature, and wave data; and an easier system for downloading weather data. An example of a multi-windowed screen is given in Fig. 9.

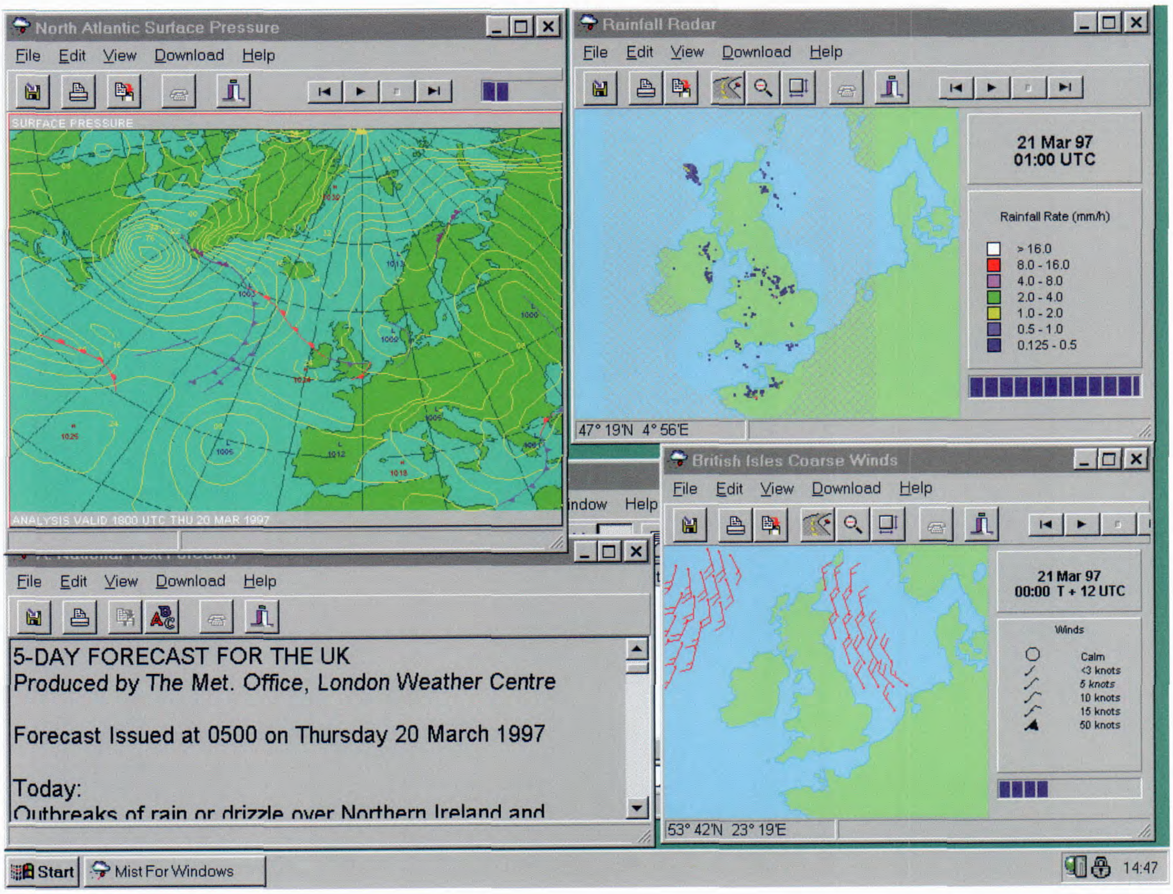


Figure 9. A typical screen configuration available on MIST for Windows 95.

MOMIDS

Military customers currently obtain meteorological information in ways which are labour-intensive for both Met. Office staff and for the military. They include requesting routine data such as TAFs and METARs by telephone and the creation of tailored products on paper which are then faxed to several recipients or copied for distribution by hand. With aircrew remaining in dispersed squadrons and the requirement for more decentralized briefing, the need for electronic distribution and briefing has grown. The Meteorological Office Military Information Distribution System (MOMIDS) addresses this need.

MOMIDS is based on Internet technology. An Internet browser is installed on the customer PC (the 'client'). This uses hypertext mark-up language (HTML) to format and display information and is the primary user interface to MOMIDS. On start-up the Internet browser will retrieve the first page (known as the home page). Once the page is displayed, customers use a mouse to click on hypertext links to the information they wish to see. At no time will it be necessary to know file names, directory structures or how the communications work. Nor will it be necessary to remember complicated key combinations, the whole system will be driven by simply clicking on links on the pages.

The information accessed by the customer PC is held on a 'server'. There will normally be one server, running Windows NT, per station. Information on the server will arrive either via the Weather Information Network (WIN) from Bracknell or the local forecast office. Customer PCs will be connected to the server via either leased lines or the station's local area network. Once set up very little work will need to be undertaken on the server or the user displays, and any configuration changes will be made remotely from Bracknell.

Customer PCs (several per station) will use Windows 95 as an operating system in a tightly controlled configuration to avoid accidental changes. The system will also look identical and operate in the same way, no matter where the customers are using the system. This is important, as this system will be used by visitors as well as by the local staff.

Local forecasters will originate textual and graphical products on their desktop PCs and transmit them to the server for display according to a pre-defined address list, much like sending e-mail. Many items produced by the forecasters will still be Microsoft Word documents, just as at present. However, the method of delivery will change. This means that the design of the document (the forecast template) is under the control of the local office and consequently can meet local requirements. Warnings (and potentially other e-mail) can be transmitted to user displays. Only authorized users will have access to the warnings and unique 'electronic signatures' can be returned to forecasters' PCs.

A prototype version has been trialled from December 1996 at the School of Army Aviation at Middle Wallop with a remote customer at the Army Air Corps base at Netheravon. Despite the prototype being an early version with few facilities, it has been well received and is used routinely.

The development and installation programme is very ambitious with about 300 displays planned to be in place across the UK by June 1998. This timescale is realizable due to the timely introduction of WIN, the flexibility of the Outstation Communication Processor (OCP) and the power of commercial software such as Microsoft Office and Internet browsers. Fig. 10 is a schematic diagram showing the dependence of MOMIDS on the other hardware components. See also the **Networks** section in the **Operational Services** chapter.

Internal systems

MIDAS

The design of the climatological database originated in the early days of computing in The Met. Office. Database technology has since moved on and the decision was taken to redevelop the database using modern design tools and a commercial Relational Database Management System (RDBMS). The RDBMS used is CA-IDMS, and the database called MIDAS (Met. Office Integrated Data Archive System).

The advantages of this approach are that industry-standard tools for querying the database are now being used, enabling the use of rapid application development methods. Structured Query Language (SQL) can be used in building and formalizing the description of queries. The database, and the applications using it, are no longer tied to particular computer systems because the design of the database has been prepared using formal methods. They can be transported to another system or RDBMS without major problems.

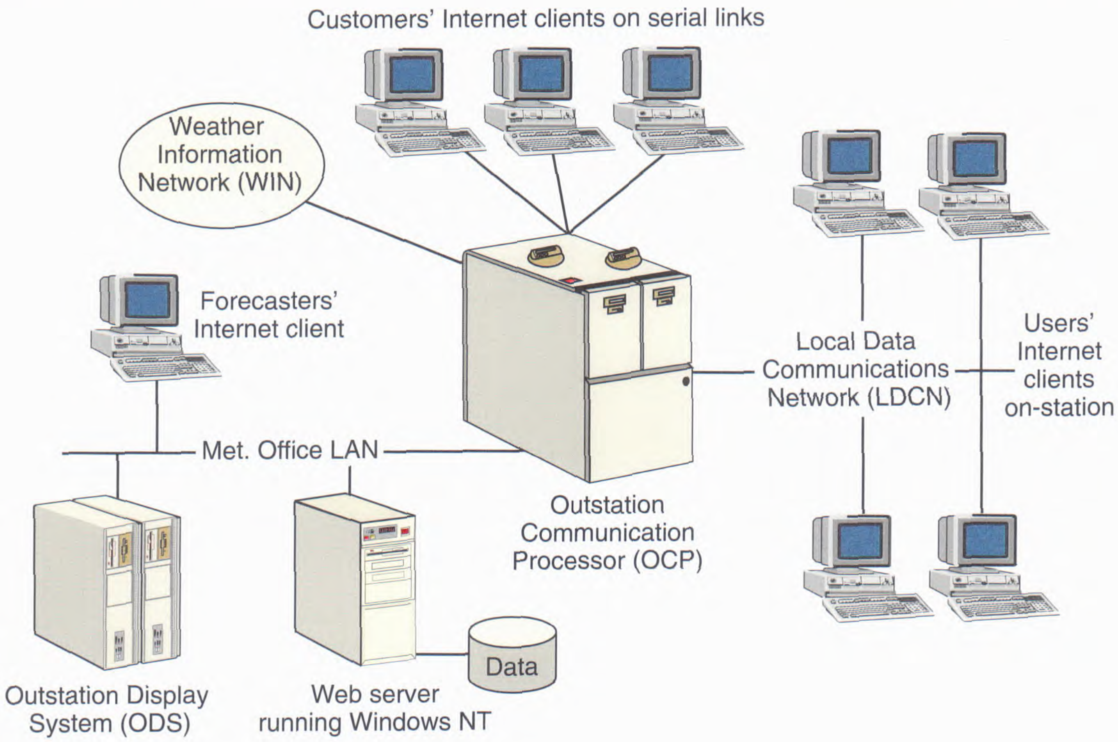


Figure 10. Forecasters' Internet client and part of MOMIDS shown as PCs, with their external links.

These new tools enable the user to build applications using a 'client–server' model of the processing environment, where the database resides on a server processor – in The Met. Office's case, the IBM 9672 model R73 mainframe computer. The applications run on client PCs, which are usually networked. The processing is shared, with the query being formulated by an interactive system on the PC, and then submitted to the server for extraction of the data. This is then returned to the PC for formatting and printing.

The applications using the climatological database may be divided into four types. The first is where Enquiry Officers need to find out information about the availability of data to meet the needs of a particular customer or service. One of the major advantages of the development of MIDAS is that it has led to much more of this 'metadata' (information about the data) being available in one place, in a consistent and logical form. Eventually this information might include site photographs, obstruction diagrams, or a history of instruments used.

The second type of applications are those presenting relatively small amounts of data, needed on demand by Enquiry Officers, where the quality of presentation is important. Both of these applications are satisfied by an interactive menu-based system running under Windows, using the client–server model. The current version has been developed using Microsoft Access, and includes the ability to browse station details using multiple criteria, data extraction and presentation in a variety of formats, such as frequency tables, means and extremes. The use of specialist graphics programs, for example to produce wind-roses, is currently under development.

The third type is bulk data extraction, where the client–server model is not appropriate because of the large volumes of data. Here, special Fortran programs extract the data and store them in files on the IBM mainframe. These files can then be transferred to an appropriate medium for the customer; increasingly The Met. Office is using CD-ROMs for this.

The final type are those data extractions which run routinely on a daily, weekly or monthly schedule. Many of these are run from a timed suite of programs within the mainframe batch environment. Others are started manually, to allow some inspection of the results before electronic despatch to the customer; usually e-mail via either X400 or the Internet.

Production technology

Only a few of the production units managed by S&B Division are in Bracknell; most are located throughout the UK and some are overseas. On-site forecasters are still required by military customers, therefore S&B supports forecasters at 33 UK and eight overseas defence sites. There are specialist production units at the BBC and at International Weather Productions (IWP) in London. More-general production units are situated at the 12 Weather Centres across the UK. These, together with the Bracknell-based production units, deliver The Met. Office's services and products.

The technology connecting these production units with Bracknell and the world at large is being upgraded as part of the WIN project. The production units use systems based on PCs, with some Apple Macintosh computers used to support specialist customers in the media sector. As an example, Fig. 10 shows a forecasters' Internet client, and a part of MOMIDS, as PCs and shows their external links. See also the **Networks** section in the **Operational Services** chapter.

In addition to production systems, each unit usually has access to the Outstation Display System (ODS) which provides forecasters with observational, forecast and other data. ODS is based on technology that is becoming difficult and expensive to support. Plans are well advanced to put ODS and production functions onto a single platform which will make greater use of the capabilities potentially offered by WIN. An additional benefit is significantly reduced support costs.

Applications of science to service provision

Synthetic Theater of War (STOW)

STOW is a project of the US Defense Advanced Research Projects Agency (DARPA). It aims to create a synthetic battle space to improve training and rehearsal capabilities and to initiate a revolutionary improvement in simulation technology. The Ministry of Defence was invited to contribute to STOW, and the UK STOW project is now being led by the Defence Evaluation and Research Agency. The development of a UK weather facility for UK STOW has been subcontracted to The Met. Office.

Met. Office mesoscale model data can be fed into the component of STOW which provides weather information to the rest of the simulation. This will be demonstrated operationally during a combined US Atlantic Command/UK Permanent Joint Headquarters Command Post exercise planned for October 1997.

Tactical Decision Aids

Tactical Decision Aids (TDAs) are computer models which are used by forecasters to give special high-value advice on the impact of meteorology on a specific mission, task or weapon system. The applications for TDAs are many and varied, including the prediction of: night-time illumination levels to support the use of night-vision goggles; radar coverage; contrail formation; and sound propagation to minimize noise pollution around army firing ranges.

- *Night-time illumination* Night-time light-level predictions are based on astronomical data and cloud conditions. To verify the model predictions, a photometer was deployed at Aberporth in 1996 and measurements of night-time light levels were made over a three-month period. The results for clear-sky cases have been analysed and corrections have been made to the model which tended to over-predict light levels in low-light conditions.

- *Radar coverage* An area of tactical meteorology which is of interest to the Royal Navy is the prediction of radar coverage. Radio waves are refracted as they travel through the atmosphere, and the amount of refraction depends on the meteorological conditions.

  Models which predict radar coverage for constant conditions along the path of the radar have been in use for many years. Such models, however, are unable to predict radar coverage in coastal regions, where the atmosphere can change rapidly along a horizontal path that crosses the coast. The Defence Projects section of S&B Technical Development Branch are working in collaboration with the Maritime Warfare Centre at Portsdown to develop a radar-coverage prediction system that can accurately and quickly predict radar coverage in range-dependent environments. The Met. Research Flight C-130 aircraft is being utilized to verify the model predictions. Flights will be made over the Baltic Sea and coastal regions around the UK.

- *Contrail formation* Under certain meteorological conditions, condensation trails (or contrails) will form in the wake of an aircraft. For many years, contrails have been forecast from the MINTRA line, which is printed on tephigrams. The MINTRA indicates temperatures below which contrails will form. Observations from modern aircraft have revealed that the MINTRA does not give accurate predictions of contrail conditions. Investigations were carried out to study the theory of contrail formation, and it has been found that the formation of contrails depends not only on the air temperature but also on the dew point and the efficiency of the aircraft engine.

A technique for predicting contrail formation has been developed which takes these parameters into account. A trial is under way to verify the results of this new technique at four defence sites. Reports of contrail conditions are being collected from pilots on a daily basis, and these reports are being compared with forecasts of contrail formation. The results of this trial will be used to determine the best method available for predicting contrails for specific aircraft types.

Marine applications

Progress has been made in the exploitation of archived wind and wave hindcasts generated by The Met. Office's European and global models. When a new interest develops in an ocean area, locally recorded wind and wave data often provide a sound basis for planning offshore activities. Data from the hindcast archive of analysed winds and waves can also help in making initial strategic planning decisions.

Currently, an area to the north of the Falkland Islands is being explored by the oil and gas industry. Time-series from the Global Wave Model hindcast archive (Fig. 11) allow appropriate data summaries and analyses to be undertaken. For example, the number of hours when conditions are expected to be unfavourable for specific offshore activities can be calculated (i.e. downtime hours), to make comparisons with other offshore areas already in production.

Extreme temperatures at Devonport

Devonport Dockyard is involved with the maintenance and refurbishment of nuclear submarines and ancillary equipment which are required to withstand rare climatic extremes. Estimates of the temperatures associated with return periods of 10,000 years were required.

Advantage was taken of a recently developed regression model which could estimate such extremes of temperature for any location in the UK. The existence of temperature records for the last 122 years in Plymouth enabled the estimates to be refined by making use of local data.

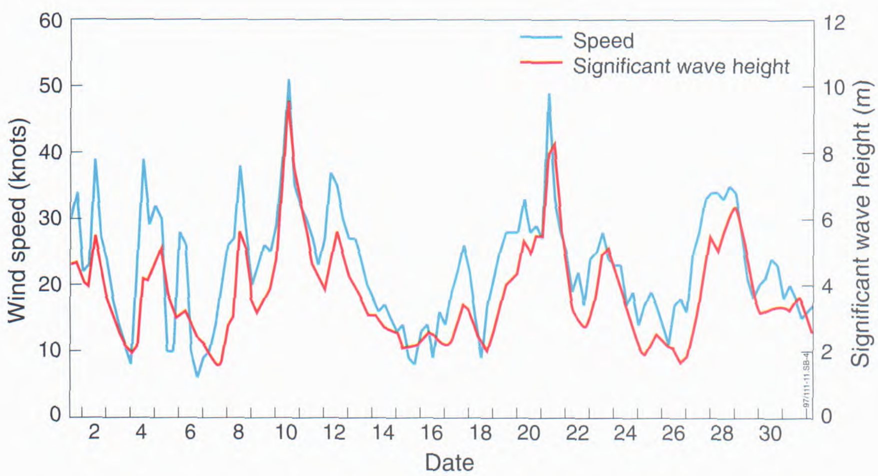


Figure 11. Time-series of wind speed and significant wave height north of the Falkland Islands for May 1996.

The temperature records were analysed and a composite series for Mount Batten was produced. Annual maximum and minimum values were extracted and a generalized extreme-value distribution fitted. The Met. Office regression model was then run for Mount Batten and Devonport Dockyard. The differences between the two locations were used to adjust the extreme-value analysis for Mount Batten to Devonport. The 1:10,000-year lowest and highest temperatures were estimated to be −13.3 °C and 35.4 °C respectively.

Geographic Information Systems (GISs)

GISs are commercially available software packages used to manipulate geographic and other data. Such systems have an obvious use in meteorology since local environments have an effect on local weather.

Various studies have taken place in 1996/97. Predicted values of the likelihood of fog in England and Wales have been computed using land use and topographic data held on a GIS and a fog model. Areas subject to pollution have also been mapped. These maps have been produced for local authorities to demonstrate what can be provided as an aid in the assessment of air quality. A high-resolution surface roughness map has been produced as part of a contract for a reinsurance broker. These data have been used to estimate winds from a historical database of severe storms which have crossed the UK; wind storm damage is a major source of claims for the insurance industry.

Soil moisture deficit and subsidence

Subsidence is another source of claims on the reinsurance industry and therefore there is a demand for relevant weather information. Soil moisture deficit (s.m.d) is an appropriate parameter to study and a method has been developed to place each year's maximum value in perspective.

S.m.d. values are calculated by the Met. Office Rainfall and Evaporation Calculation System for a number of long-period weather stations with complete records. The calculations are performed for deciduous trees as these are the most likely cause of subsidence. The annual maximum s.m.d. values are then extracted. These annual maximum values are subjected to extreme value analysis so that return periods of s.m.d. can be estimated. Regressions are plotted for the input parameters of the extreme-value analyses against climate and soil factors so that the return periods can be estimated for any location.

A GIS is then used to determine the appropriate climate factors over the postcode areas which are used by the insurance companies to assess premiums and claims.

Snowstorm assessment

In early December a severe snowstorm struck the Borders area of Scotland, snapping steel pylons and bringing down power lines. Strong winds were a feature of the storm. These were accompanied by wet snow at altitudes above 100–150 m. An assessment of the severity and rarity of the storm was required.

Weather observations from the Observatory at Eskdalemuir at an altitude of 242 m proved ideal for the assessment. During the snowstorm, moderate wet snow and strong winds lasted for eight hours. The computer archive of hourly observations, started in 1957, showed that there had been two other storms of similar severity in the last 40 years. A more severe storm occurred in December 1978 with moderate wet snow and strong winds lasting 17 hours. At Eskdalemuir, therefore, the return period of the December 1996 storm is between 10 and 20 years.

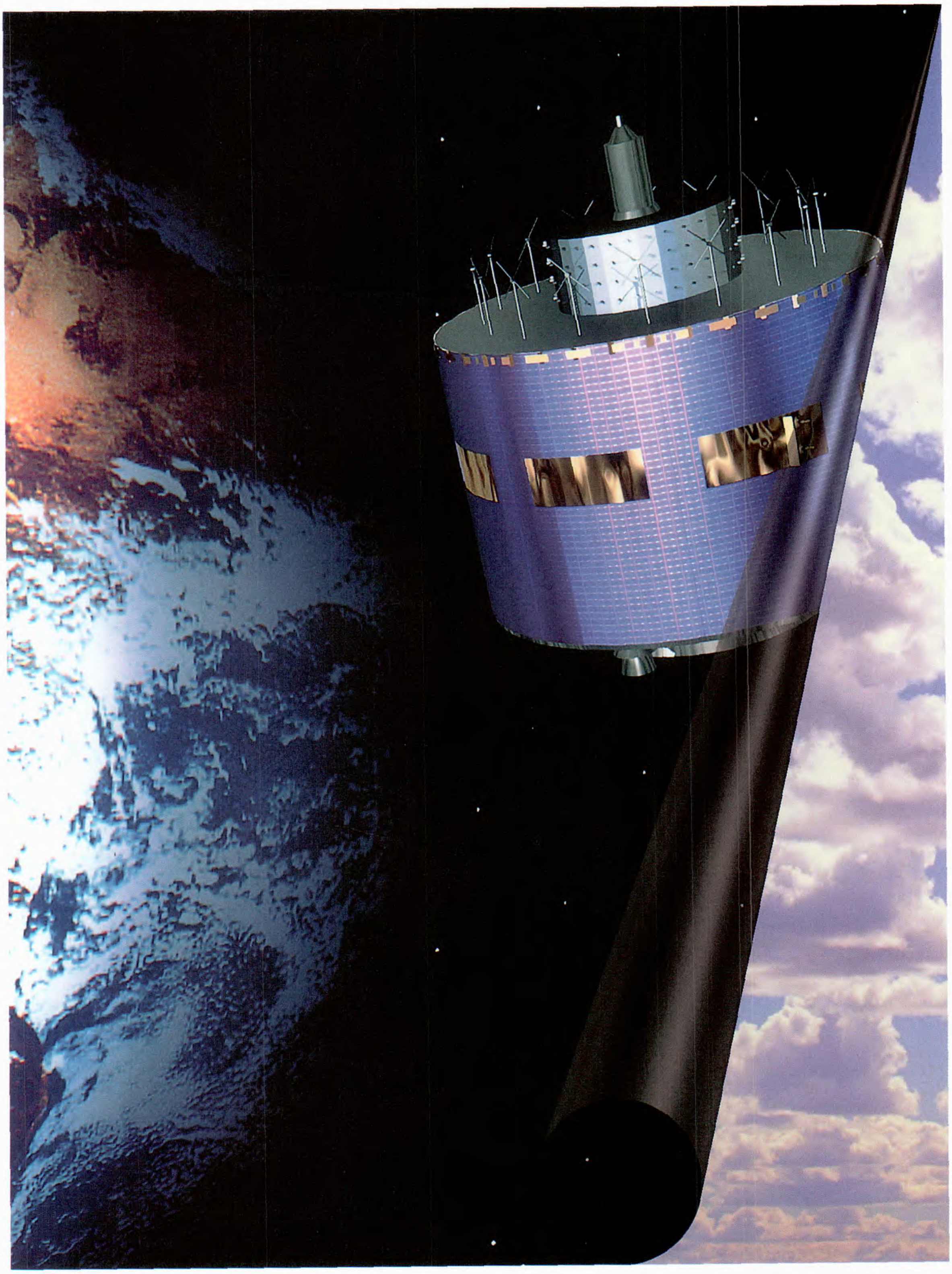
Estimating gas demand

The gas industry has an obligation to store enough gas to meet demand for a '1-in-20 year' peak day and a '1-in-50 year' severe winter. Since gas demand is highly correlated with temperature, one of the best ways to estimate these values is to use temperature data. The data needed should ideally be a population-weighted average over the whole of the UK, so the well known Central England Temperature series was used. Daily values calculated by the Hadley Centre identified the coldest day in each year. Return period statistics for the coldest day, coldest month and coldest three months were easily obtained.

Services to agriculture

Although the Agricultural Development and Advisory Service (ADAS) is no longer a Government Agency, the collaboration with The Met. Office in providing specialist advice to the agricultural industry continues. Significant advances were made in 1996/97 by the National Agrometeorological Unit at Wolverhampton in compiling databases of relevant information, and making them readily available to non-experts. The storage of climate records on the ADAS computer system has been reorganized, making it easier to use, and new global data sets have been added.

Dispersion modelling studies, based on records from the nearest suitable Met. Office site, are sometimes criticized for not taking account of local wind flow patterns. In response, the Agrometeorological Unit has developed software routines to pre-process the weather records to take account of predictions of local topography effects on wind directions. These local predictions are based on the algorithms used to help in the siting of wind energy converters (wind turbines).



ESA

Numerical Weather Prediction

An artist's impression of the Meteosat Second Generation satellite.

The Numerical Weather Prediction Development Programme is designed to improve the capability of The Met. Office's computer modelling system in operational forecasting. The models are also designed to be used in climate prediction and other environmental research, and are available for use by UK universities.

The computer code is freely exchanged internationally, and the complete system is offered with consultancy to other centres on a commercial basis. This wider use of the forecast models results in feedback on their performance, and hence substantial benefit to Met. Office customers receiving weather forecasts.

The model is used in operational predictions in a global, regional and mesoscale configuration for short-range forecasts. It has been used experimentally in medium-range ensemble forecasts in a joint experiment with the European Centre for Medium-range Weather Forecasts. It is also used for monthly probabilistic forecasts which are made on behalf of specific customer groups, and for experimental seasonal forecasts.

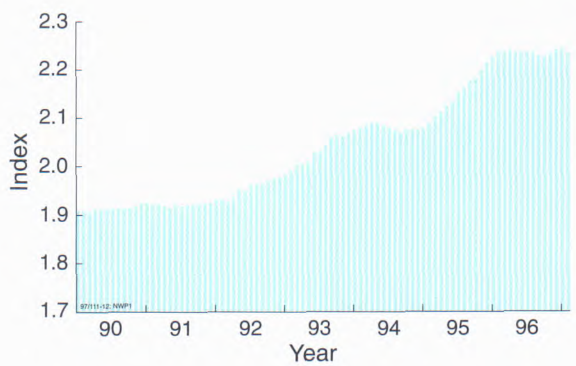


Figure 12 (top). Global NWP skill score index from 1990 to present. Figure 13 (bottom). Improvement in global skill score index over 1-, 3- and 5-year periods ending on date shown.

Forecast performance

The overall performance of the global forecast model is illustrated in Figs 12 and 13. A composite measure of the global model performance is illustrated in Fig. 12; based on individual measures of accuracy in the surface and upper air for all parts of the world. The index is weighted according to the relative importance of aspects of global model performance to The Met. Office's customers. Thus greatest weight is given to 24-hour forecasts of northern hemisphere sea-level pressure and 250 hPa wind. The latter is the most important product for civil aviation.

The index is calculated from skill scores based on the ratio of root-mean-square (r.m.s.) forecast errors to those of a no-skill persistence forecast. This reduces interannual changes caused by changes in atmospheric variability. Figure 13 shows how the index has improved over recent years. There has been a 16% improvement over the last five years.

The model is also used to forecast weather parameters, such as cloud and precipitation, primarily for the UK. Precipitation forecasts up to 36 hours ahead are obtained from a regional version of the model covering the North Atlantic Ocean and Europe with a 50 km grid. Over the UK, extra guidance up to 24 hours ahead is obtained from a mesoscale version of the model with a 17 km grid. This gives more-detailed precipitation forecasts, together with predictions of other weather parameters such as cloud and fog.

The quality of these predictions is illustrated in Figs 14 and 15. The accuracy of precipitation forecasts is shown in Fig. 14, calculated from the r.m.s. ratios of forecast to observed values. A minimum ratio of 2.0 is assigned where precipitation is missed altogether or forecast wrongly. The results are then converted to a skill score, expressing whether the model forecast is better or worse than a no-skill persistence forecast. A positive value indicates that the mesoscale model gives useful guidance. A value of 1.0 is a perfect forecast. The results indicate skill at all forecast ranges, with the lowest values for 6-hour forecasts. The latter indicates that it is still difficult to exploit the precipitation observations fully in the model analyses.

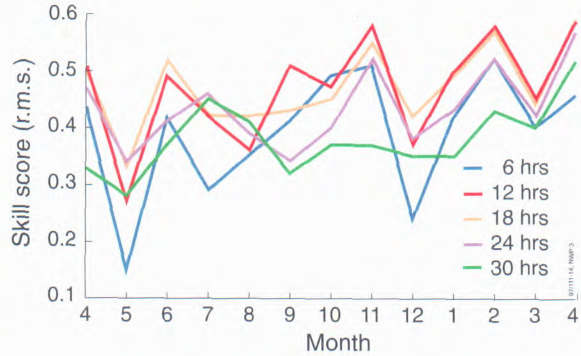


Figure 14. Time-series of monthly mean skill scores for precipitation (r.m.s. error of accumulated precipitation), using the mesoscale model at various forecast ranges.

Figure 15 illustrates the model's skill at forecasting the total amount of cloud below 1,500 m. Low-cloud forecasting is the most important aspect of cloud forecasting for many customers. The measure is again a skill score where the model forecast is compared with persistence. A positive value indicates that the mesoscale model gives useful guidance and a value of 1.0 is a perfect forecast. The results show skill at most forecast ranges, but not for 6-hour forecasts. The latter reflects the difficulty of making effective use of the observations. The results also show a period of very low skill in December and January. This was a very cold period where the cloud was primarily made up of ice crystals. The cloud physics used in the operational forecast model is not yet able to treat such clouds correctly. A new scheme which treats the ice phase more realistically is under development.

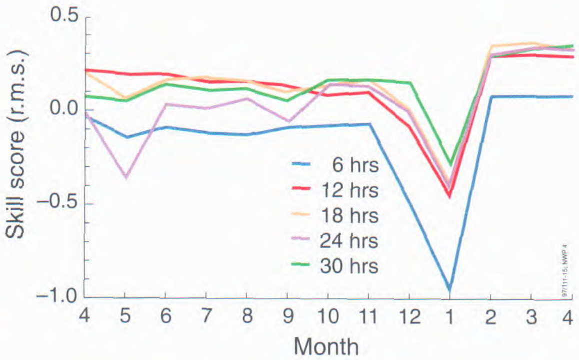


Figure 15. Time-series of monthly mean skill scores for cloud cover at 1,500 m or below, using the mesoscale model at various forecast ranges.

Development of the forecasting system

New operational configurations

The Met. Office is currently installing a new Cray T3E supercomputer which is expected to give at least five times the processing power of the C90. This provides an opportunity to review the operational forecast configurations of the Unified Model (UM). Many customers need timely output on which to base their decisions. Runs of the current global model deliver output approximately 4 hours after data time, which is too late for many applications. Decisions therefore have to be based on the regional model or an earlier run of the global model. In addition, the regional model forecasts have to rely on output from a global model forecast from 12 hours earlier for boundary conditions.

It is therefore proposed to exploit the power of the new computer to increase the resolution of the global model to near that of the current regional model. It is to be run with the earlier data cut-off used for regional forecasts, and will provide output within 2 hours 30 minutes after data time. The existing, later, global run will continue because significant extra data are available, especially from aircraft. Thus an updated and more-accurate forecast can be issued 4 hours after data time.

Figures 16 and 17 illustrate the performance of the new global model configuration. Figure 16 shows that by reducing the grid-length in the model from the current 90 km to about 60 km, a good forecast of a tropical cyclone can be made. The current resolution captures the cyclone in the analysis, but the structure is lost in a 3-day forecast. The higher resolution retains the structure.

Figure 17 compares 36-hour forecasts of an intense jet stream over the UK. The higher resolution improves the global model forecast, and allows it to outperform the forecast from the regional model which has similar resolution. The latter improvement comes from the removal of the need to use boundary conditions from an earlier forecast.

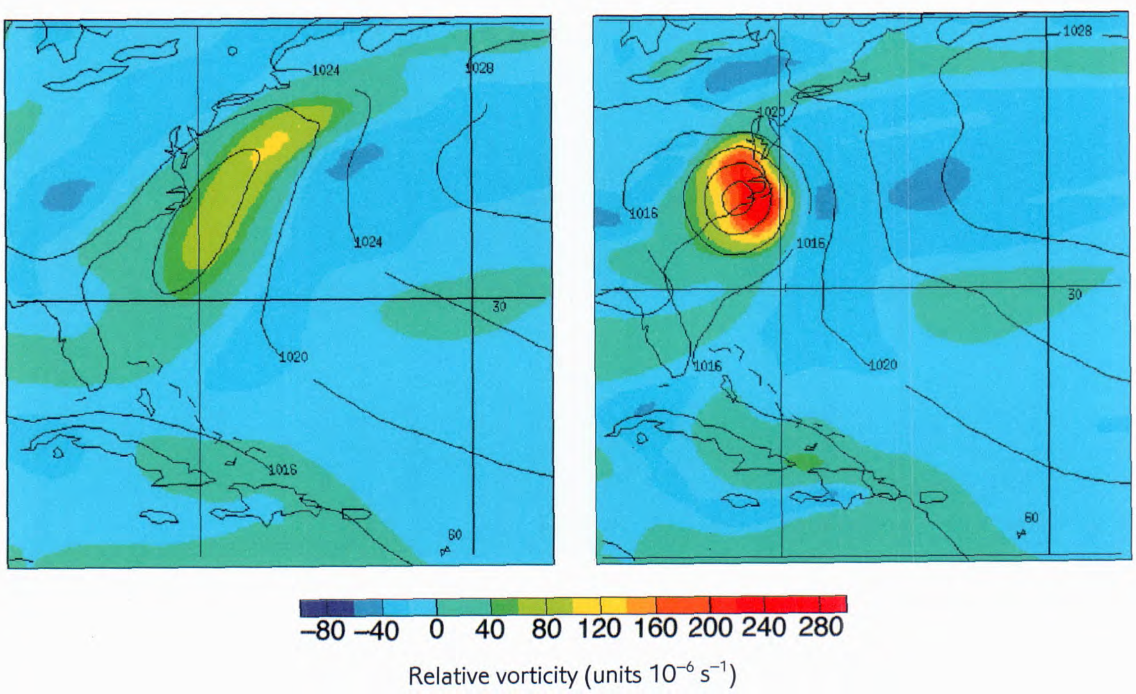


Figure 16. Relative vorticity at 850 hPa and mean sea-level pressure for a 72-hour forecast valid at 1200 UTC on 12 July 1996. Left, the operational global model; right, the same forecast using 60 km horizontal grid.

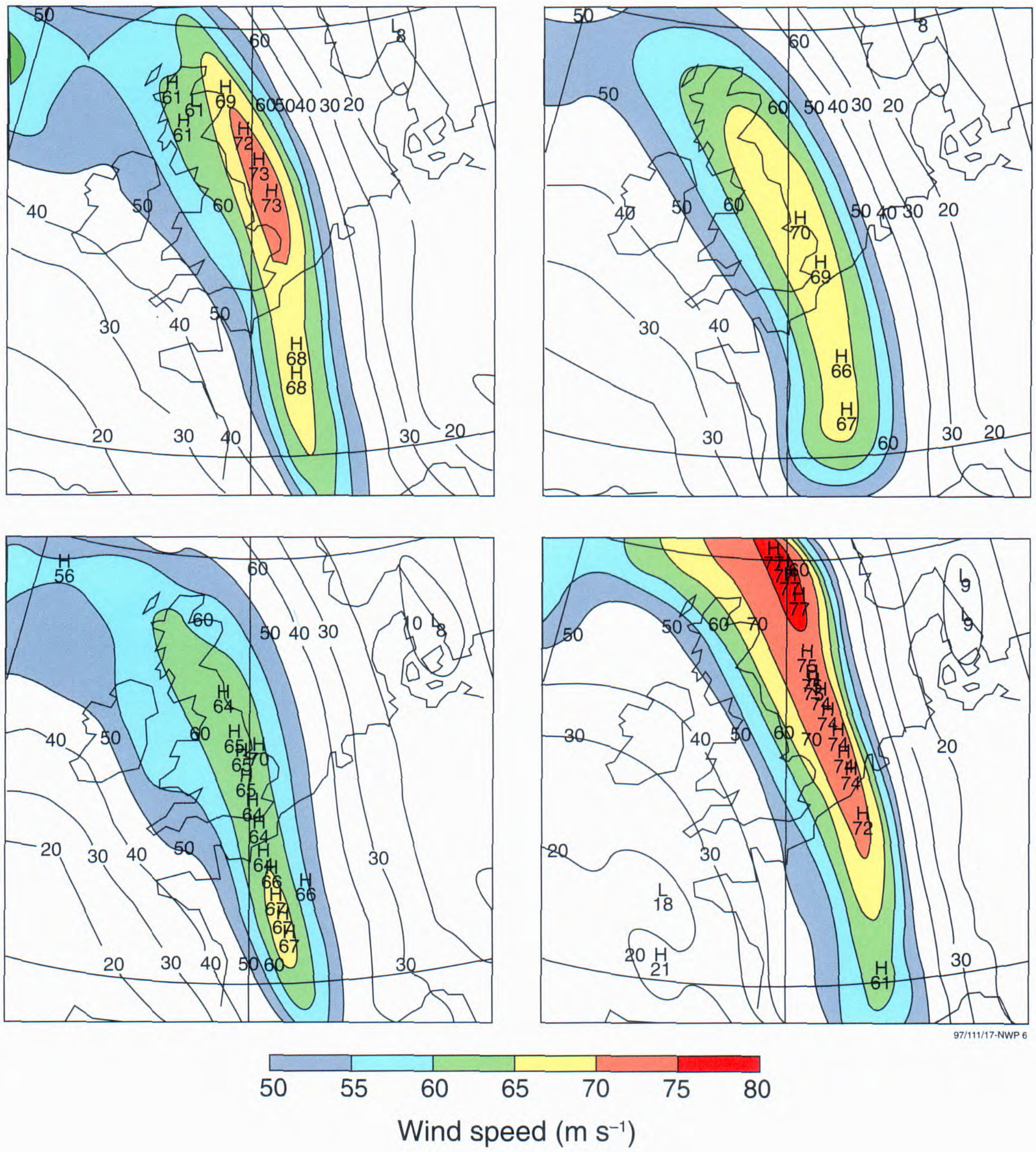


Figure 17. Six-hour forecasts of 250 hPa winds valid at 0000 UTC on 28 May 1996. Top left, high-resolution global forecast. Top right, operational global forecast. Bottom left, regional model forecast. Bottom right, verifying analysis.

Objective scores also show that a high-resolution global forecast model outperforms the regional model. The advantage is between 5% and 10% of forecasts for pressure and wind at various levels in the atmosphere.

While these illustrations show only the effect of increased horizontal resolution, it is also planned to increase the vertical resolution from the current 19 levels to 30 levels. The horizontal resolution of the mesoscale model will probably be increased to give a grid length of around 12 km, and the vertical resolution increased to 38 levels. The domain size will probably be increased to cover areas where high-resolution products will be particularly beneficial to customers.

Improvements to the global model

In November 1996 a package of changes was made to the global model to improve its performance. These were as follows:

a) using humidity data retrieved from the TOVS (TIROS Operational Vertical Sounders) satellite sounding instrument (this has a large impact on the Tropics, not only in humidity but also in wind);

b) increasing the order of accuracy of the advection scheme in the model dynamics from second to fourth order;

c) revising the gravity-wave-drag scheme, particularly to reduce the upper-level drag;

d) including a representation of the vertical transport of momentum by cumulus clouds (this has a large impact on the tropical winds, in particular the removal of a spurious westerly wind bias at low levels).

The overall effect was to reduce the global model errors by about 5%, as measured by the composite of verification figures illustrated earlier. An example of the impact on individual fields is shown in Fig. 18. This shows the upper-level wind forecasts averaged over a period from January to March 1995. The changes reduce the area of large errors over the Pacific, and also the errors in the subtropical jet near 60° E.

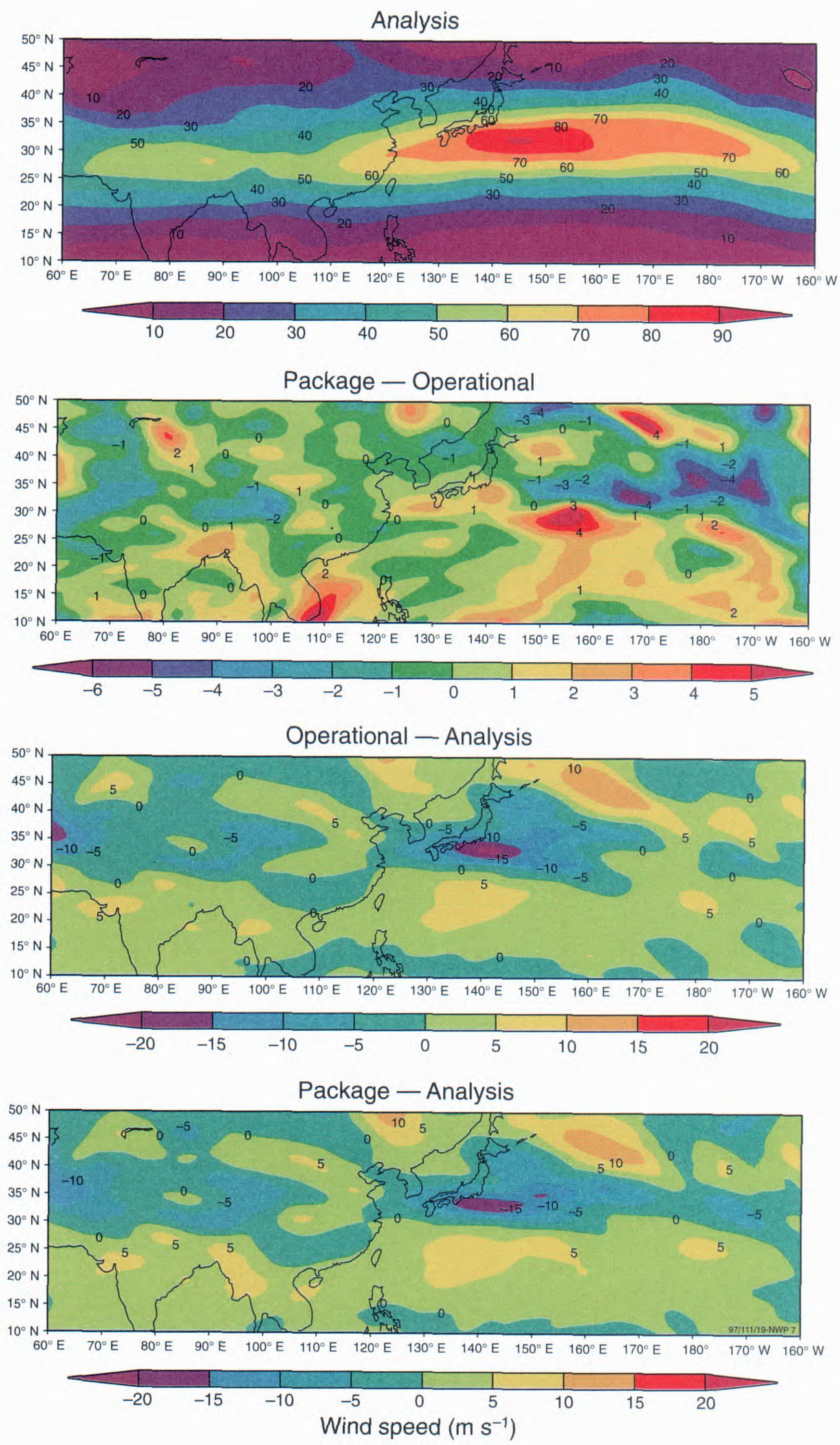


Figure 18. 72-hour forecasts of 250 hPa winds over the Pacific region. Charts labelled 'package' refer to forecasts made with the model changes listed.

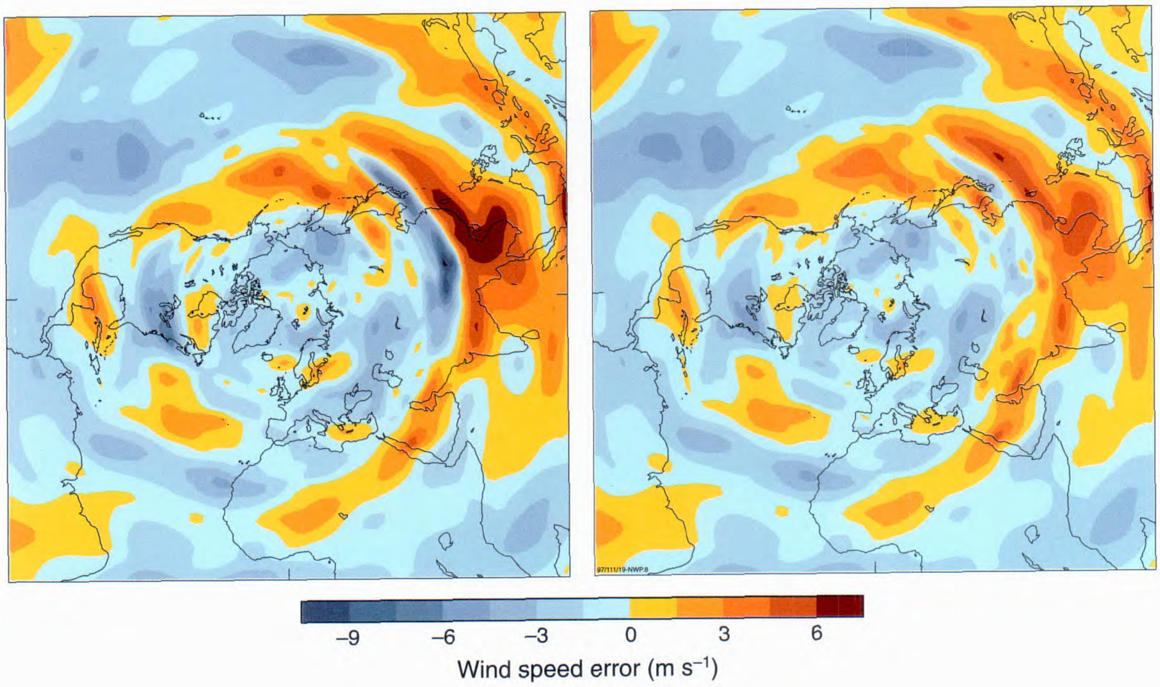


Figure 19. Zonal wind error at 70 hPa for 3-day forecasts, averaged over five winter cases. Left, original scheme; right, revised scheme.

A revision to the orographic gravity-wave-drag parametrization was necessary because, although the scheme is designed to be as realistic as possible, uncertainty remains as to where in the vertical the drag should be exerted. With the original implementation of the scheme too much drag was exerted in the stratosphere. Consequently, in the northern hemisphere's stratosphere in winter, the largest systematic wind errors occurred over and downstream of the major orographic regions (Fig. 19, left).

Furthermore, the dynamical response to these stratospheric wind errors led to the tropospheric jets below being too weak. In collaboration with the Atmospheric Processes Research Branch, the scheme has been revised within the bounds of uncertainty so that more drag is exerted in the troposphere and less in the stratosphere. The impact of the revisions has been to substantially reduce the stratospheric wind errors (Fig. 19, right)

Dynamical formulation

A revised solution of the dynamical equations in the UM has been developed. It is designed to improve the balances between the various processes described by the model. These are both dynamical balances and balances between physical and dynamical effects. The latter include, for example, the balance between heating due to large-scale subsidence and cooling due to radiation or turbulent entrainment of cooler air.

The techniques necessary involve a more-accurate advection scheme, and a semi-implicit integration scheme, where the large-scale vertical motion is computed implicitly as a response to the various forcing terms. The variables in the model are arranged in a different way on the grid, removing undesirable oscillatory solutions from the implicit solution. The use of this form of semi-implicit scheme allows the model to be non-hydrostatic without extra cost.

The better treatment of balances results in a more coherent forecast field, as illustrated by the potential vorticity maps (Fig. 20). This is a sensitive test, because potential vorticity is a highly differentiated quantity, and thus tends to magnify numerical errors. These results are obtained with no explicit spatial smoothing in the new scheme, while a highly scale-selective filter has been applied to fields from the current UM.

Work is now proceeding to see if this new scheme should be implemented in the UM. A particular advantage will be the ability to run at extremely high resolution, because of the use of a non-hydrostatic formulation.

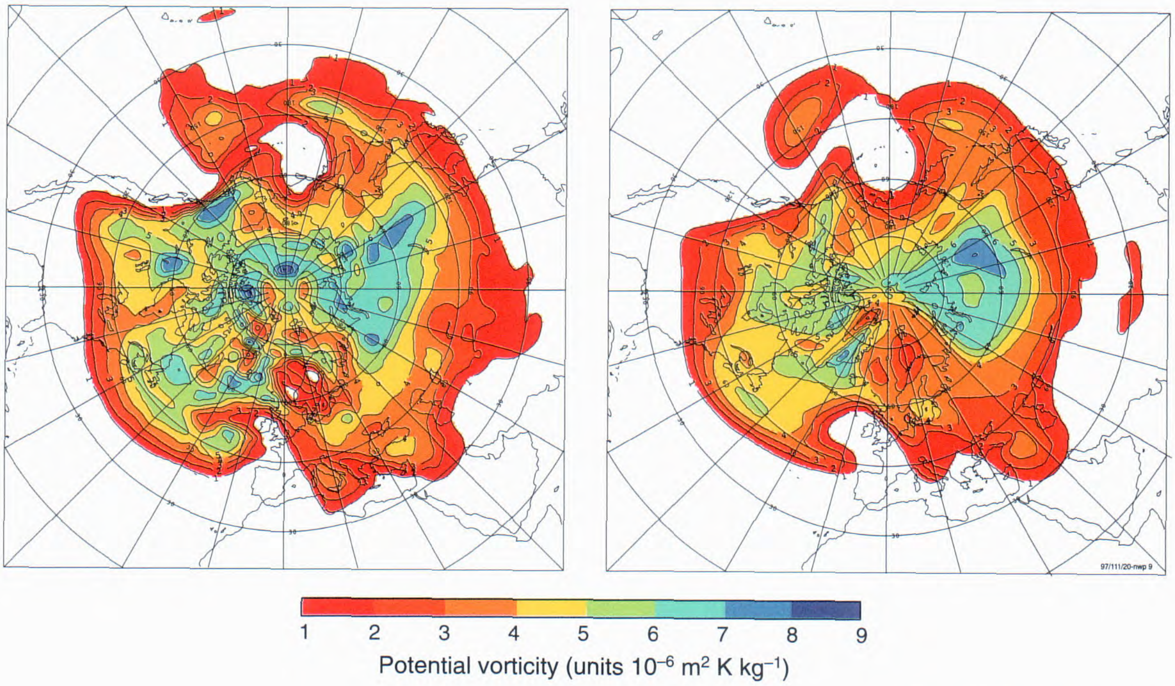


Figure 20. Ten-day forecasts of potential vorticity at 315 K using the current *Unified Model* in a climate model configuration (left) and the same with the new dynamics (right).

Atmospheric Processes Research

The Met. Research Flight C-130 Hercules aircraft.

Treatment of atmospheric flow as that of a compressible fluid, obeying classical physical laws, has led to successful weather forecasting by computer. However, many processes are poorly understood, or occur at too fine a scale to be resolved on a forecast model grid, and must be represented (or parametrized) as mathematical expressions in terms of other model variables (Fig. 21). The quality of numerical weather prediction (NWP) forecasts depends to a large extent upon the accuracy of these parametrizations.

The level of complexity involved in some phenomena (e.g. radiative transfer in a field of convection clouds) is often formidable and requires a deep understanding of the underlying physics. The role of Atmospheric Processes Research (APR) and the Meteorological Research Flight (MRF) is to combine observational, numerical modelling and theoretical studies in order to improve the representation of these processes through greater understanding. APR and MRF scientists collaborate with other experts in the UK and international research communities through the Joint Centre for Mesoscale Meteorology, based at the University of Reading, through the visiting scientist scheme and through participation in international research projects such as EUCREM and FASTEX. See under Convection and Mesoscale dynamics.

The Met. Office has two facilities for the gathering of research-quality field observations: the Lockheed C-130 aircraft operated from Boscombe Down by the MRF, and the tethered balloon and surface instrumentation site at APR's Meteorological Research Unit, Cardington. The facilities not only provide data for in-house projects but also allow The Met. Office to play a lead role in major international collaborative projects and to gain access to the resulting data sets in a very cost-effective way. Nevertheless, for reasons of cost or practicality, field observations seldom provide all the information that

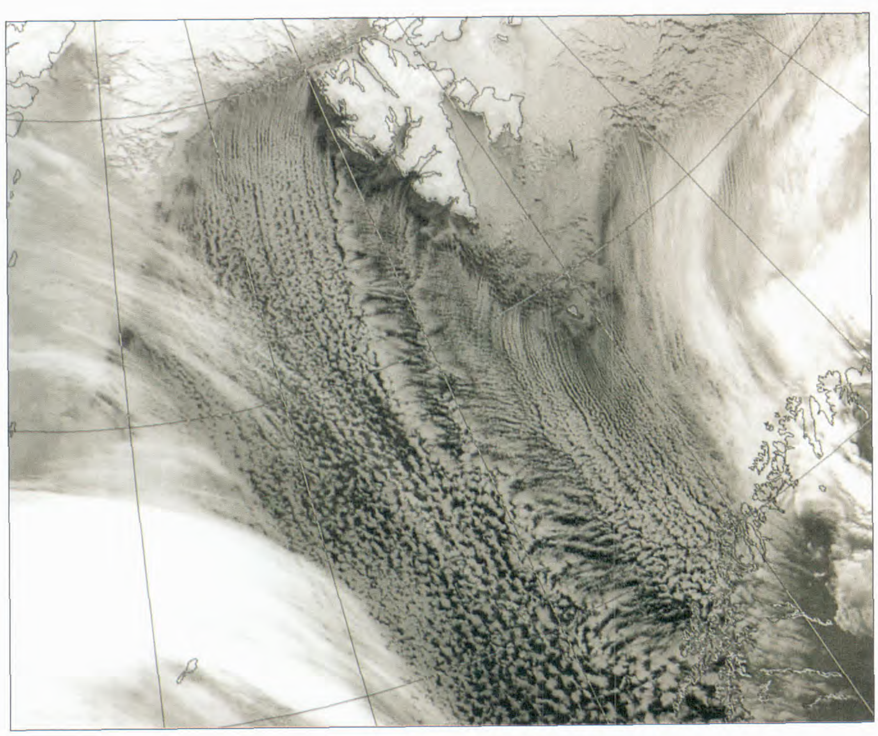


Figure 21. Clouds form in a wide range of shapes and sizes, as this infrared satellite picture demonstrates. Small clouds (centre) cannot be resolved by operational NWP models but they can be represented through mathematical expressions or 'parametrizations'. This view shows the Greenland Sea and part of the Norwegian Sea. The coastlines of eastern Greenland and of northern Norway are at the top left-hand and bottom right-hand corners respectively; Spitsbergen is visible at the top of the picture.

is needed, and high-resolution numerical models such as the Large Eddy Simulation (LES) model have become extremely important and efficient tools for devising parametrizations for The Met. Office's Unified Model (UM). These models are sufficiently realistic in their description of processes like boundary layer flow or convection that, once validated, their output data sets may be used as a substitute for real observations.

Research supporting improvements to parametrizations within the UM is part of core research. APR also supports the Public Met. Service (PMS) in the development of advisory and emergency response models, such as the Nuclear Accident Model (NAME) and STOCHEM, describing the movement, dispersion and chemical transformation of material in the atmosphere. Other external customers in government and industry gain benefit from the expertise and mathematical models developed within APR and MRF through contract research projects. See under **Atmospheric dispersion** and **Modelling of tropospheric chemistry**.

Figure 22. Liquid nitrogen being transferred into one of the C-130 instrument pods containing the Scanning Airborne Filter Radiometer (SAFIRE).

Data gathering

Meteorological Research Flight

The C-130 aircraft carries a range of instrumentation capable of measuring not only the basic meteorological variables but also cloud and aerosol particles, atmospheric radiation (Fig. 22) and atmospheric chemistry.

One of the most important additions to the C-130's instrument portfolio is the GPS (Global Positioning System) dropsonde. Dropsondes are expendable instrumented packages ejected from the aircraft. Falling by parachute, they transmit meteorological data back to the aircraft and allow vertical cross-sections of weather systems to be derived. Early dropsondes were large, heavy and expensive, but the new GPS sonde is both light and sufficiently cheap to be deployed in large numbers. It uses conventional mass-produced radiosonde technology and relies on the GPS for accurate location. During the FASTEX project in January and February 1997, the C-130 deployed over 600 dropsondes.

During the year the aircraft was involved in three large international experiments detailed later. In addition to missions around the UK it has operated over the Arabian Gulf, the Mediterranean and Baltic Seas, the North Atlantic Ocean and various sites in Spain, Sweden and Finland.

Met. Research Unit, Cardington

In 1996 the Met. Research Unit installed a surface instrumentation array at the Cardington field site, consisting of sonic anemometers, resistance and infrared thermometers, soil thermometers, dew-point, infrared and capacitative humidity

Figure 23. Surface instrumentation on masts at Cardington with the moored balloon silhouetted in the background.

sensors, radiometers, a solarimeter, a visiometer, a rain gauge and a pressure sensor. The instruments, mounted in the ground or at various heights on masts, are logged continuously at a high rate to measure mean and turbulent quantities (Fig. 23). The surface measurements complement the daily balloon profile (CABLES, previously known as BALTHUM) measurement programme and are used for routine validation of boundary layer forecasts produced by the mesoscale model (Fig. 24).

Soil moisture probes and additional thermometers at depths of up to 1.6 metres are being added to the surface instrumentation site. These will provide reference data for surface moisture in the forecast model which has shown significant errors in recent years, having a tendency to predict unrealistically low values of soil moisture in hot summers. Improvements have also been made in the balloon ascent programme by increasing the maximum height of the ascents, keeping the balloon on a mast mooring which avoids most

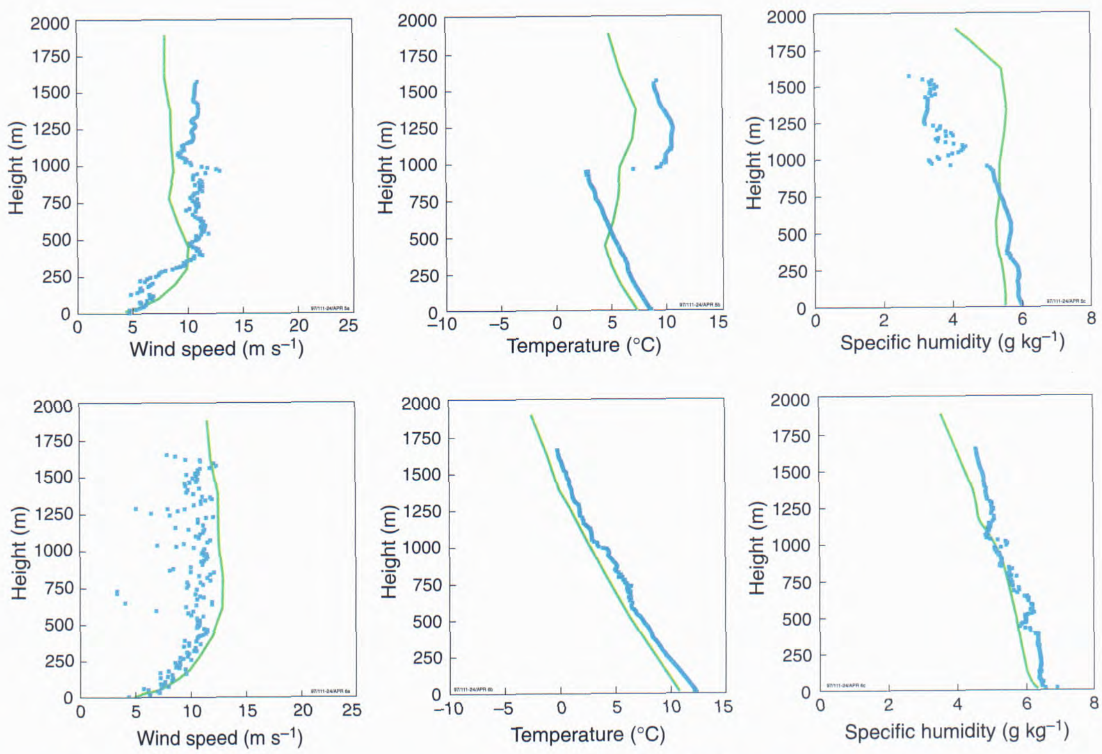


Figure 24. Top row, profiles of wind, temperature and specific humidity from 7 March 1997 as measured by from the tethered balloon (symbols) and as forecast by the mesoscale model (continuous line). The comparison shows that both a strong (7 °C), sharp inversion and an associated hydrolapse were not captured by the forecast. Bottom row, profiles of wind, temperature and specific humidity from 14 March 1997 demonstrating generally good correspondence between the mesoscale forecast and balloon data.

operational wind limitations, and by flying additional sondes on the 20% of occasions when lightning risk prevents the balloon from flying.

Stable boundary layers (SBLs)

Stably stratified boundary layers occur when the land or sea surface is colder than the overlying atmosphere. SBLs occur worldwide, particularly over land and ice-covered areas at night, and also over the sea. Because SBLs inhibit the transfer of heat, water vapour and momentum to and from the surface, they have an important effect on, for example, surface temperature and fog formation. Their correct parametrization in numerical models is important for both weather and climate prediction.

Under stable conditions, turbulence is weak but not negligible, and is governed by a delicate balance between thermal stability and wind-shear. This balance is characterized by the Richardson number, *Ri*, a fundamental stability parameter in the study of turbulence. This parameter largely determines the depth of the boundary layer, and how much heat is transferred towards the surface.

Balloon-borne turbulence measurements have been made at Cardington's relatively flat and open site. When analysed in terms of mixing length versus *Ri*, they show lower levels of turbulence at higher values of *Ri* than predicted by an existing parametrization used in the UM (Fig. 25). Work is in progress to develop improved schemes, taking into account the sensitivity of SBLs to such factors as hills and non-uniform terrain.

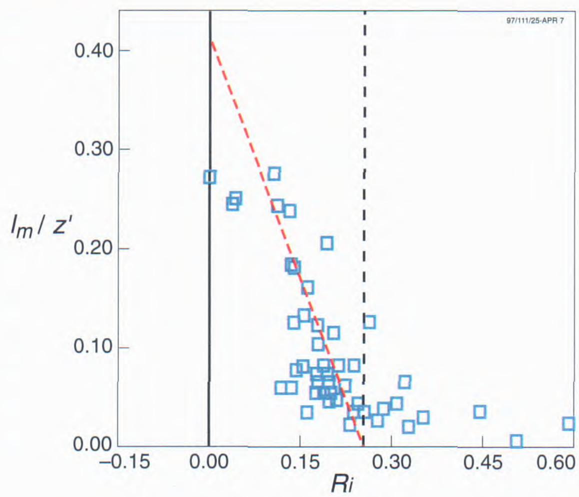


Figure 25. Results from several night flights at Cardington. Mixing length l_m is scaled by a modified height z' and plotted against *Ri*. The line at $Ri = 0$ marks the transition from stable to unstable conditions. The dashed line shows a theoretical stability boundary at $Ri = 0.25$; and the red line depicts the parametrization currently used in the UM.

Cloud physics

Drizzle is an important process in stratocumulus clouds. It can deplete the cloud liquid water content, stabilize the boundary layer at the level at which it evaporates and also contribute to decoupling the cloud layer from the sea surface. These processes may strongly influence the subsequent evolution of the cloud layer and the development of inhomogeneities within it. Flights by the C-130 have been made specifically to investigate the spatial and temporal variability of drizzle occurrence in these clouds.

Precipitation rates in a stratocumulus layer producing drizzle-size droplets are extremely variable. A typical example is shown in Fig. 26 of how these rates can vary

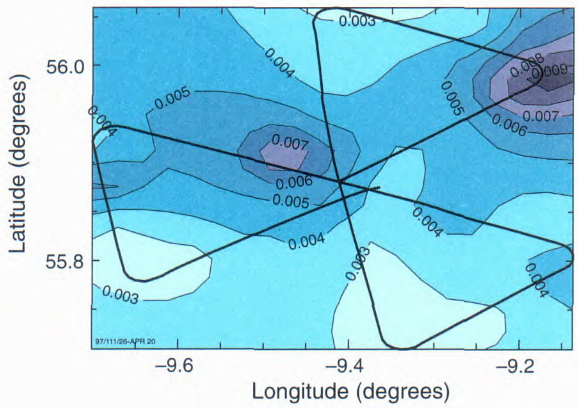


Figure 26. Contour map of the precipitation rate ($gm^{-2} s^{-1}$) in a stratocumulus layer as measured by the MRF C-130 on 29 February 1996 to the north-west of Ireland. The overplotted 'clover leaf' is a representation of the aircraft flight track.

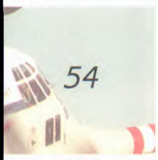
on length scales of 20–30 km. Precipitation rates at cloud base in maritime air masses have also been found to be up to six times larger than those in continental air masses. The aircraft measurements have shown that the maximum precipitation rate is a function of the cloud liquid water content, cloud thickness and the effective radius and number concentration of cloud droplets, but more data are required to understand why the production of drizzle-size droplets has such large spatial and temporal variability.

These important drizzle processes occur on length scales much smaller than NWP model grid-box length scales. Work is continuing to develop parametrizations of these processes so that adequate model simulations can be produced.

Radiation and aerosols

Atmospheric aerosol particles are capable of scattering and, in some cases, absorbing solar radiation. The magnitude of this clear-sky direct forcing is a source of uncertainty in the radiative balance of the Earth's atmosphere. Model calculations suggest that, when globally averaged, this forcing is a significant fraction of anthropogenically induced greenhouse gas forcing, but opposite in sign. Assessment of this effect is complicated by the strong regional and temporal variation in aerosol distribution; aerosol particles are associated with industrial areas, regions of biomass burning and may have lifetimes of the order of days.

The main chemical components are sulphates, organic compounds, elemental carbon from incomplete combustion, ammonium and nitrates. A complete description of direct aerosol effects is not yet possible, however, the magnitude of the forcing can be quantified by relating observed changes in the flux of solar radiation to the observed aerosol loading.



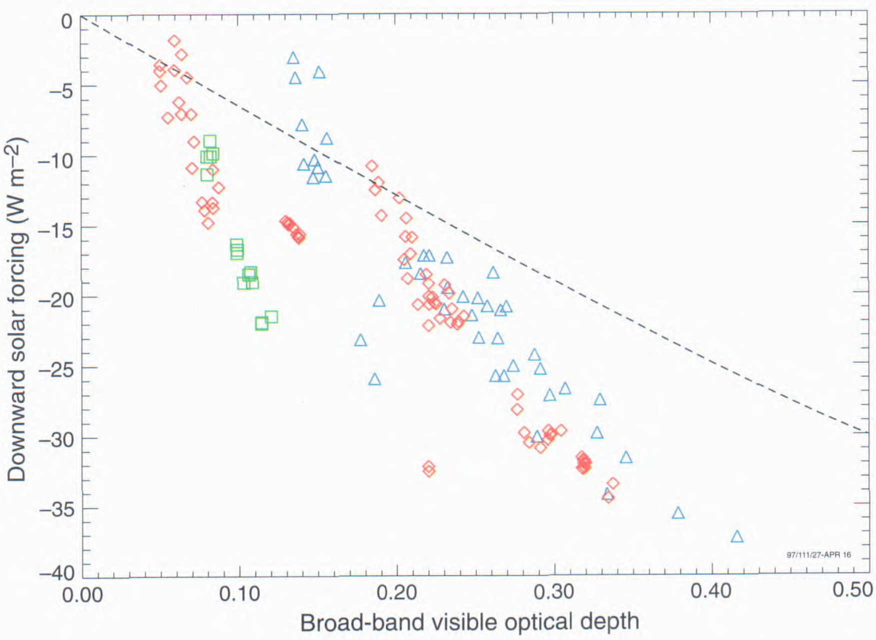


Figure 27. The downward solar forcing measured by the MRF C-130 during TARFOX plotted against the aerosol optical depth. The dashed line is the forcing predicted for a dry ammonium sulphate aerosol. The colour symbols indicate data from different flights.

TARFOX

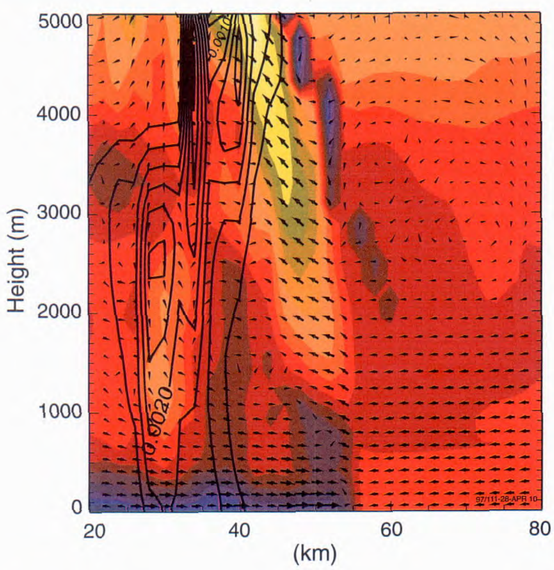
The Tropospheric Aerosol Radiative Forcing Experiment (TARFOX) was conducted in July 1996 off the east coast of the USA to examine the direct forcing in detail. The area is known for high summertime aerosol amounts. TARFOX is an international, multi-platform project designed to measure the physical, chemical and radiative properties of the aerosol from surface sites, aircraft and satellites. The C-130 aircraft was uniquely equipped to measure the upwelling and downwelling solar radiative fluxes, and to split the downwelling flux into its direct and diffuse components (the greater the aerosol loading, the larger the diffuse to direct ratio). At the highest aerosol loadings encountered the deficit in the downward solar flux at the surface was around 60 W m^{-2}.

Various cross-checking experiments are being carried out by TARFOX participants. Directly measured aerosol properties, such as optical depth, are compared with the results of calculations based on scattering theory with aerosol refractive indices and size distributions, derived from observation, as input. The C-130 data allow the measured and calculated optical properties to be used in a radiative transfer model with the resulting predicted direct and diffuse fluxes to be compared with observation. The direct aerosol forcing can be expressed as the difference between the observed and aerosol-free solar fluxes. In this case the Edwards–Slingo radiative transfer code from the UM is used to define the aerosol-free state, using aircraft measurements of temperature, pressure and humidity. Fig. 27 shows the diurnally averaged downward direct aerosol forcing over three days during TARFOX, as a function of aerosol optical depth, a measure of the extinction of the incoming solar radiation. For comparison, the dashed line is the predicted forcing under the same average atmospheric conditions for a dry ammonium sulphate aerosol, the type of aerosol usually included in general circulation models used for climate studies.

Convection

The infrared satellite picture shown in Fig. 21 depicts the Greenland Sea and part of the Norwegian Sea. The coastlines of eastern Greenland and of northern Norway are at the top left-hand and bottom right-hand corners respectively; Spitsbergen is near the top of the picture. Two main types of cloud are seen: large swathes of high cloud associated with large-scale weather systems (bottom left), and smaller clouds which lend a 'dappled' view and indicate convection as cold polar air moves southward over a comparatively warm sea surface (centre).

The dappled convective 'cloudscape' shows structure on a range of scales, most of which are too small to be resolved by NWP models used in weather forecasting and climate simulation. The small-scale circulations associated with these convective clouds are nevertheless accomplishing transfers of heat and moisture which must be adequately parametrized in these models. Convection studies make use of high-resolution, LES-type numerical models to test and improve parametrizations. These cloud-resolving models concentrate their computational power on a small horizontal domain (typically 100 km by 100 km) and can reproduce the small-scale circulations explicitly. This allows direct calculation of the heat and moisture transfers achieved by these circulations.



Work has centred on five cases that were intensively observed during earlier international programmes. One case is shown in Fig. 21: aircraft and surface-based observations were made in the region to the west and south-west of Spitsbergen where vigorous convection was occurring. The other four cases cover a range of convective cloud episodes, from a tropical squall-line to an outbreak of continental thunderstorms. Comparisons between observations and results for the cloud-resolving models have been done partly in collaboration with other meteorological centres under the EU-financed EUCREM project (European Cloud Resolving Models). As well as allowing specific parametrizations to be tested and improved, the work has focused attention on some issues fundamental to the parametrization problem, especially those which occur when the clouds are organized on a scale comparable with the resolution scale of the forecasting model.

Figure 28. A vertical cross-section of the gust front of an Oklahoma squall line simulated using the cloud-resolving model. Colours represent perturbations of potential temperature (blue = −5 K, red = 0 K, orange = 5 K). Line contours show rain mixing ratio (at 0.5 g kg^{-1} intervals) and arrows show velocity. Evaporation of rainfall in the downdraught generates a pool of cold air at the surface, which forces inflowing warm, moist air upwards, thus developing a new convective cell which will rain out into the cold pool and perpetuate the cycle. This accounts for the longevity of the system and is one of the features of MCSs that the new parametrization will attempt to represent.

Mesoscale Convective Systems (MCSs) are large complexes of thunderstorms, forming a continuous cloud area some several hundreds of kilometres in diameter, which may last for well over 10 hours. These are important in both forecasting and in climate modelling. They are associated with severe weather such as heavy rain, gusts, hail and even tornadoes, and they are the chief sources of rainfall over summer continents and areas such as the Sahel.

The representation of MCSs in the UM is challenging because they begin as sub-gridscale areas of deep convection but mature to be partially or fully resolved features which can have significant effects on the larger-scale flows. A recent study has shown shortcomings in the UM's ability to model MCSs, but current work aims to improve this. Comparisons between a series of MCS cases and corresponding simulations by a cloud-resolving model (Fig. 28) will be used to evaluate a new parametrization scheme being developed.

Entrainment and shallow convection

In Large Eddy Simulation (LES) of turbulent flow the aim is to resolve the dominant energy-containing scales responsible for most of the transport, while parametrizing the smaller scales which are mainly associated with dissipation. An example of the type of detailed simulation possible with LES is shown in Fig. 29. Overturning eddies associated with entrainment at the top of a boundary layer are shown. These eddies are well-resolved in spite of having a length scale of 25 m, which is very small compared to the boundary layer depth (700 m).

The current version of the UM contains no explicit representation of entrainment at boundary layer top, which is a serious deficiency. A recent LES study has led to an entrainment parametrization which includes the effects of surface heating, as well as cooling due to radiative and evaporative processes, where the boundary layer is cloud-capped. This is being evaluated for operational use.

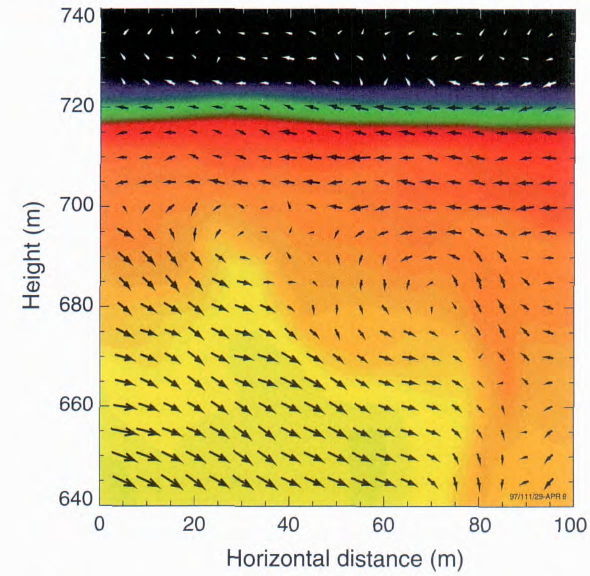


Figure 29. A close-up of the region around boundary layer top from an LES with 5 m resolution; the inversion marking the top of the boundary layer is at about 720 m. A vertical cross-section through a very small fraction of the model domain is shown. The velocity vectors are parallel to the instantaneous flow in the plane of the plot, revealing overturning eddies with a scale of about 25 m. The coloured background on which they are superimposed represents the mixing ratio of a tracer which is being advected with the flow.

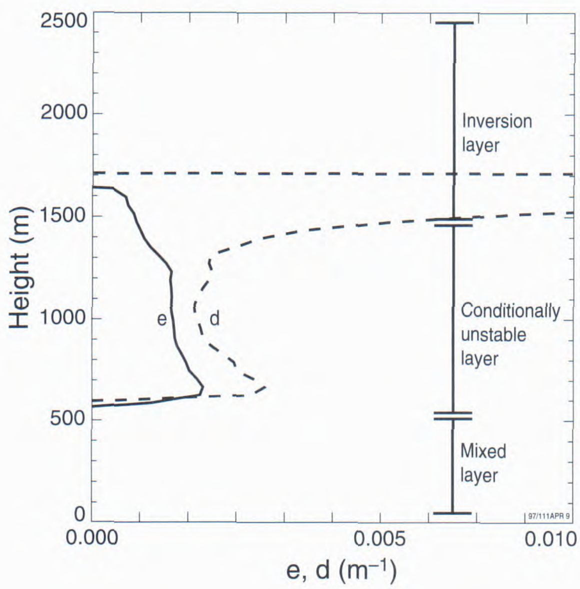
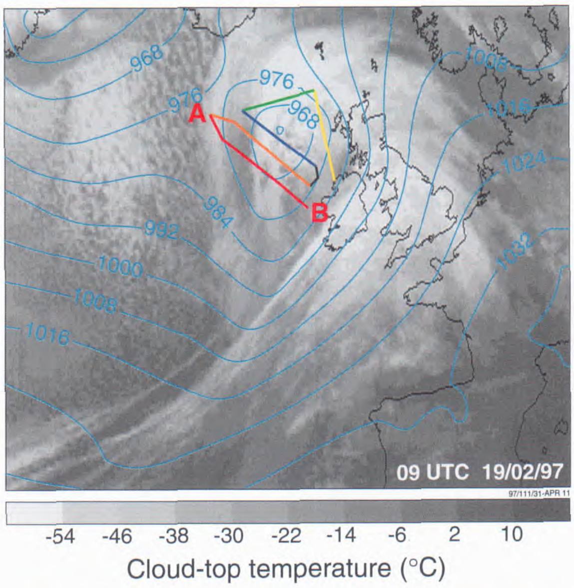


Figure 30. Profiles of the fractional rates of entrainment into (e) and detrainment out of (d) an ensemble of cumulus clouds in an LES. The profiles represent averages across the whole horizontal computational domain and over a period of 4 hours.

LES studies have also found a potential shortcoming in the UM convection scheme. Studies of an ensemble of shallow cumulus clouds indicate that entrainment exceeds detrainment (indicating a net loss of plume material to the environment) at almost all levels including throughout the conditionally unstable layer (Fig. 30). An individual cumulus updraught tends to grow in area through entrainment as it ascends. But in an ensemble, the net excess of detrainment over entrainment results from detrainment of weaker updraughts to extinction at different levels below the inversion, with relatively few clouds reaching the inversion. In contrast, the current UM convection scheme specifies that entrainment exceeds detrainment below the inversion, with both being an order of magnitude smaller than the rates seen in LES. Research is being carried out to discover whether similar discrepancies are found in other cases, and to find out if a more complex parametrization of detrainment is needed.



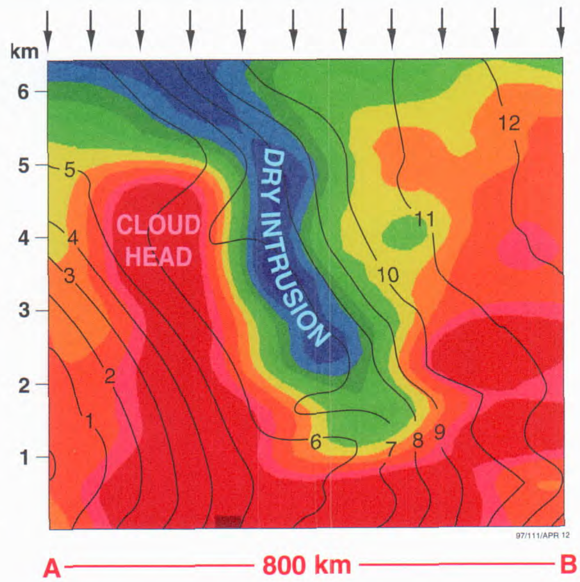


Figure 31. Meteosat infrared image with the MRF C-130 aircraft track superimposed for 0900 UTC, 19 February 1997. The grey shades indicate cloud-top temperature according to the scale shown. The blue contours show a 3-hour forecast of mean sea-level pressure at 8 hPa intervals from the operational Limited Area Model. Coloured lines indicate the aircraft track shifted in space to a frame moving with the velocity of the cyclone.

Figure 32. Analysed cross-section from the flight leg marked AB in Fig. 31. Wet-bulb potential temperature is overlaid in contours on relative humidity in colour shading. Dropsonde locations are marked with arrows above the top axis. To the left-hand side is the exit flow from the ascending cloud head north of the low centre, while in the centre is the mesoscale dry intrusion associated with strong descent near the low centre.

Mesoscale dynamics

Fronts and Atlantic Storm Track Experiment (FASTEX)

Frontal waves account for most of the severe weather approaching north-western Europe and the aim of the FASTEX international experiment is to develop better predictive capability of the timing and character of these storms. Though centred on the North Atlantic Ocean, much of the understanding gained from FASTEX will also apply to similar systems in the Pacific.

The observational phase of FASTEX (January–February 1997) studied the life cycle and structure of Atlantic storms using some of the most powerful mesoscale observing systems developed over recent years, including the C-130 and four US research aircraft, two of them equipped with dual Doppler radar.

The observations were carried out in two main regions, an upstream area west of 30° W and a Mesoscale Sampling Area (MSA) in the eastern Atlantic. The upstream experiment recorded the early development of weather systems in the western Atlantic with dropsondes and ship-launched radiosondes. The MSA experiment examined the internal structure of the systems at a more mature stage. Full life-cycle measurements of ten cases were completed, including some of the weather systems that brought severe weather to Britain during February 1997.

The C-130 and Doppler radar aircraft flew closely co-ordinated patterns in the MSA to characterize both the mesoscale environmental structure of the developing weather, and also the kilometre-scale airflow within the cloud and precipitation (Figs 31, 32). Many ancillary measurements of cloud, radiative and other properties were also made. A novel and exciting aspect of the experiment was the combination of dropsonde and Doppler radar observations, which will allow deduction of three-dimensional temperature distributions at cloud scale. These should enable study of the internal structures and effects of latent heat transfers in frontal cloud to a degree not previously possible.

Most additional soundings were transmitted to the Global Telecommunication System in real time, making them immediately available for operational weather forecasting. The resulting higher-quality forecasts not only aided flight planning but also provided a basis for studies of the sensitivity of operational forecasts to the location and quantity of observational data.

Data from FASTEX will provide a basis for the investigation of mesoscale processes and the testing and improvement of model parametrizations. The combination of high-resolution sounding and other data also has great value for improving algorithms used for retrieval of satellite data, with benefits for forecasting through better data assimilation and analysis.

Influences of orography on atmospheric flow

Gravity wave drag

Most current schemes describing the effect of mountain-forced wave drag in NWP models are based on restrictive two-dimensional studies. The wave-induced drag force is assumed to be independent of height unless a break-up of the wave occurs due to overturning, dissipation or the occurrence of a 'critical level' (where the wind becomes aligned with the mountain ridge). Wave drag due to critical-level effects is far more prevalent when this result is generalized to the full three-dimensional picture (where wind turns with height flowing over real mountains). A drag force which continuously varies with height may be deduced for many atmospheric conditions. These effects are now undergoing tests for incorporation into the UM.

Theoretical analysis of the approach of gravity waves radiated from a localized source towards a critical level shows that the presence of directional wind shear fundamentally alters their behaviour (Fig. 33).

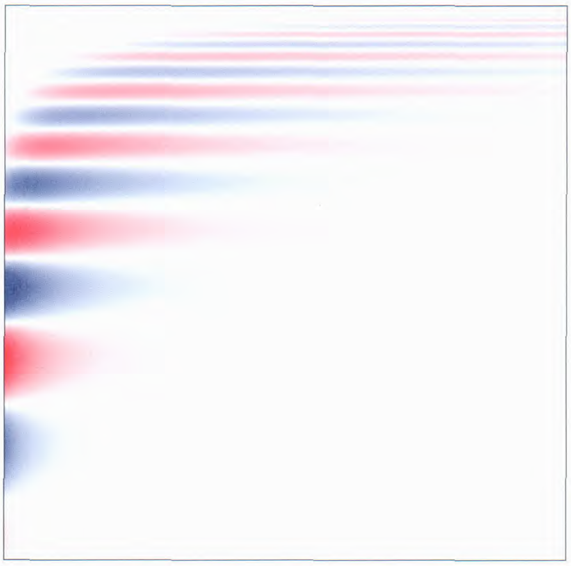


Figure 33. The horizontal wind perturbation derived from an analytic solution of flow over an isolated hill plotted in a vertical plane oriented at 45 degrees to the surface wind direction. The flow backs continuously with height and becomes parallel to the section at a height of 10 km where the shrinking vertical wavelength indicates the presence of a critical level.

Unlike the purely two-dimensional critical level, the existence of a wind component parallel to the phase lines causes wave energy to be dispersed downwind thereby avoiding a steady build-up of wave energy beneath the critical level.

Boundary layer flow over hills

The 'roughness length' of a surface is a scaling factor that determines the drag exerted by the surface on the wind. This must be correctly specified within the UM if wind speeds are to be correctly simulated. Over flat terrain, roughness lengths are determined by the physical characteristics of the vegetation. The way that

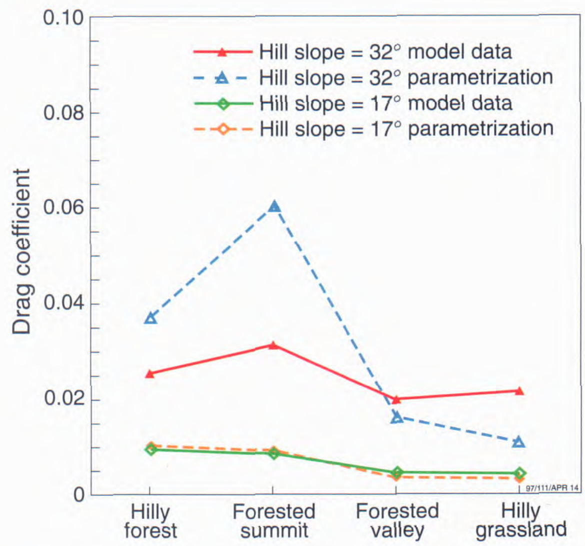


Figure 34. The total drag coefficient calculated from the numerical simulation (solid lines) and from the parametrization (dashed lines). The lines with diamonds are results for a low sloped hill and the triangles are for a steep hill where flow separation occurs. Four cases are presented for each hill: hill covered completely by forest; only the summit area forested; only the valley forested; and hill covered completely by grass.

roughness lengths for complex terrain increase over corresponding flat terrain values is not fully understood. Past research has examined idealized cases of regular hills and valleys covered in uniform vegetation, but in reality many hills are partially forested.

Numerical simulations of flow over such hills indicate that, for steep slopes where flow separation occurs, the total drag coefficient is over 50% larger when the forest is on the crest of the hill than when it is in a valley (Fig. 34). A similar result is also found for the scalar transfer coefficient. A simple parametrization to model this behaviour has been developed.

Atmospheric dispersion

Understanding the way material disperses in the atmosphere is important for predicting routine pollution levels and for responding to accidental releases of hazardous material. The Met. Office develops and maintains models for predicting the movement, dispersion and chemical transformation of material in the atmosphere.

These include the Atmospheric Dispersion Modelling System, for calculating dispersion over short ranges where the dispersion is dominated by the turbulence in the atmospheric boundary layer (developed jointly with Cambridge Environmental Research Consultants Ltd and the University of Surrey). NAME is a multiple-particle dispersion model for mesoscale and longer ranges, and BOXURB is an urban box model for predicting routine urban pollution levels.

Short-range dispersion

Hazards from some pollutants are due more to the size of short-term peaks in concentration than to the average values over an hour or more. For example, this is the case in the effect of sulphur dioxide on asthmatics, or in assessing the hazard from an accidental chemical release. The understanding of such fluctuations has improved in recent years, but an area of uncertainty is the effect of multiple sources. If a plume meanders without significant mixing, the peaks may be no worse than for a single source. If it mixes, the hazard may increase. A joint field experiment, carried out with the Chemical and Biological Defence Establishment, showed that the type of behaviour likely to occur can be determined from the source separation and downwind distance, using a simple scaling with various turbulence variables.

Medium and long-range dispersion

NAME has been used to estimate the emission of chlorofluorocarbons (CFCs) in Europe, and the contribution to the European regional CFC budget of emissions from North America. Using observations made by the University of Bristol at Mace Head, a remote location on the Atlantic coast of Ireland and ideally situated for the

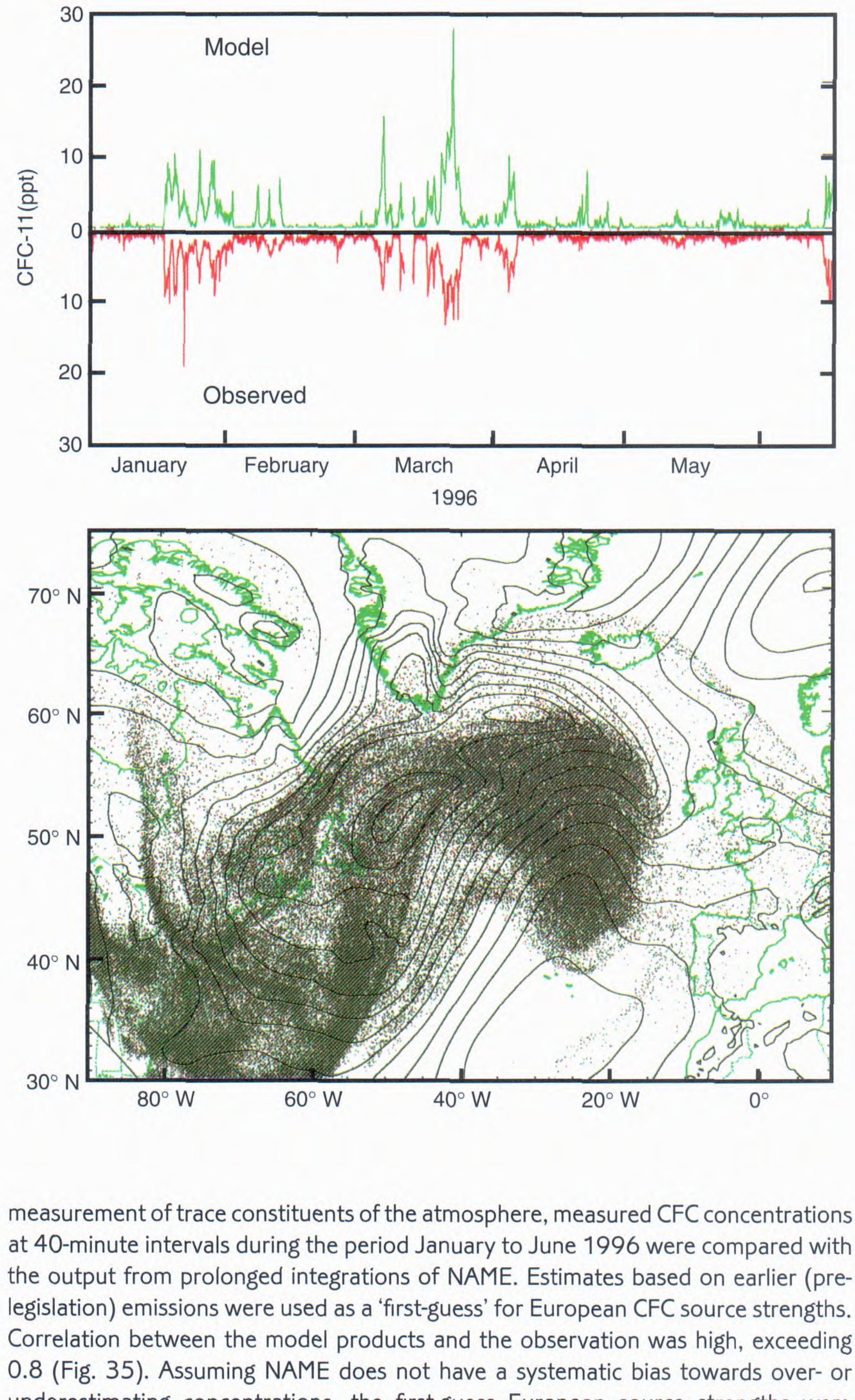


Figure 35. Top, modelled versus observed concentrations of CFC-11 from European and North American sources 8 January to 17 June 1996; correlation 0.84. Each modelled concentration was scaled by a factor equal to the slope of the line of best fit between observed and modelled concentrations. Bottom, the source of the peak values observed at Mace Head during 21–23 March was identified by the NAME model as a plume of North American CFC emissions, here shown at 1200 UTC on 20 March 1994.

measurement of trace constituents of the atmosphere, measured CFC concentrations at 40-minute intervals during the period January to June 1996 were compared with the output from prolonged integrations of NAME. Estimates based on earlier (pre-legislation) emissions were used as a 'first-guess' for European CFC source strengths. Correlation between the model products and the observation was high, exceeding 0.8 (Fig. 35). Assuming NAME does not have a systematic bias towards over- or underestimating concentrations, the first-guess European source strengths were scaled by the mean ratio of observed-to-modelled concentrations to arrive at an estimate of 1996 emissions. On average North American sources were found to account for only a few per cent of the trace gas amounts observed above the hemispherical base-line concentrations.

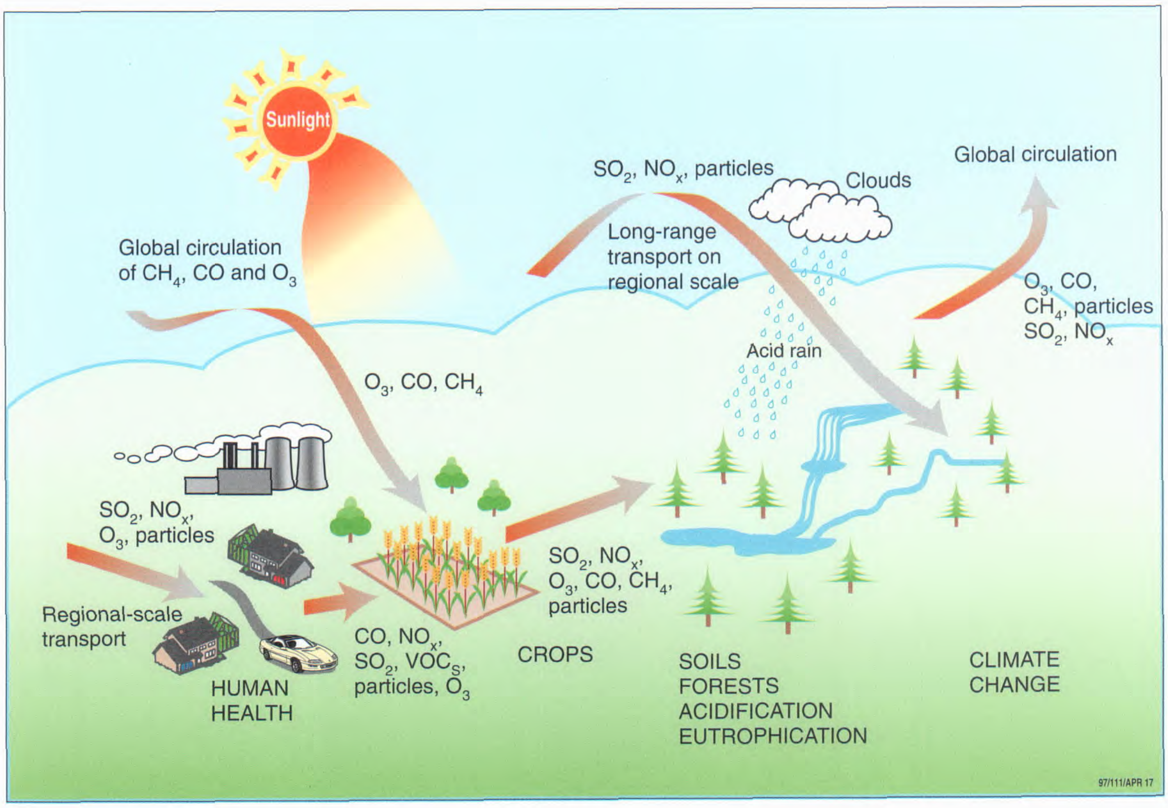


Figure 36. How regional- and global-scale processes are linked.

Modelling of tropospheric chemistry

Atmospheric chemistry research is supported through the PMS programme and through commercial contracts, largely with the DoE. The current research programme mainly addresses the role played by the nitrogen oxides (NO_x) emitted by human activities in a wide range of environmental issues. These issues cover an expanding range of spatial scales from wintertime urban pollution episodes, regional-scale acid rain and photochemical smog formation, through to the global-scale formation and accumulation of greenhouse gases (methane and ozone) and the fate of ozone-depleting chemicals (methyl chloroform and the hydrochlorofluorocarbon, HCFC-22). Some of the ways in which these regional- and global-scale issues are coupled are shown in Fig. 36.

A global three-dimensional Lagrangian chemistry model (STOCHEM) has been assembled to help understand the close coupling between the environmental impacts of NO_x. The model follows 50,000 air parcels each containing 70 chemical species emitted from industrial activities and combustion processes, from biomass burning, oceans, soils, wetlands, forests and agriculture, or formed in over 150 diurnally dependent chemical reactions. A detailed description is given of dry deposition to the Earth's surface, exchange with the stratosphere, transport with the atmospheric circulation, dispersion, convection, interaction with clouds and wet scavenging. The description of these meteorological processes uses 6-hourly data from a global archive of analysed fields from the UM at a spatial resolution of 0.833° latitude and

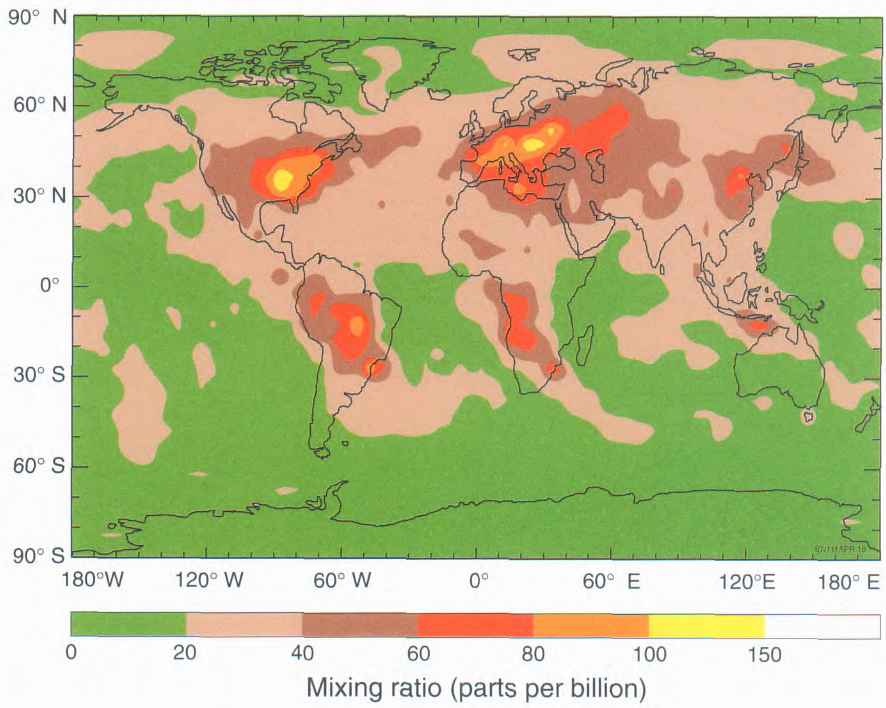


Figure 37. The surface ozone field for 24 June 1995 as produced by STOCHEM.

1.25° longitude. The surface ozone field for 24 June 1995 (Fig. 37) shows evidence of photochemical smog formation over the northern hemisphere continents, and long-range transport from North America across the North Atlantic Ocean towards Europe.

A further version of the STOCHEM model is being used within the DoE Climate Prediction Programme to follow and predict the future global increase in methane, ozone and sulphate aerosols using the Hadley Centre's climate models. STOCHEM takes meteorological data from the 'slab' version of the climate model and in turn provides data back in the form of future atmospheric compositions. A programme of model experiments is planned to study the coupling between atmospheric chemistry and climate change up to the year 2100.

The experimental atmospheric chemistry work of The Met. Office centres around the use of the C-130 in collaboration with various UK and European groups (MRF activities in atmospheric chemistry are increasingly being funded by the Natural Environment Research Council and the European Commission). The data gathered are essential to development of tropospheric chemistry modelling. To understand the changing concentrations of tropospheric ozone, a range of species which contribute to ozone production or destruction must be measured.

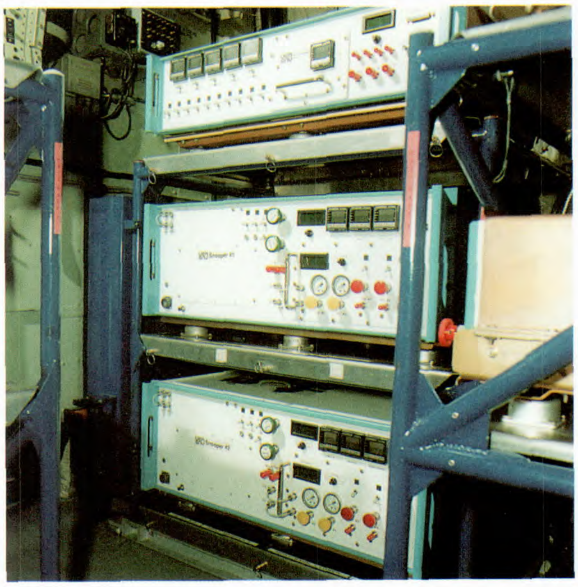


Figure 38. The four-channel NO_x/NO_y instrument installed on the C-130. The photograph shows three of five control boxes in the forward cargo area.

Table 1. Species measured in TACIA 1996
Water vapour
Ozone
Carbon monoxide
Non-methane hydrocarbons (C2 to C7 including alkanes, alkenes, alkynes and aromatics)
Hydrogen peroxide
Organic peroxides
Peroxyacetyl nitrate
Formaldehyde

A wide range of chemistry equipment has been fitted to the C-130 (Table 1 and Fig. 38) in preparation for an international experiment called TACIA (Testing Atmospheric Chemistry In Anticyclones). This includes a four-channel NO_x/NO_y instrument developed in collaboration between University of East Anglia and the US National Oceanographic and Atmospheric Administration. It is capable of detecting nitric oxide, nitrogen dioxide, nitric acid and combinations of species such as organic nitrates and dinitrogen peroxide. Several TACIA missions were flown by the C-130 in 1996; TACIA will be completed in 1997.

Modelling of stratospheric chemistry and transport

Stratospheric chemistry affects climate mainly through its influence on the amount and distribution of stratospheric ozone. The understanding of observed ozone amounts, and prediction of future amounts, depend on understanding not only stratospheric chemistry, but also stratospheric dynamics and radiation.

The accuracy of the simulated stratospheric winds and temperatures from the UM has been assessed by generating a ten-year climatology of the stratospheric version (49-level) of the model (Fig. 39). Model behaviour in the northern hemisphere is satisfactory but relatively poor in the southern hemisphere winter, with larger planetary wave amplitudes than observed and more interannual variability. The meridional circulation shows the expected rising motion in the Tropics, with descent in higher latitudes. In the northern hemisphere winter, there is not enough descent close to the pole, with even some ascent. These transport weaknesses resulted in unrealistic amounts of ozone being generated in a 19-month simulation that included fully interactive stratospheric chemistry.

In the southern hemisphere, total column ozone amounts were in agreement with observations, but in the northern hemisphere the amounts were some 30% lower in places than those observed.

Further development of the core photochemical model has also taken place. A scheme simulating the chemistry on the surfaces of aerosol droplets has been used to simulate the effect of the eruption of Mt Pinatubo on the Antarctic ozone hole. The chemistry of polar stratospheric clouds has also been incorporated in more detail in a test version of the photochemical model. These clouds are implicated in the ozone hole, as well as ozone depletion in the northern hemisphere in recent years.

Improvements in the photolysis scheme have also been made by comparisons with ground-based observations of UV irradiance. This has led to improved simulations of the diurnal variation of ozone in the stratosphere and lower mesosphere compared with satellite data.

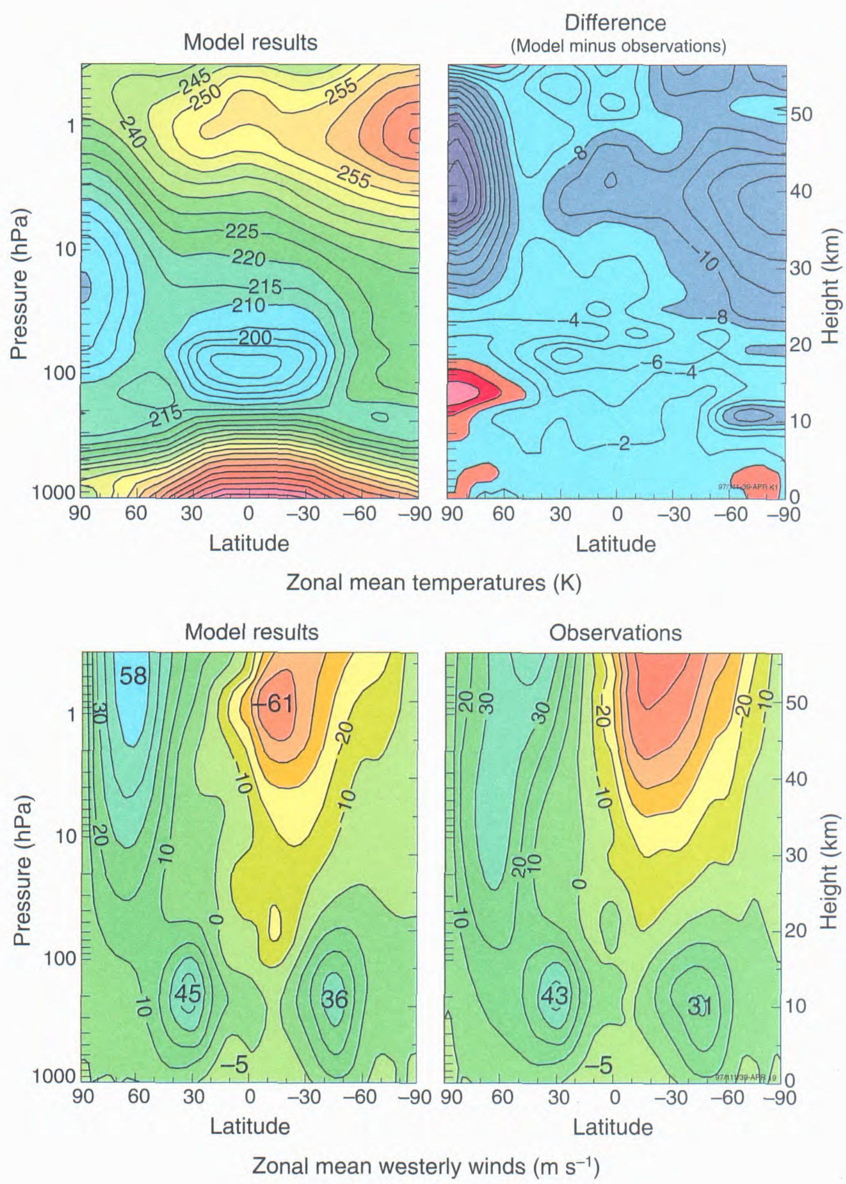
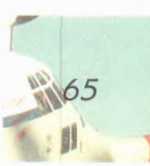


Figure 39. A 10-year climatology of temperatures and zonal mean westerly winds from the 49-level Unified Model, compared with observations.



Climate Research

A Campbell-Stokes sunshine recorder.

Prediction of climate change

The prediction of human-induced climate change is important not only for planning adaptation, but also for assessing the required extent of regulations on the emissions of greenhouse gases. The ability to make predictions is limited by the natural internal variability of climate. This uncertainty is illustrated in Fig. 40 where four simulations of the recent past, started from slightly different initial conditions, have been extended into the future using a non-intervention emissions scenario. Neither the observations nor the simulations evolve smoothly, but vary from year to year about the longer term trend. The observations of the recent past generally lie within the envelope of model simulations (except for a brief period during the middle of this century) indicating that the simulated year-to-year variability is realistic. The uncertainty in the projected global mean temperature rise at 2050 due to natural climate variability is a few tenths of a degree Celsius.

The impact of stabilizing greenhouse gas concentrations on climate change is of critical importance in assessing the effectiveness of restrictions on emissions. Even if greenhouse gas concentrations are stabilized, climate will continue to change for some time. For example, in an idealized scenario in which atmospheric carbon dioxide concentrations are slowly increased to twice present levels and then held constant, the global mean temperature will continue to increase by a further 70% after the concentrations stabilize (Fig. 41a). This is a common test of a climate model, not intended as a prediction of the future, but similar to realistic scenarios. The timescale for reaching a steady state is so long because of the large heat capacity of the ocean. The graph shows that the surface temperature change at the time when carbon dioxide concentrations stop increasing is only about half the value it would reach eventually.

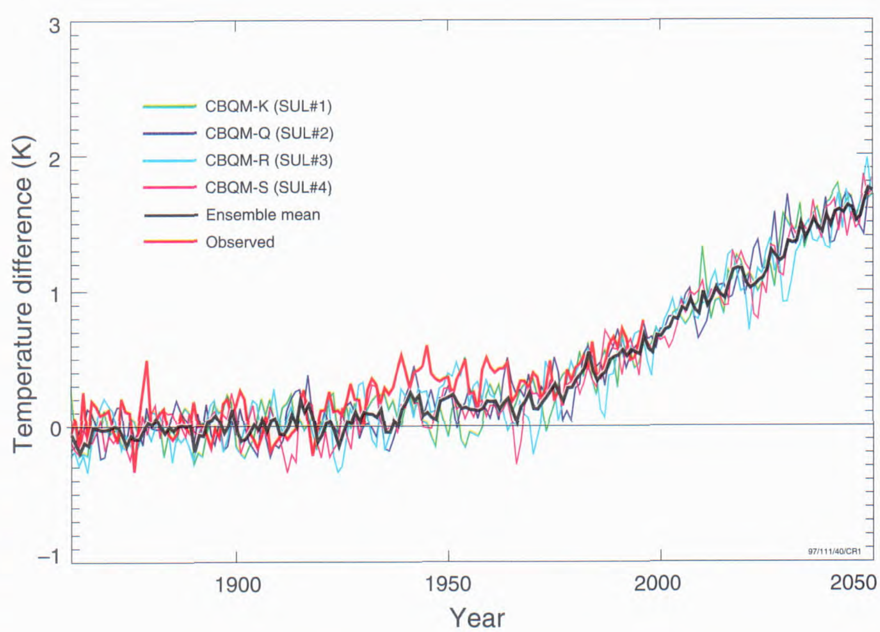


Figure 40. A graph of observed global temperature changes since 1860 (thick red line) compared with an ensemble of coupled model simulations which models the effects of both greenhouse gas and sulphate aerosol emissions. The thin coloured lines show the individual responses in four independent model predictions started from slightly different initial conditions and the thick black line shows the average or best-guess. The spread between model runs gives an impression of the uncertainty associated with the predictions.

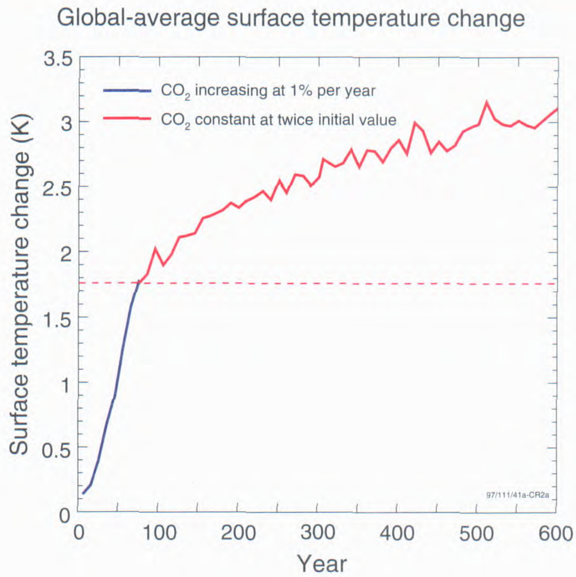


Figure 41a. This experiment with the Hadley Centre coupled atmosphere–ocean climate model (HadCM2) begins from current conditions at year 0. Atmospheric carbon dioxide increases at 1% per year compounded until year 70, at which time it reaches twice its initial concentration. The global average temperature change during this period is shown in blue. After year 70, the carbon dioxide concentration is held constant. The temperature continues to rise, shown by the red line, and does not level off even 500 years later. (The natural variability of the system is responsible for the jaggedness of the red line.)

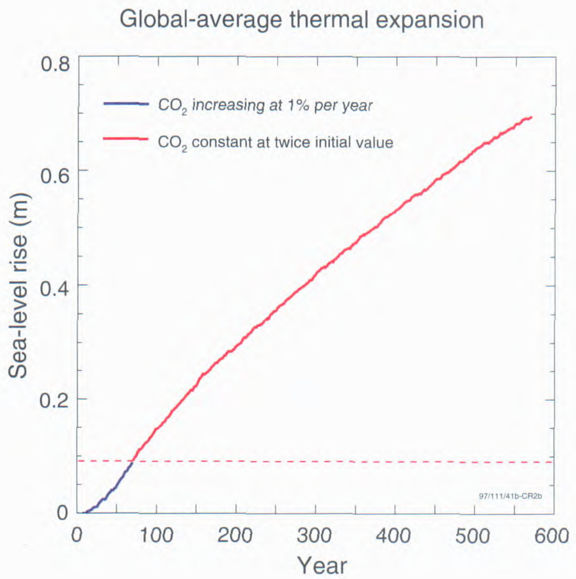


Figure 41b. This graph shows the sea-level rise from thermal expansion in the experiment of Fig. 41a. Although the surface temperature is no longer rising as fast in the later centuries, the deep ocean takes much longer to warm up, because of its large heat capacity, and is responsible for the continuing rise in sea level. After 500 years, thermal expansion reaches seven times the level it had when the carbon dioxide concentration was stabilized at year 70.

The largest contribution to global average sea-level rise in the next century will be the expansion of the water in the ocean as it gets warmer. The size of this effect provides an indication of how much heat has been taken up by the ocean. The increase in sea-level rise due to thermal expansion continues for several centuries (Fig. 41b), reaching seven times the initial rise 500 years after the concentrations stabilize. This is an illustration of the large 'commitment' to future sea-level rise which will exist even if carbon dioxide concentrations stop increasing.

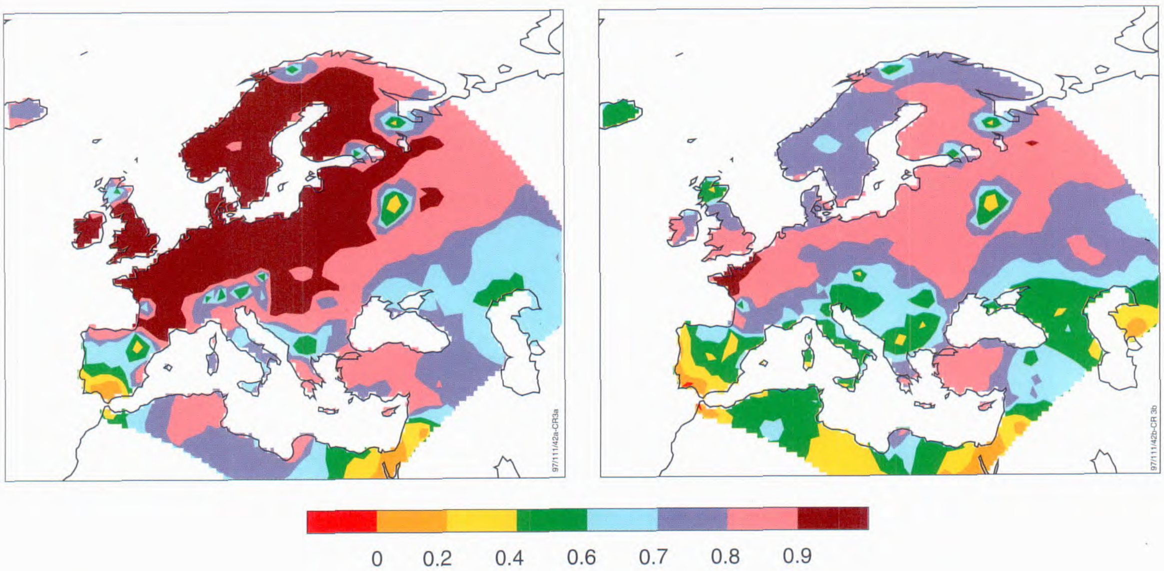


Figure 42a (above left). Correlations between predicted and observed monthly mean surface temperature for January between 1984 and 1994. The predicted values come from a high-resolution regional model nested in an integration of the Atmosphere–Ocean General Circulation Model which has been constrained to reproduce the observed atmospheric circulation over the period of interest.

Figure 42b (above right). As Fig. 42a except that the predictions are obtained from linear statistical regression equations linking the observed temperature to the first three principal components of the observed mean sea-level pressure field.

Model validation

Whereas the short-term performance of the Unified Model (UM) can be tested in a series of weather forecasts, a climate model cannot be assessed in the same way. One way to improve credibility is to ensure that the processes included in the model are physically based. A second is to compare the simulation by the model with current climate. For example, the degree of agreement between observed monthly mean January temperature over Europe and that simulated in a regional climate model driven by the observed circulation on the boundaries is shown in Fig. 42a (0 = no correspondence, 1 = perfect skill). For comparison, the level of skill derived directly from the observed circulation using statistical techniques is also shown (Fig. 42b). The regional model shows considerably more skill in reproducing the details of regional climate. One can also test the model against palaeoclimates, though this has the disadvantage that the nature and causes of past climates are imperfectly known. Figure 43 shows the simulated annual mean temperature change from present during the last glacial maximum (about 21,000 years ago). The changes in land ice and carbon dioxide are prescribed in the climate model. The global mean cooling in the model and in the reconstructions (4–5 °C) are similar, indicating that the magnitude of the model response is about right, although there are noticeable differences in the patterns.

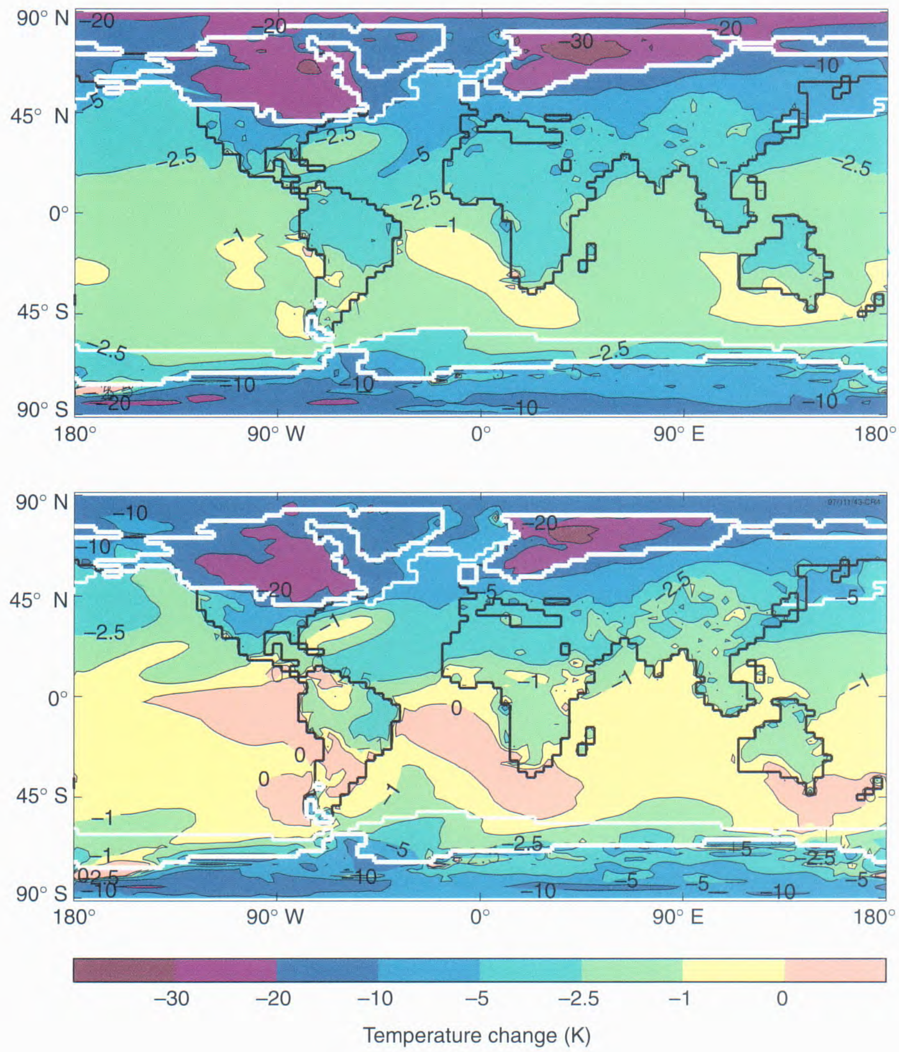


Figure 43. Change in annual mean temperature between the Last Glacial Maximum (21,000 years before present) and today using an atmospheric model coupled to a simple ocean model. Contours are at −30, −20, −10, −5, −2.5, −1 and 0 K. The thick white lines mark the edge of the glacial ice sheets, thin white lines show simulated glacial sea-ice extents, and black lines show the Ice Age model coastline. The top figure is the total cooling, and the bottom figure shows the temperature change due to the presence of the glacial ice sheets alone.

Detection and attribution of climate change

The detection of climate change and the attribution of at least part of recent observed changes to human activity remain controversial issues. In 1995, the Intergovernmental Panel on Climate Change concluded that the 'balance of evidence suggests a discernible human influence on global climate'. New work has looked at changes through the depth of the atmosphere. In Fig. 44, the simulated zonally averaged trend in atmospheric temperature from 1963 to 1988 due to anthropogenic changes in greenhouse gases, sulphate aerosols and stratospheric ozone is compared with data from a new data set using radiosonde observations. The simulated pattern is the average of four experiments. There is a broad agreement between the simulations and observations which, if the magnitude of variability in the model is correct, is unlikely to have occurred by chance. This indicates that we have

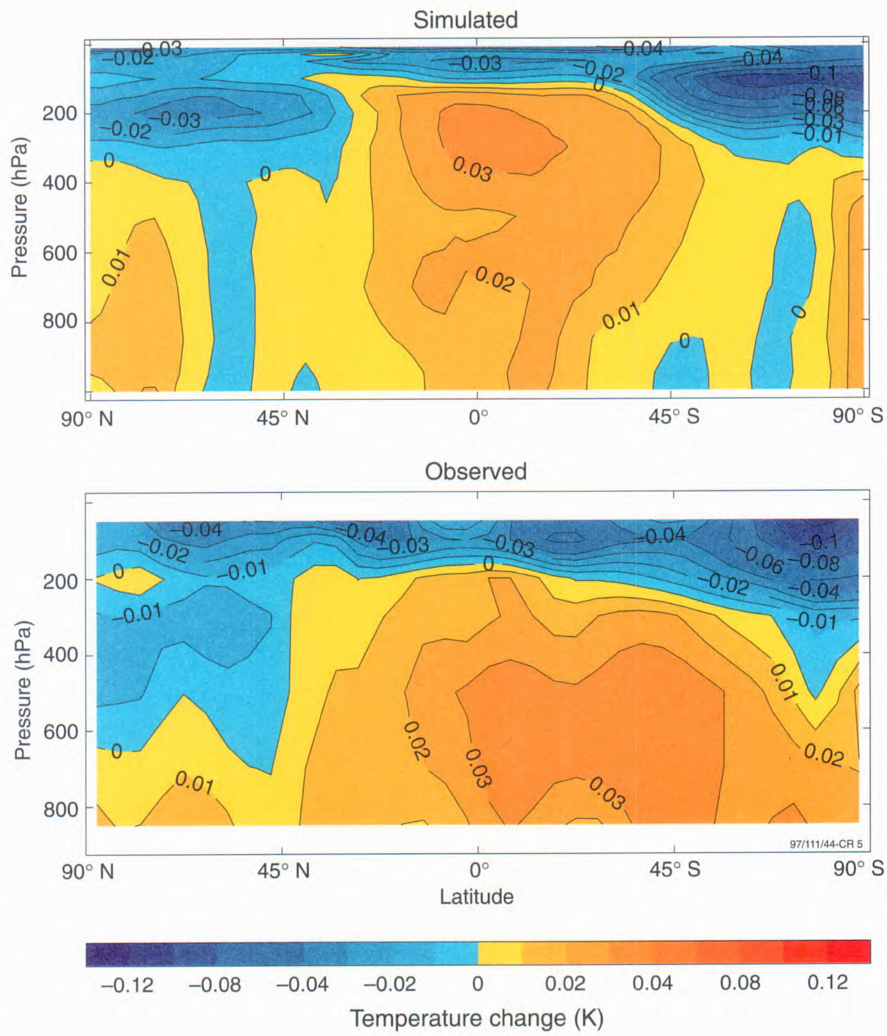


Figure 44. The simulated zonally averaged trend in atmospheric temperature from 1963 to 1988 due to anthropogenic changes in greenhouse gases, sulphate aerosols and stratospheric ozone is compared with data from a new data set using radiosonde observations.

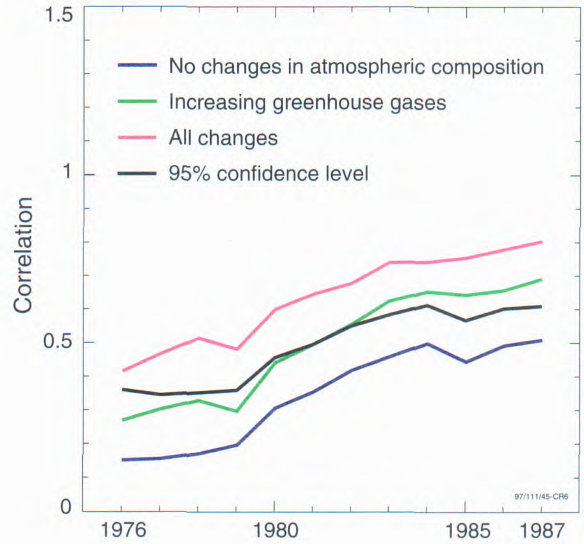


Figure 45. Correlation between observed and modelled changes in temperature in the troposphere and stratosphere since 1961–75, for 8-year periods starting at year shown. Results shown for experiments with no changes in atmospheric composition, changes in greenhouse gases alone, and all modelled changes in atmospheric composition.

detected a change in climate. Furthermore, since natural events such as changes in solar output or a long-term variation in volcanic activity are unlikely to produce both a cooling in the upper atmosphere and a warming near the surface, at least some of this change can be tentatively attributed to human activity.

A second technique for investigating the attribution of climate change to human activity uses the Hadley Centre atmospheric climate model forced with the observed history of sea-surface temperature (SST) and sea-ice extents over the last half century. Experiments have been run with changes in greenhouse gases, aerosols, stratospheric ozone and most recently with tropospheric ozone as simulated by a Lagrangian global atmospheric chemistry model STOCHEM. Statistical methods have been developed to determine whether modelled changes in temperature in the troposphere and stratosphere that include these changes in atmospheric composition are more like those observed than when the ocean surface temperatures are used alone. Modelled temperature changes are most similar to those observed when changing tropospheric ozone is included and are clearly significantly more similar than when ocean surface temperatures are used alone (Fig. 45). The impact of tropospheric ozone is to provide additional warming of the northern hemisphere troposphere and land surface, and slightly reduce the height in the modelled upper troposphere at which warming changes to cooling. The experiments, and published work elsewhere, indicate that it is likely that some of the warming of the northern hemisphere in winter since 1970 has a natural component.

Simulations of recent climate variability and change

Simulations of climate for the period 1871–1994 have been carried out with an atmospheric version of the model forced with the latest version of the Global sea-Ice and Sea-Surface Temperature data set (GISST). The major focus has been on the South Pacific Ocean where improvements in the ocean surface data set are expected to have a major impact. For the first time, good simulations have been made of the main climatic variations in this region associated with the El Niño Southern Oscillation (ENSO) fluctuations from the late nineteenth century onwards. Figure 46 shows the simulated and observed Southern Oscillation Index (SOI) of atmospheric circulation variations. Analyses of model and observed data indicate the existence of a mode of atmospheric circulation associated with the El Niño centred on the South Pacific convergence zone of high rainfall, distinct from well established patterns. The remote influences of El Niño may depend on the strength of this pattern.

Further theoretical work has been done within the statistical framework of the analysis of variance to assess the strength of the influences of SST on atmospheric climate using atmospheric model runs. The main aim is to assess both the size and the reality of simulated atmospheric variations which are due to SST in the presence of unpredictable internal climate variations that are not related to SST. These are known to be substantial in many regions. Figure 47 shows analyses of decadal variance of mean sea-level pressure in September to November, a season that shows a particularly large influence of ocean surface forcing on decadal climate variations in the Tropics and parts of the North Atlantic Ocean.

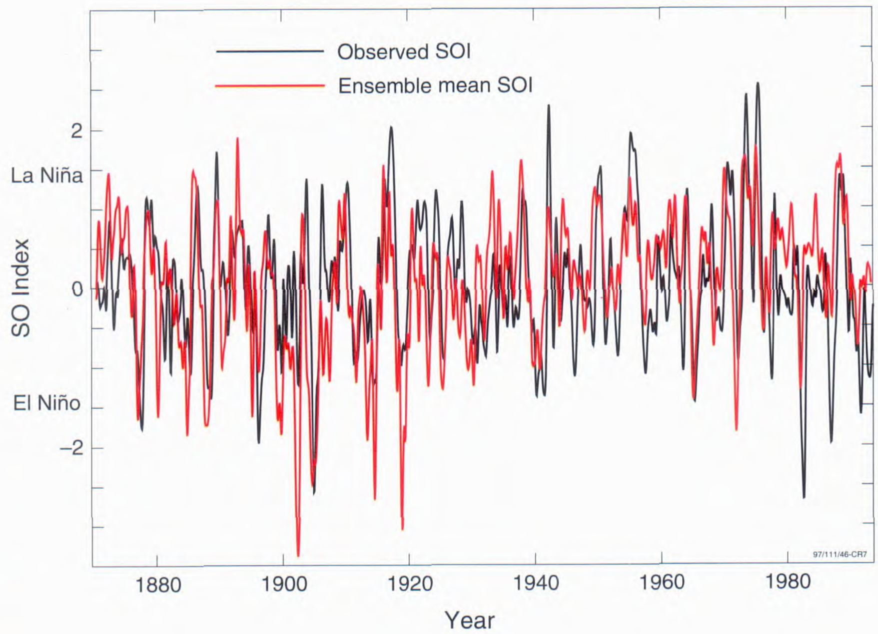


Figure 46. Simulated and observed Southern Oscillation Index calculated from standardized differences in mean sea-level pressure at Darwin, Australia, and Tahiti, central tropical Pacific, 1871–1994, and smoothed to exclude variations on timescales of less than nine months.

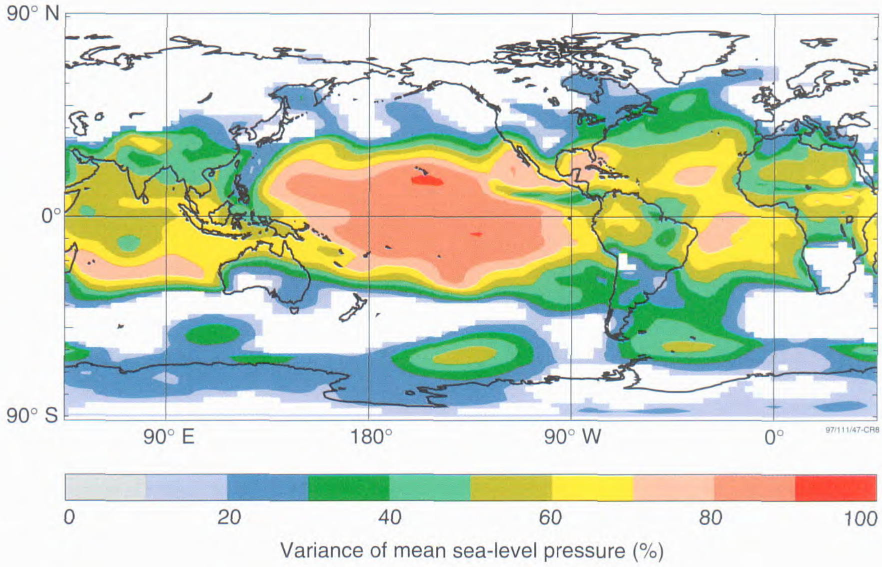


Figure 47. Percentage of the total decadal variance of September–November seasonal mean sea-level pressure due to oceanic forcing, computed from an ensemble of six 1949–93 model simulations. The contour interval is 10%, and white areas show where values do not significantly exceed zero with 95% confidence.

Observed climate variability and change

Atmospheric temperatures

The global radiosonde temperature database has been improved, especially in the stratosphere, by making adjustments for some recent instrumental changes, using satellite Microwave Sounding Unit (MSU) retrievals as a reference. Analysed zonal-mean cooling in the lower stratosphere (50 hPa) between 1965–74 and 1987–96 in low to middle latitudes of the southern hemisphere has been reduced by about 1 °C. Multivariate statistical methods have also been used to remove noise from the data, estimate some missing values and identify erroneous stations. The new analysis has been used in two recent studies described in the **Detection and attribution of climate change** section. A comparison between trends of surface temperature data, radiosonde and MSU data for the lower troposphere suggests that real physical differences contribute to the greater warming trend observed at the surface. This conclusion cannot be attributed totally to any errors in the MSU data.

Ocean surface temperature

The monthly GISST data set is now updated in near-real time using SST data from a combination of ship, buoy and satellite-based Advanced Very High Resolution Radiometer observations. Sea-ice extents are derived from the Special Sensor Microwave Imager (SSMI) satellite data. The SSMI data have to be adjusted for systematic overestimates of sea-ice coverage near coasts, and for deficits over the central Arctic in summer owing to exaggerated effects on assessed sea-ice extent of melt-ponds.

Over much of the South Pacific, ocean surface temperature data are not plentiful. Annual sea-surface and night marine air temperature variations and trends have been compared with air temperatures at 34 islands spread over an area of 20,000 km^2.

A strong pattern of influence of the fluctuations of wind patterns associated with the ENSO warming and cooling episodes in the tropical Pacific is seen in all the data sets. There is also good agreement between island and marine temperature trends over the last century for four distinct zones in the South Pacific, Fig. 48.

Historical night-time marine air temperatures have been reanalysed using observations made between an hour after sunset and an hour after sunrise. This much reduces some geographically varying warm biases owing to residual warmth of ships' decks in the early evening. Long-term trends are now in even better agreement with those of SST, and there is somewhat closer agreement with changes of air temperature at coastal and island stations.

Atmospheric circulation

Regional climate is much affected by regional changes in atmospheric circulation. Reliable analyses are lacking before about 1950 for many parts of the world as the work is inherently difficult. Collaborative efforts with scientists in several institutions to create a more reliable global atmospheric circulation data set spanning the last 120 years for as much of the world as possible led this year to the publication of a major atlas of patterns of pressure at mean sea level, and also SST. A powerful method of identifying problems in past pressure data, where documentation is often poor, is to compare them with similar data simulated by a climate model. As a result, otherwise unsuspected biases have been identified in pressure data observed by barometers on ships at sea earlier this century in some tropical regions, traced to differing observational practices between nations, and are being corrected.

Rainfall

A study is well advanced of variations in rainfall this century throughout Africa south of the Sahara. On decadal timescales, the most prominent pattern of variation is a relative wetting or drying of the equatorial region relative to tropical regions both to the north and south. This behaviour is related to large-scale SST variations. Particularly strong links exist between SST and decadal rainfall variations in southern Africa. Such results are being compared with model atmospheric simulations of rainfall over the last century.

Recent past

Land and marine temperature data analysed at the Hadley Centre and the University of East Anglia show that 1996 was globally nearly 0.2 °C cooler than 1995, being 0.22 °C above the 1961–90 average. One reason for cooler conditions than in 1995 was the development of colder conditions in the tropical Pacific associated with a La Niña event. This occurs naturally every few years. The other main influence was cooler conditions over Europe and Asia in Winter 1995/96 due to less frequent westerly flow from the warm North Atlantic.

Over much of the UK 1996 was very dry. The annual rainfall value for England and Wales was only 73% of average, the third driest year in a 230-year period, Fig. 49.

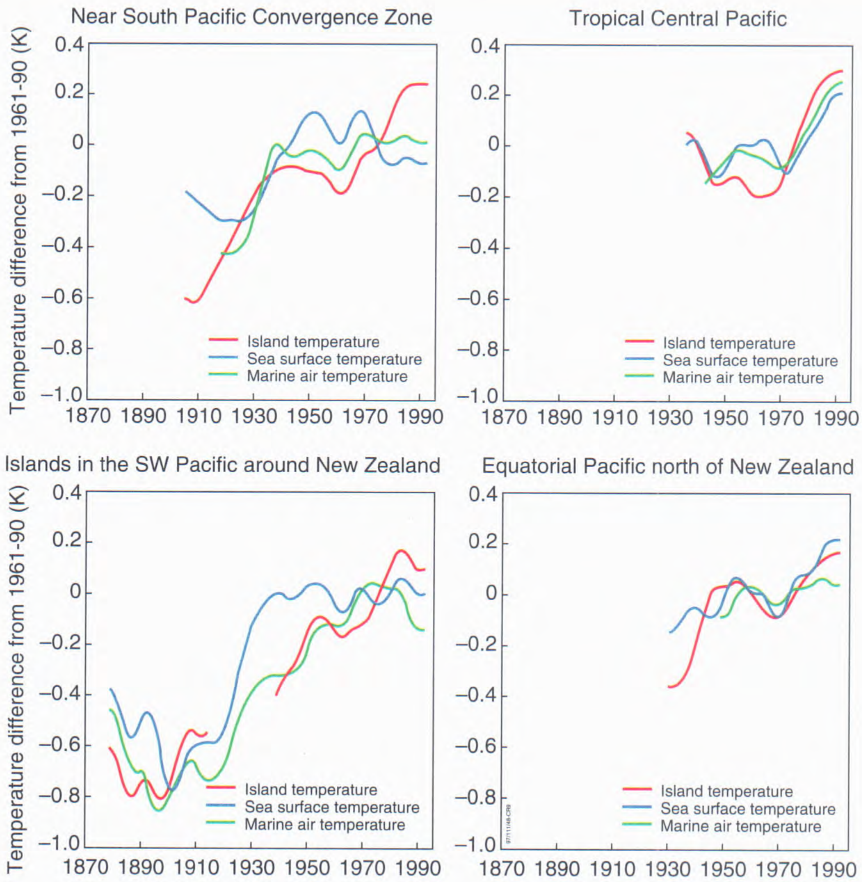


Figure 48. Trends in island air temperature in the South Pacific Ocean and those of nearby sea-surface and night marine air temperature for two selected South Pacific zones.

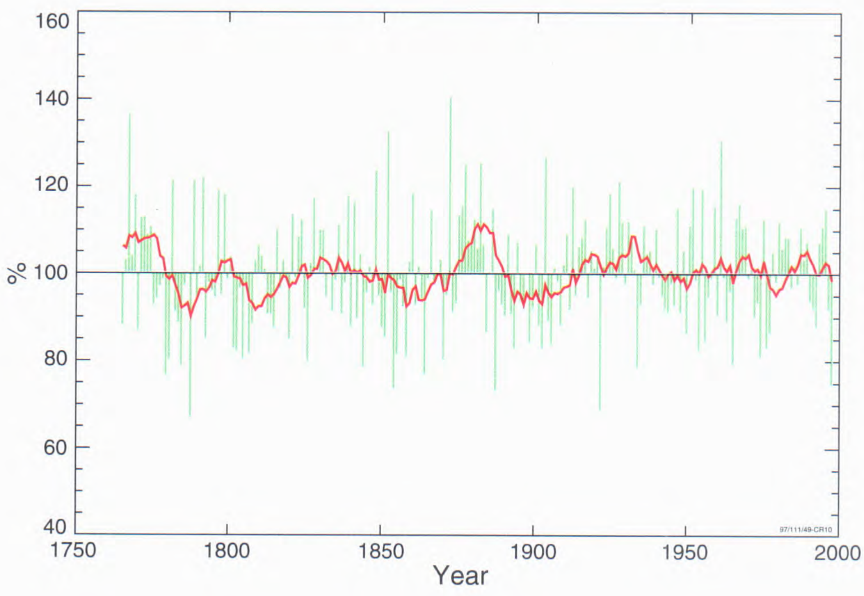


Figure 49. Annual England and Wales rainfall 1766–1996 expressed as a percentage of the 1961–90 average. The smoothed curve gives averages on a near-decadal timescale.

Model development

Testing has been completed of a new version of the Atmospheric General Circulation Model (AGCM), HadAM3, for inclusion in the next coupled atmosphere–ocean climate model (AOGCM), HadCM3. A comparison of the zonal wind for the December–February seasonal mean averaged over the 10 years of a standard test run of HadAM3 and ECMWF reanalyses is shown in Fig. 50. Several changes have been incorporated in the new atmospheric model. A new radiation scheme (the Edwards–Slingo radiation scheme) has been included, which significantly improves the cold bias and allows the explicit representation of aerosols and trace gases. A parametrization of convective momentum transport has been added which improves the representation of tropical winds. The Met. Office Surface Exchange Scheme (MOSES) has been implemented within HadAM3. MOSES includes a plant photosynthesis and canopy conductance module and a new soil thermodynamics

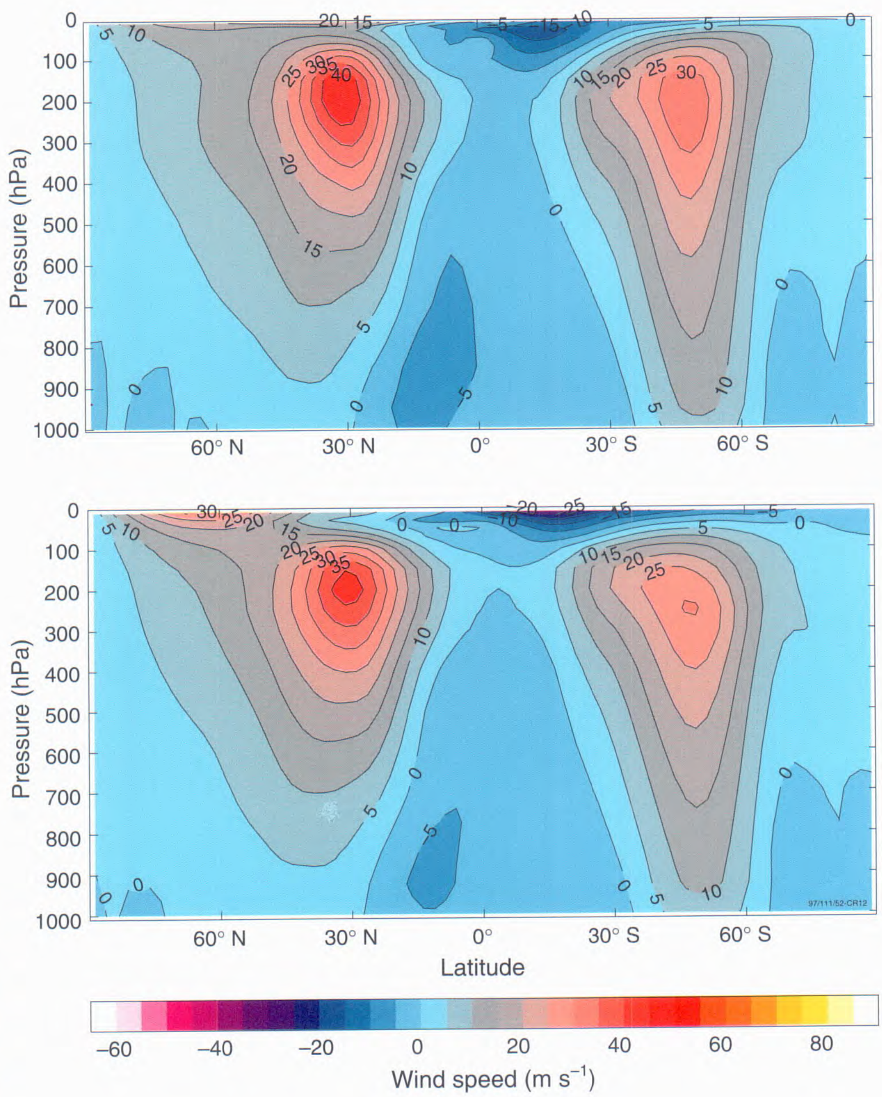


Figure 50. The zonal wind for the December–February seasonal mean averaged over the 10 years of a standard test run of HadAM3 (top) compared with ECMWF reanalyses (bottom). Positive values indicate a westerly wind, i.e. into the page.

scheme which takes account of freezing and melting of soil water. Early indications are that MOSES influences the AGCM climate sensitivity by suppressing transpiration in high CO_2 conditions.

An improved representation of the radiative properties of ice crystals has been developed and tested in the UM. The current assumption is that ice cloud consists of spheres of a fixed size. The new scheme treats four common crystal shapes (columns, rosettes, plates and polycrystals) and calculates their radiative properties as a function of their size distribution (which is allowed to vary with temperature). The main impact of the new scheme is to warm the upper troposphere, thus counteracting the model's tendency to be too cold in that region, see Fig. 51.

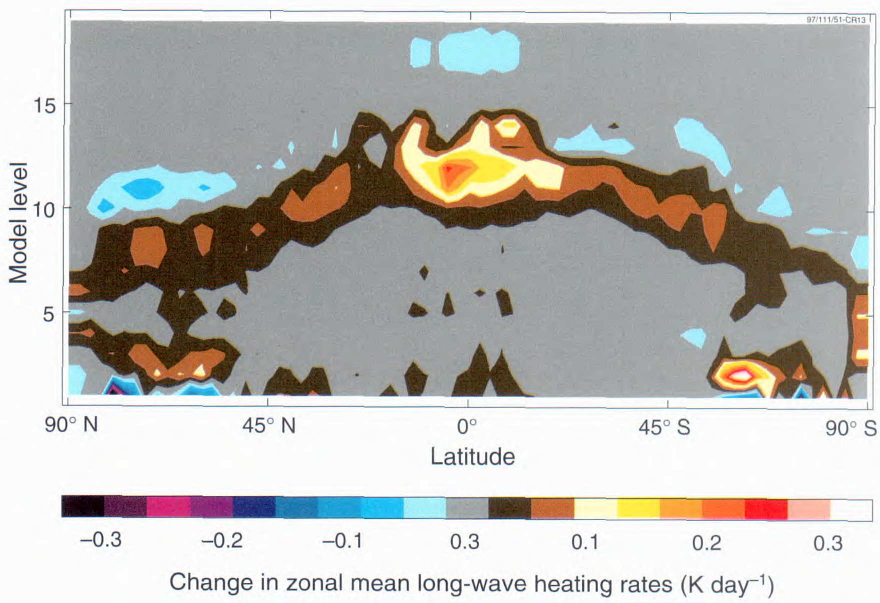


Figure 51. The impact on heating rates when ice cloud is treated as polycrystals instead of spheres. The chart is averaged around latitude circles. Model levels 5, 10 and 15 are roughly 2, 8 and 16 km above ground level respectively.

A terrestrial carbon cycle model has been developed for use in coupled climate–carbon cycle simulations. The model, called TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) updates the carbon contents of the soil and five vegetation types based on CO_2 fluxes calculated within MOSES. The response of the terrestrial carbon cycle to transient climate change has been simulated by driving TRIFFID off-line with data from a HadCM2 climate simulation. The mean carbon contents of both vegetation and soil are predicted to increase significantly from 1860 to 2100 (Fig. 52). Enhanced photosynthesis, as a result of CO_2 fertilization and warming in the high latitudes, leads to widespread increases in biomass within the tropical and boreal forests. However, some regions of the globe become sources of CO_2 as a consequence of becoming drier and warmer.

The UM's representation of convective activity in its various forms is being tested by comparing the single column version of the model with more-detailed simulations made using high-resolution models. These models resolve the convective circulations explicitly and are providing validation data for cases ranging from stratocumulus (Fig. 53), through shallow convection, to deep convection in the Tropics. This work is

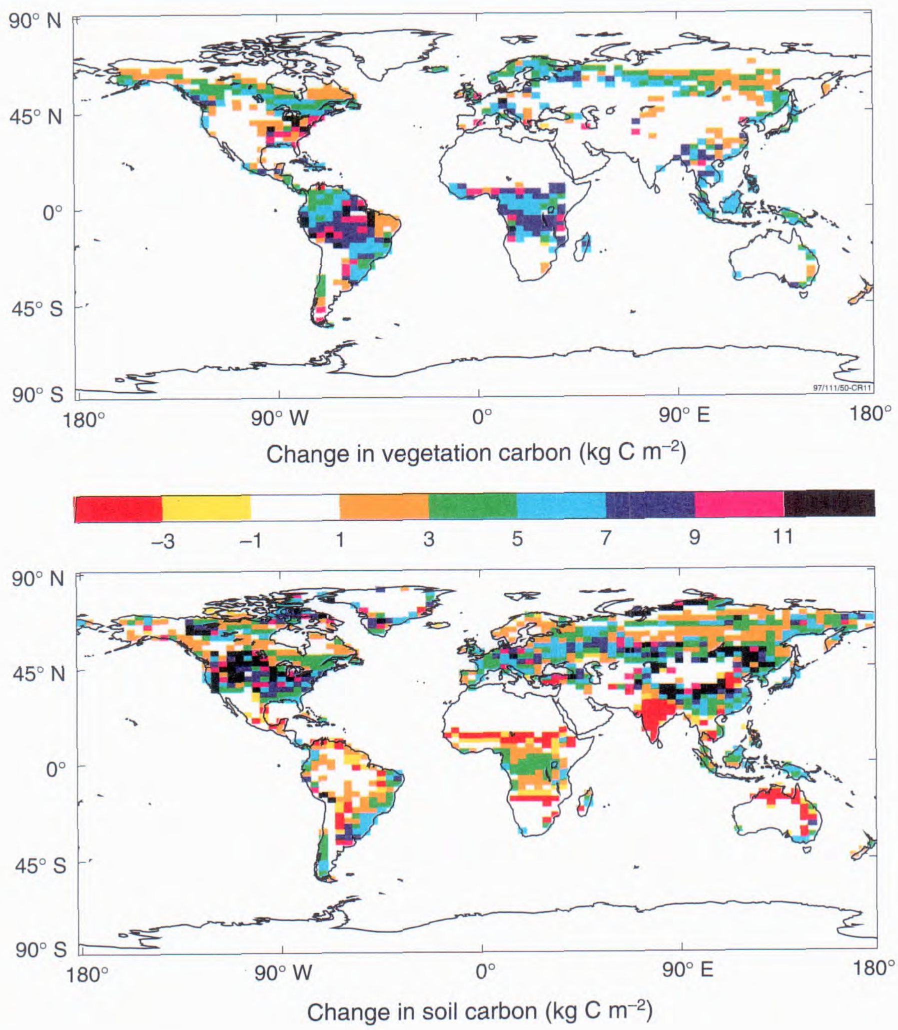


Figure 52. Change in vegetation and soil carbon storage from 1860 to 2100 as simulated using TRIFFID driven by climatological monthly means from the HadCM2 'greenhouse gas plus sulphate' experiment.

part of a continuing collaboration with colleagues in Atmospheric Processes Research, as well as in Europe and the USA.

The Lagrangian tropospheric chemistry model (STOCHEM) has been further developed to include a comprehensive oxidation scheme for dimethyl sulphide (DMS) and a representation of aqueous-phase sulphur dioxide (SO_2) oxidation to form sulphate aerosol (Fig. 54). The model is now being used with 50,000 particles which are transported using meteorological data from climate model archives with a 6-hourly resolution. The model chemistry now comprises some 70 species with around 180 reactions. Current work with this model includes prediction of aerosol species in pre-industrial and future conditions. The STOCHEM model is too complex to be included within the UM. However, a sulphur cycle model using oxidant fields from STOCHEM has been integrated into the UM. This represents three size classes of particulate sulphate. For the first time, the sulphate distribution and its direct radiative effect have been modelled simultaneously in the same experiment.

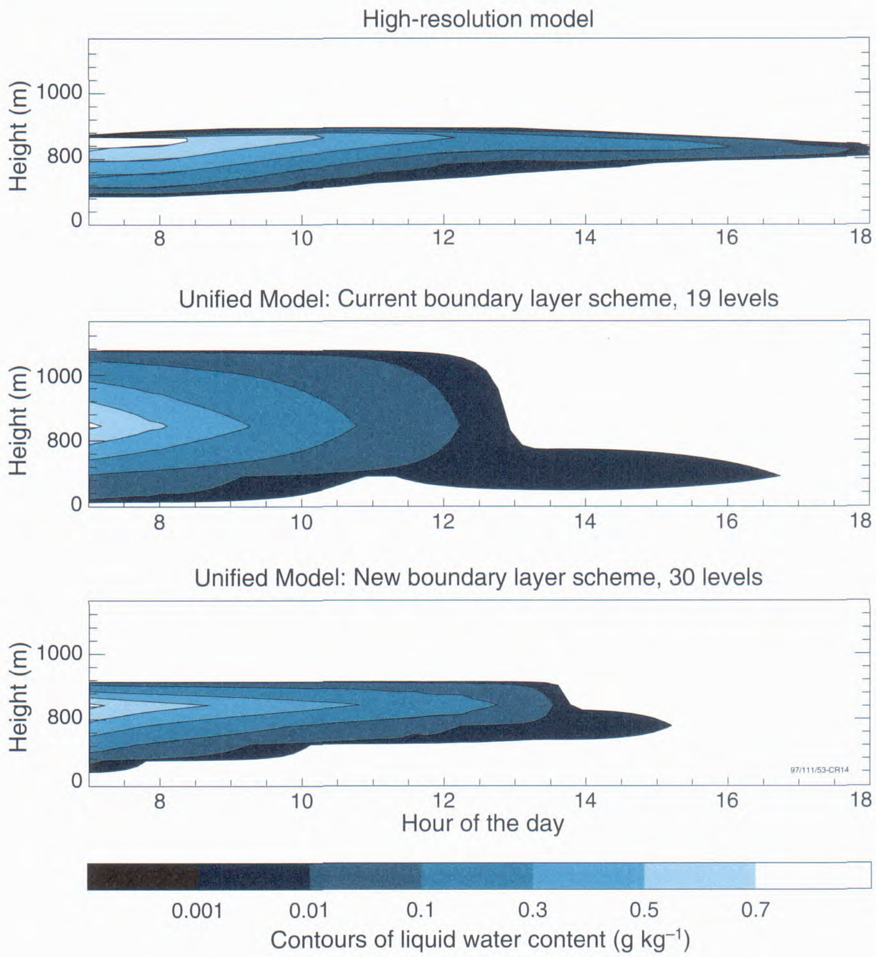


Figure 53. An example of the use of a high-resolution simulation of stratocumulus to validate changes in resolution and boundary layer parametrization in the Unified Model. Each figure is a height–time diagram showing the evolution of liquid water content of the cloud.

In contrast to the cooling effect of sulphate, black carbon aerosol may warm the climate system by absorbing solar radiation. UM experiments with a prescribed black carbon distribution suggest that this effect may be significant, so work has begun on modelling black carbon interactively within the UM.

Work on the indirect radiative effect (via changes in cloud properties) of anthropogenic aerosols has been extended to include mixed nitrate and sulphate particles, using nitrate distributions simulated by the STOCHEM chemistry model. Some preliminary results are shown in Fig. 55.

Middle atmosphere research

In collaboration with the Centre for Global Atmospheric Modelling at the University of Reading, a five-year simulation has been carried out using a version of the UM which extends from the surface into the lower mesosphere. The model uses a set of physical parametrizations based on the HadAM2B atmospheric climate model. The model produces a realistic simulation of the seasonal evolution of the stratospheric circulation (Fig. 56).

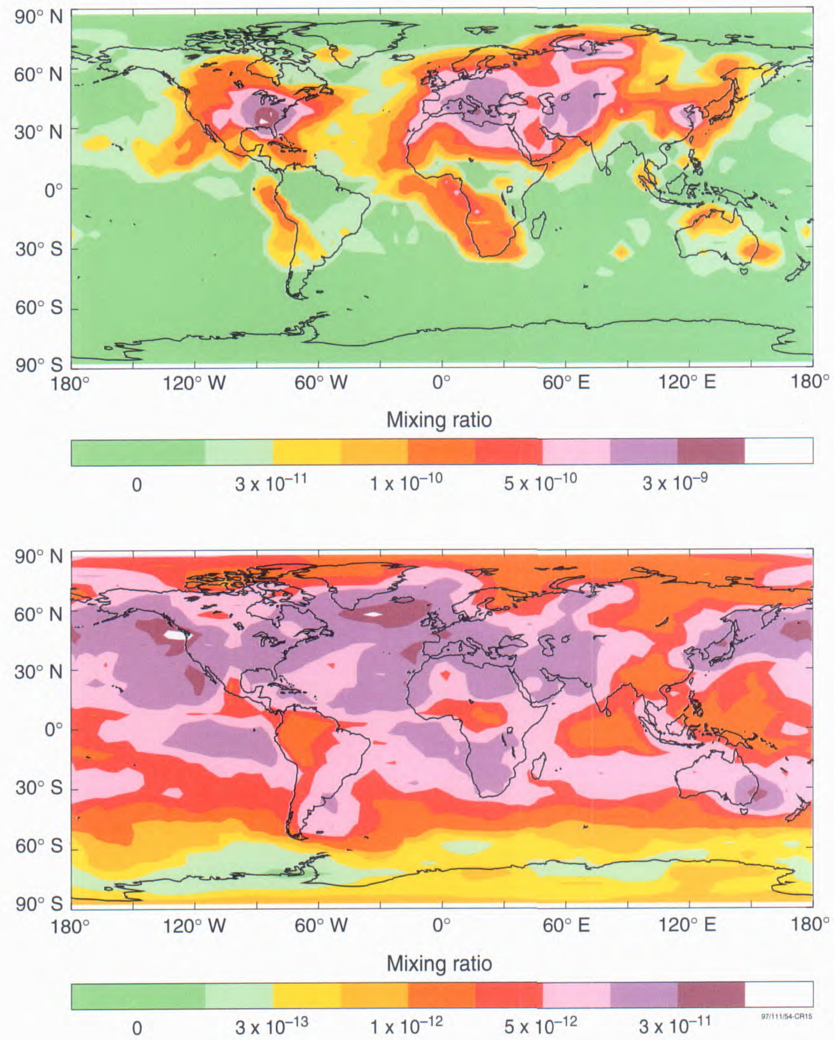


Figure 54. Near-surface sulphate aerosol from SO_2 and DMS oxidation (top) and methanesulphonic acid (MSA) from DMS oxidation (bottom).

Stratospheric analyses from the UM data assimilation system and from the Stratospheric Sounding Unit analysis system form an invaluable record for the study of the stratosphere. The analyses have been used in a number of published studies to help interpret measurements from the Upper Atmosphere Research Satellite (UARS). They are now also being used to help evaluate measurements from the Improved Limb Atmospheric Spectrometer recently launched on the Japanese Advanced Earth Observation Satellite (ADEOS). *(Editor's note: ADEOS has since ceased to function. However, sufficient data were gathered to allow useful work to be done and warrant its inclusion in this Review.)*

The stratospheric data assimilation system has been adapted to assimilate measurements made by UARS. On an experimental basis, stratospheric winds measured by the UARS High Resolution Doppler Imager have been successfully assimilated, and were shown to have a small but positive impact on the analyses. Work is also in hand to assimilate ozone measurements from the UARS Microwave Limb Sounder; some test data have been successfully assimilated, but further adjustments need to be made to improve the system.

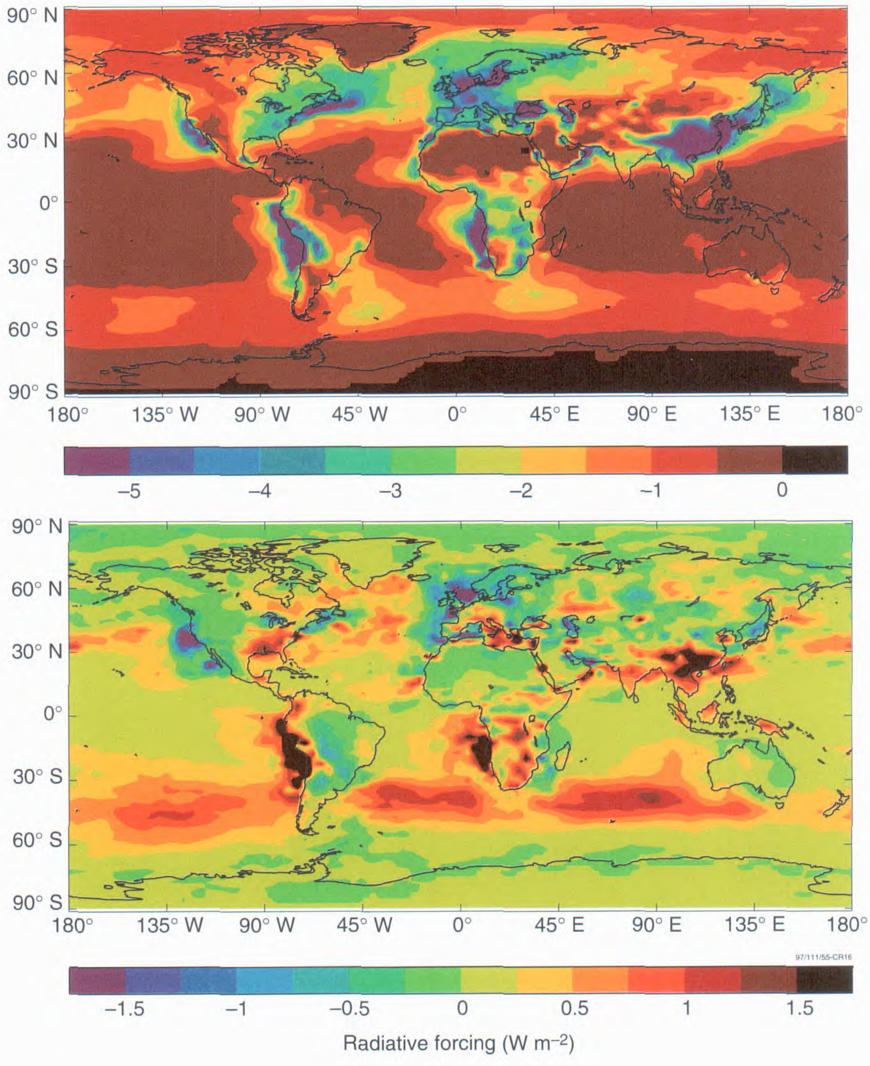


Figure 55. Top, distribution of annual mean indirect radiative forcing due to anthropogenic sulphate aerosols. Bottom, the impact of including nitrate chemistry on the indirect forcing; positive areas indicate a reduction in the magnitude of the forcing, and vice versa.

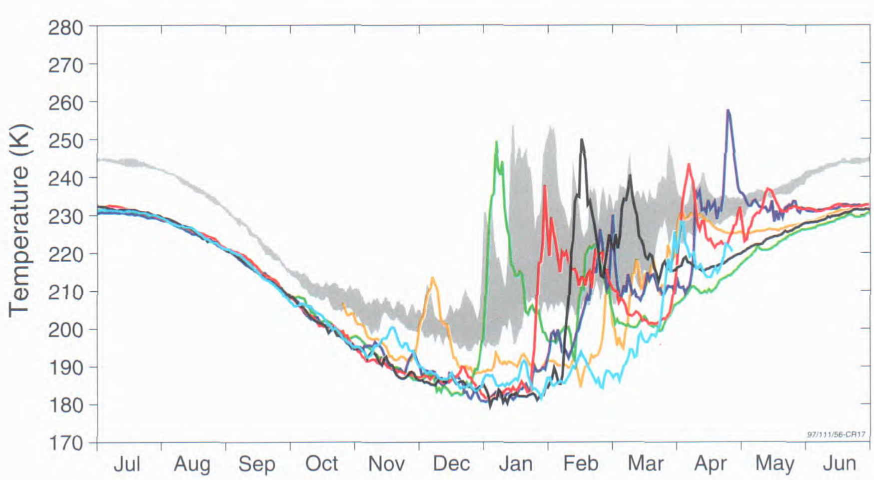


Figure 56. A time-series of mid-stratosphere (10 hPa) temperatures over the North Pole from a 5-year simulation with the Unified Model. The lines indicate the simulated temperatures, while the grey envelope indicates the observed temperature range, derived from Met. Office stratospheric analyses. The model is simulating the strong variability typical of the northern hemisphere winter stratosphere, although there is a cold bias in the model results.

S. Cagnoni

Ocean Applications

Inspecting instrumentation on an open-ocean buoy.

The Ocean Applications Branch develops the ocean models required to meet Met. Office customers' needs. This work supports climate research, seasonal forecasting, specifically providing the ocean component of coupled atmosphere–ocean models, and operational ocean forecasting. The latter includes development of the Forecasting Ocean–Atmosphere Model, an ocean analysis and forecast system for the Royal Navy, the development and maintenance of the operational wave models and trials of an ocean shelf-seas model. An important overarching task in 1996/97 has been the adaptation of ocean-model code to run efficiently on the new Cray T3E supercomputer. See under **Information technology** in the **Operational Services** chapter.

Ocean climate model development

Small-scale processes

An essential process which must be included in ocean models is vertical mixing of the upper ocean. The scheme which represents this has been enhanced, allowing a more realistic treatment of momentum mixing and improving the simulated direction of surface currents.

The effects of mesoscale eddies in the ocean, which have typical scales of 100 km or less, must also be represented. Data from eddy-resolving models on grids of some 25 and 12.5 km in a simple rectangular domain have been analysed in collaboration with the Department of Meteorology at the University of Reading. Particular attention has been given to tests of a representation of the effects of horizontal eddy mixing which allows water mass properties to be preserved. This scheme has also been used in the large-scale ocean model.

Other model developments include a simple representation of the overflow of water over ocean sills and a revised treatment of Mediterranean outflow water.

Ocean component of global coupled model

These improvements have been incorporated into the 1.25° x 1.25° global ocean model. This has been coupled to the latest version of the Hadley Centre Atmospheric General Circulation Model (AGCM) to create the new coupled model (HadCM3) to be used in future climate change simulations (Fig. 57). The simulation of sea-surface temperature (SST) by the new coupled model is much improved over previous versions; the resulting annual mean SSTs simulated over 50 years for much of the world's oceans are within 2 °C of those obtained from climatology.

Ocean heat transport

Heat transport is an important role of the oceans in determining climate. A comparison of the mechanisms of ocean heat transport in climate simulations has been made with direct estimates from hydrographic cross-sections (completed as part of the World Ocean Circulation Experiment). This has shown improved simulations of heat transport in the new coupled model. A comparison with observations of the components of the heat transport carried by boundary currents, the surface layer and the ocean interior is shown in Table 2.

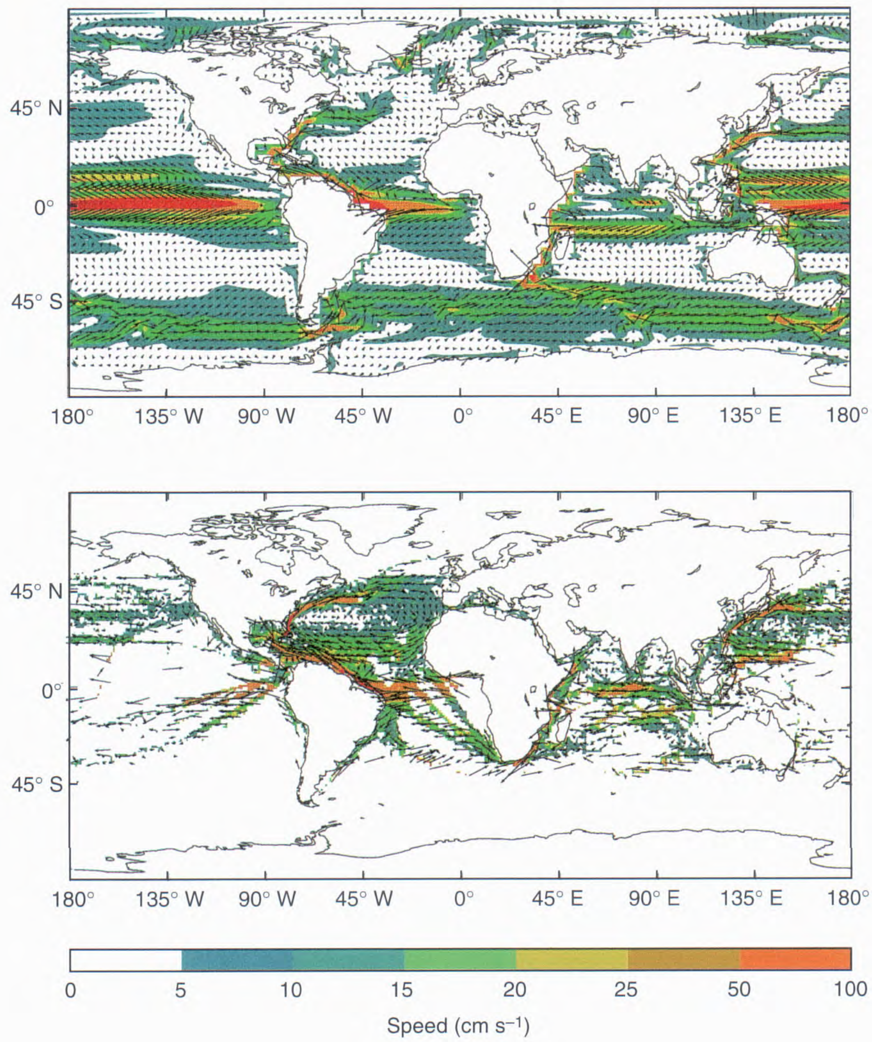


Figure 57. Top, the simulated surface currents after 100 years of simulation in the latest Hadley Centre coupled model. The ocean model has a 1.25° x 1.25° grid and the current direction arrows are plotted every three grid points. Note the strong equatorial currents and the Antarctic Circumpolar Current. Bottom, the surface currents from The Met. Office historical ship drift current data sets are shown for comparison. Note the scarcity of observations over many areas. In regions where comparisons can be made, the model agrees well with observations.

	Atlantic 24° N		*Pacific 24° N*	
Component	*Model*	*Observed*	*Model*	*Observed*
Boundary currents	1.81	1.73	1.94	1.73
Surface layer	0.35	0.42	0.58	0.93
Interior	–0.93	–0.93	–1.86	–1.91
Total	1.23	1.22	0.66	0.75

Table 2. Components of the northward heat transport (PW) for the Atlantic and Pacific at 24° N.

Model spin-up

For climate experiments, it is necessary to 'spin up' the coupled model to bring it to an equilibrium climate. This process can be made faster if ocean-only model runs are carried out for part of it. However, the present way of specifying the flux data to drive the sea-ice model leads to different equilibrium states in ocean-only runs compared to fully coupled runs. Improvements in the way the fluxes are specified have led to considerable reductions in these differences.

Alternative co-ordinate systems

The Met. Office's present ocean model uses a vertical co-ordinate system with levels at fixed depths. An alternative approach is to use isopycnic models, which use density as a vertical co-ordinate. These two approaches are being compared in a collaboration with the Southampton Oceanography Centre. This has shown that a 'slumping' of the Antarctic Circumpolar Current in the isopycnic model may be because of differences in the treatment of sub-gridscale eddies. Large differences in the modelled northward transport of heat in the North Pacific Ocean have been traced back to differences in the representations of the tropical Pacific circulation. These are thought to be due partly to the limited density resolution of the isopycnic model.

Ocean carbon cycle

A model of the global carbon cycle is under development to help study the response of the atmospheric greenhouse gas concentrations to various emission scenarios (Fig. 58). A first simulation of the global carbon budget has allowed the role of ocean biological processes to be assessed. This has led to several improvements in their representation, including biology time-steps as long as 24 hours, longer than the plankton growth timescale of a few hours. This will allow long spin-up simulations to be carried out with ocean biology included.

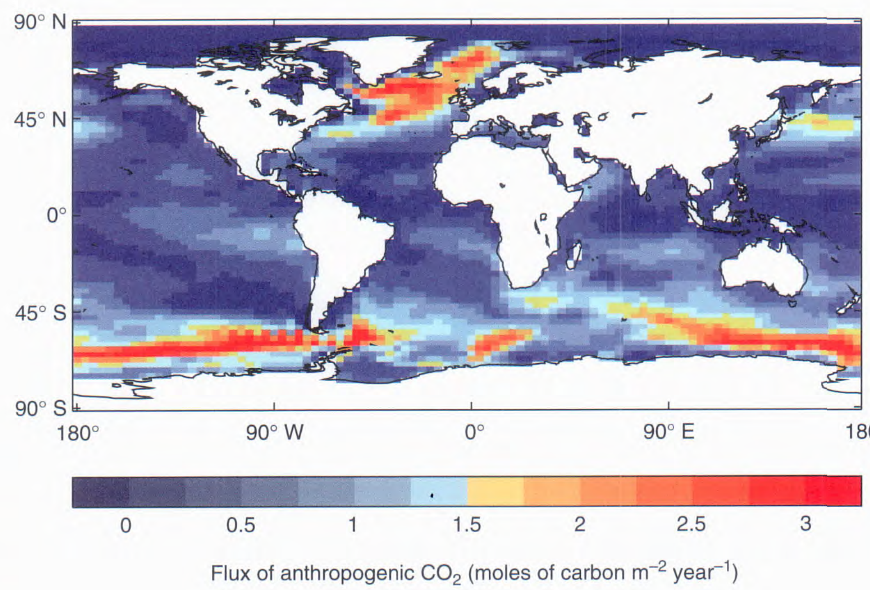


Figure 58. The distribution of simulated anthropogenic CO_2 in the year 1990 from a non-biological ocean carbon cycle model. The model was integrated from 1770 to the present day using the historical record of rising atmospheric CO_2 concentration.

Atmospheric carbon dioxide experiments have been performed for historical and future scenarios as a contribution to the international Ocean Carbon Cycle Intercomparison Project. The intercomparison aims to better understand the behaviour of the different carbon-cycle models currently in use.

Ocean forecasting

Operational implementation of FOAM

The Forecasting Ocean–Atmosphere Model (FOAM) is being developed to forecast the temperature and salinity of the upper ocean for the Royal Navy. It is driven by fluxes of momentum, heat and fresh water from the ocean component of the numerical weather prediction (NWP) system and assimilates observations of ocean temperature. A prototype version of FOAM has been run routinely since August 1994.

A project to implement this model in the operational NWP suite is well under way (OPFOAM). It has the target of delivering output on a daily basis to the Royal Navy's Fleet Weather and Oceanographic Centre at Northwood by October 1997. The OPFOAM project has involved significant changes to the system to pre-process the surface fluxes, development of the ocean assimilation code for the Cray T3E supercomputer and close liaison with the Forecasting Systems team who control the operational suite. The observation processing system, developed for the NWP system, will be used to pre-process the observations.

FOAM development

Satellite altimeter instruments are able to measure the dynamic height of the sea surface. High-quality data have been assimilated into an ocean model of the equatorial Pacific using a technique developed previously by a CASE student with the University of Edinburgh. The assimilation improves the representation of oceanic Kelvin waves which move from west to east along the equator and which are otherwise too smooth (Fig. 59).

When run for three months without input from observations, the FOAM ocean model has errors of more than 2 °C in its thermal field at 100 m depth in the north-west Atlantic. Some of these errors appear to arise from the simulation of the depth-independent flow, driven by mechanisms involving interaction with the ocean bottom. The modelling of these is adversely affected by the model's stepped topography, implying that alternative approaches to its treatment need to be considered.

Future versions of FOAM are expected to incorporate high-resolution, nested, limited-area ocean models. As a step towards this, a high-resolution version of the FOAM model on a 0.125° grid has been developed for the Mediterranean Sea, and work has been carried out to enable the model to run with a free ocean surface.

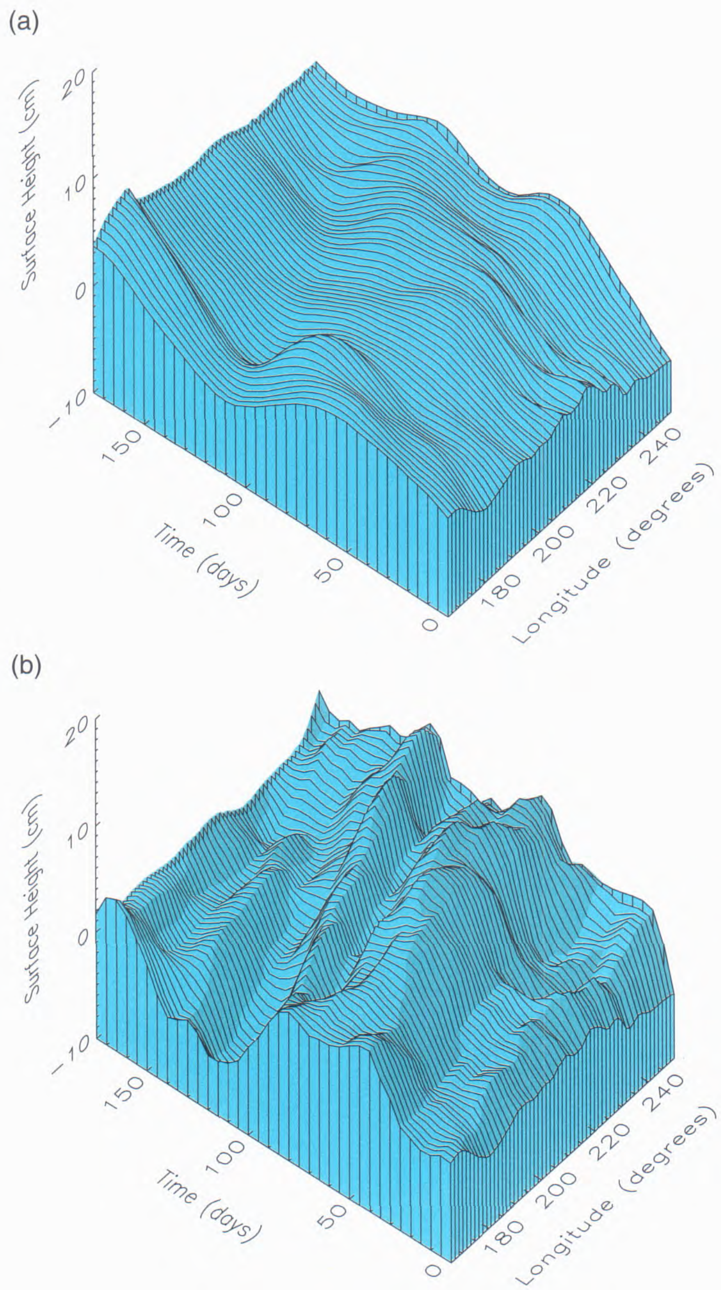


Figure 59. Sea-surface height evolution along the equator in the Pacific Ocean for the FOAM model (a) without, and (b) with, assimilation of altimeter data.

Shelf-seas modelling

A customer trial is being carried out of forecast products from a model of the north-west European continental shelf. The model (UKOPMOD) was developed by the Natural Environment Research Council's Proudman Oceanographic Laboratory. It enables the sea-surface elevation and current profile to the ocean bottom, due to both tides and meteorological forcing, to be forecast (Fig. 60). The products are being assessed through a combination of real-time forecasts and case-studies, in collaboration with customers. The present trial is planned to continue until June 1997.

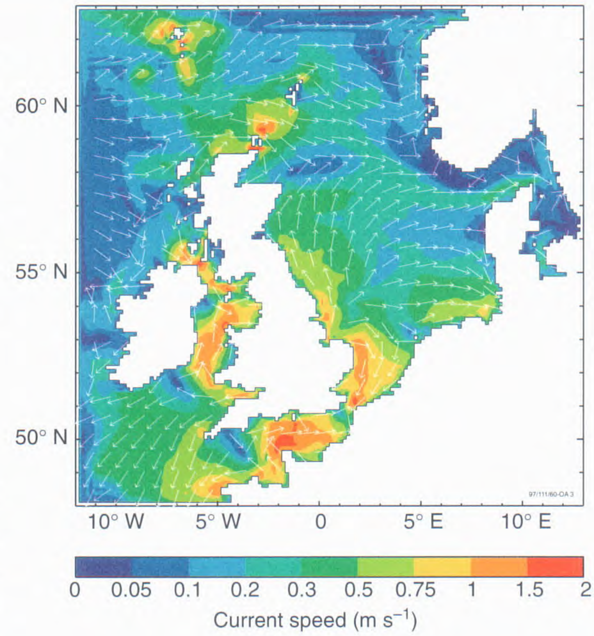


Figure 60. Total water elevation and surface current vectors for 19 February 1997 from the UKOPMOD ocean-shelf model.

Wave modelling

Sea-state forecasts provided by The Met. Office's second-generation wave model are central to many of the marine services provided by The Met. Office. This model provides good forecasts of wave height, but increasingly applications are demanding more detail from the underlying wave energy spectrum. The international third-generation wave model (called WAM) has now been included within the UM system. It will form the basis for future improvements in forecast accuracy.

Second-generation models are still able to provide useful spectral forecasts, however, and The Met. Office and British Petroleum (BP) have combined forecast wave spectra with a vessel-response algorithm, to provide forecasts of heave for the BP floating production system west of Shetland. In September 1996 the global wave model tracked long-period swell energy generated as ex-hurricane 'Hortense' moved up the east coast of the USA (Fig. 61). This swell energy, at the resonant period of the BP vessel, took three days to travel the great-circle route across the Atlantic, eventually reaching the Western Isles and passing north of Scotland.

The global wave model assimilates altimeter wave observations from the European Remote-sensing Satellite, ERS-2. A comparison of collocated moored buoy and ERS-2 observations showed that the altimeter underestimated the higher waves and stronger winds. This work provides a basis to correct the altimeter observations before they are used in the wave model.

Seasonal prediction

The role of sea-surface temperature

Averaged over timescales of weeks or more, the behaviour of the atmosphere is strongly related to surface conditions, particularly in tropical regions. With their huge mass and heat capacity the oceans change relatively slowly, so SST anomalies provide a persistent bias on atmospheric conditions through a season. Predictions on seasonal to inter-annual timescales are being made by using statistical and dynamical models that represent the important ocean–atmosphere connections.

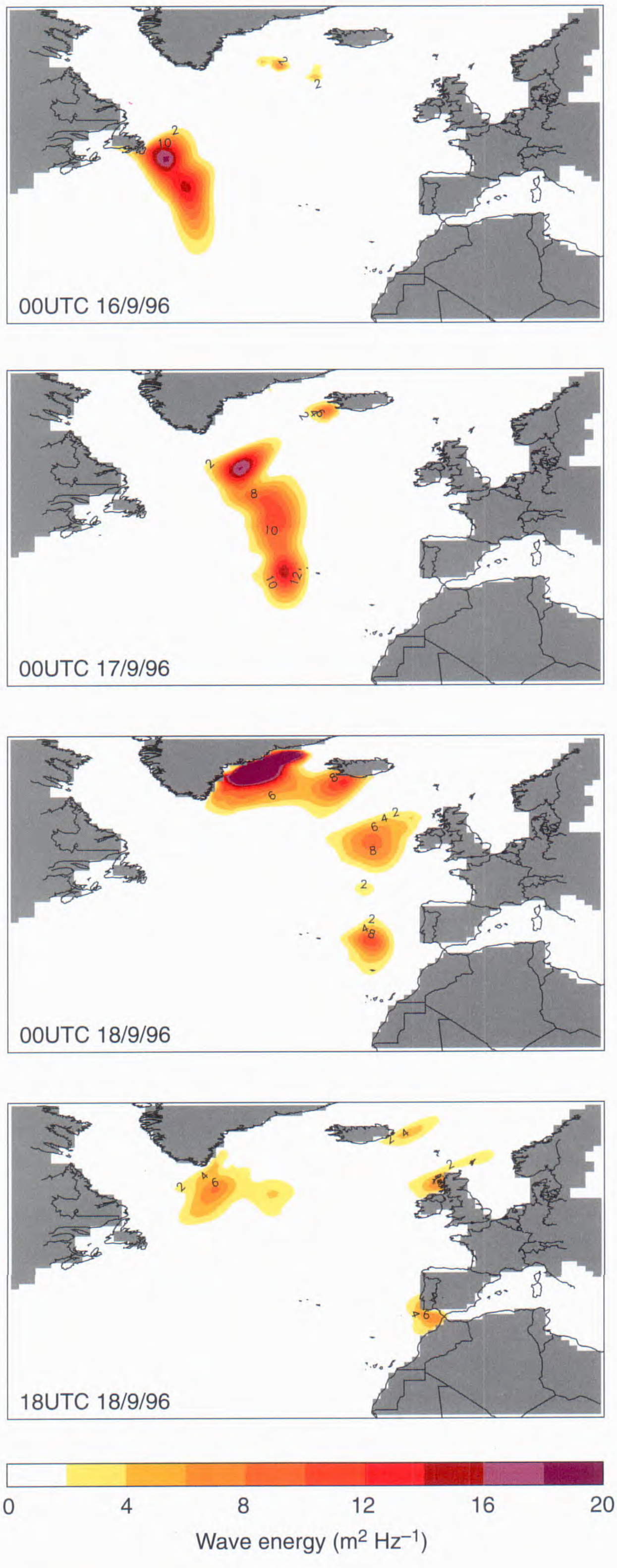


Figure 61. Track of long-period wave-swell energy from ex-hurricane 'Hortense'.

El Niño Southern Oscillation (ENSO)

The largest year-to-year SST changes occur in the tropical Pacific, and they have global effects on the atmosphere which can extend as far as Europe. These ocean variations, known as El Niño events, are predictable at a range of several months. Investigation of ENSO and its impacts, forming part of The Met. Office's effort in seasonal prediction, is a major component of international climate research programmes. See under **Simulations of recent climate variability and change** in the **Climate Research** chapter.

Dynamical models

GCMs provide detailed representations of the feedback between the oceans and atmosphere that are needed for good seasonal predictions. A new version of the tropical Pacific Ocean model coupled to the Hadley Centre AGCM has been developed. The ocean component has high resolution (up to 0.3° north–south) to represent important processes that are concentrated in the equatorial region. The same ocean model forms part of another simpler El Niño forecasting system; it uses statistical methods to produce the atmospheric winds, that in turn interact with the ocean.

A good prediction requires a good initial ocean state. For the ocean models this can be partly obtained by forcing with preceding atmospheric conditions. A version of the FOAM system is also being used to include oceanic observations in the analysis. Sea-level estimates from satellite altimeters provide additional information.

Statistical forecasts

Statistical relations between seasonal rainfall and pre-season SST have been used successfully to produce forecasts for some specific tropical regions in Africa and South America. Recent research has led to the application of similar methods to predict summer Central England Temperature using winter SST anomalies in the North Atlantic.

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

Airey, M.J., Hulme, M. and JOHNS, T.C., 1996. Evaluation of simulations of terrestrial precipitation in UK Met. Office/Hadley Centre climate change experiments. *Geophys Res Let*, **23**, 1657–1660.

Allan, R., Lindesay, J. and PARKER, D.E., 1996. El Niño Southern Oscillation and Climatic Variability (Atlas). Melbourne, CSIRO Publishing.

Belcher, S.E. and WOOD, N., 1996. Form and wave drag due to stably stratified turbulent flow over low ridges. *QJR Meteorol Soc*, **122**, 863–902.

BHASKARAN, B., JONES, R.G., MURPHY, J.M. and NOGUER, M., 1996. Simulations of the Indian summer monsoon using a nested regional model domain: domain size experiments. *Clim Dyn*, **12**, 573–587.

Bower, K.N., MOSS, S.J., JOHNSON, D.W., Choularton, T.W., Latham, J., BROWN, P.R.A., Blyth, A.M. and Cardwell, J., 1996. A parametrization of the ice water content observed in frontal and convective clouds. *QJR Meteorol Soc*, **122**, 1815–1844.

BROAD, A.S., 1996. High resolution numerical model integrations to validate gravity wave drag parametrization schemes: a case study. *QJR Meteorol Soc*, **122**, 1625–1653.

BROWN, A.R., 1996. Large-eddy simulation and parametrization of the baroclinic atmospheric boundary layer. *QJR Meteorol Soc*, **122**, 1779–1798.

BROWN, A.R., 1996. Evaluation of parametrization schemes for the convective boundary layer using large-eddy simulation results. *Boundary Layer Meteorol*, **81**, 167–200.

BROWN, A.R. and GRANT, A.L.M., 1997. Non-local mixing of momentum in the convective boundary layer. *Boundary Layer Meteorol*, **84**, 1–22.

Browning, K.A. and ROBERTS, N.M., 1996. Variation of frontal and precipitation structure along a cold front. *QJR Meteorol Soc*, **122**, 1845–1872.

Browning, K.A., ROBERTS, N.M. and Sim, C.S., 1996. A mesoscale vortex diagnosed from combined satellite and model data. *Meteorol Appl*, **3**, 1–4.

Carnell, R.E., SENIOR, C.A. and MITCHELL, J.F.B., 1996. An assessment of measures of storminess: simulated changes in northern hemisphere winter due to increasing CO_2. *Clim Dyn*, **12**, 467–476.

CARSON, D.J., 1996. Modelling climate change: achievements and prospects. *Commonw For Rev*, **75**, 12–18.

CARSON, D.J., 1996. Global warming: basis for concern. *RSA Journal*, **144**, 52–61.

Cess et al, including INGRAM, W.J., 1996. Cloud feedback in atmospheric general circulation models: an update. *J Geophys Res*, **101**, 12,791–12,794.

Christensen, T.R. and COX, P.M., 1996. Modelling response of methane emission from Arctic Tundra to climatic change: an overview of relevant controlling factors. *In* Proceedings of the Conference on Global Change and Arctic Terrestrial Ecosystems, Oppdal, Norway. Springer Verlag.

CLOUGH, S.A., DAVITT, C.S.A. and Thorpe, A.J., 1996. Attribution concepts applied to the omega equation. *QJR Meteorol Soc*, **122**, 1943–1962.

Collier, C.G. and HARDAKER, P.J., 1996. Estimating Probable Maximum Precipitation using a Storm Model approach. *J Hydrol*, **183**, 277–306.

COLLINS, W.J., STEVENSON, D.S., JOHNSON, C.E. and DERWENT, R.G., 1997. Tropospheric ozone in a global-scale three-dimensional Lagrangian model and its response to NO_X emission controls. *J Atmos Chem*, **26**, 223–274.

DAVEY, M.K., Anderson, D.L.T. and Lawrence, S., 1996. A simulation of variability of ENSO forecast skill. *J Clim*, **9**, 240–246.

DERWENT, R.G., 1996. The influence of human activities on the distribution of hydroxyl radicals in the troposphere. *Philos Trans R Soc*, **Series A, 354**, 501–531.

DERWENT, R.G. and Grennfelt, P., 1996. NO_X in my backyard. *Atmos Environ*, **30**, i–ii.

DERWENT, R.G., 1996. 1001 ways to reduce summertime smog. *Water and Environ Manager*, **1**, 23–24.

DERWENT, R.G. and MIDDLETON, D.R., 1996. An empirical function for the ratio NO_2:NO_X. *Clean Air*, **26**, 57–60.

DERWENT, R.G., Jenkin, M.E. and Saunders, S.M., 1996. Photochemical ozone creation potentials for a large number of reactive hydrocarbons under European conditions. *Atmos Environ*, **29**, 181–199.

Dickinson, R.E., Meleshko, V., Randall, D., Sarachik, E., Silva-Dias, P. and SLINGO, A. (SENIOR, C. also contributed), 1996. Climate Processes. *In* Climate Change 1995. The Science of Climate Change. The second assessment Report of the IPCC Contribution of WGI, Eds J.T. Houghton, L.G. Meirho Filho, B.A. CALLANDER, N. Harris, A. Kattenberg and K. MASKELL. Cambridge University Press.

EDWARDS J.M., 1996. Efficient calculation of infrared fluxes and cooling rates using the two-stream equations. *J Atmos Sci*, **53**, 1921–1932.

EDWARDS, J.M. and SLINGO, A., 1996. Studies with a flexible new radiation code. Part I: choosing a configuration for a large-scale model. *QJR Meteorol Soc*, **122**, 689–719.

Forster, P.M., JOHNSON, C.E., Law, K.S., Pyle, J.A. and Shine, K.P., 1996. Further estimates of radiative forcing due to tropospheric ozone changes. *Geophys Res Lett*, **23**, 3321–3324.

Foster, J.L., Liston, G., Koster, R., ESSERY, R.H., Behr, H., Dumenil, L., Verseghy, D., Thompson, S., Pollard, D. and Cohen, J., 1996. Snow cover and snow mass intercomparisons of general circulation models and remotely sensed datasets. *J Clim*, **9**, 409–426.

Foster, J.L., Liston, G., Koster, R., ESSERY, R.H., Behr, H., Dumenil, L., Verseghy, D., Thompson, S., Pollard, D. and Cohen J., 1996. Snow-mass intercomparisons in the boreal forests from general circulation models and remotely sensed data sets. *Polar Record*, **32**, 199–208.

FRANCIS, P.N., TAYLOR, J.P., HIGNETT, P. and SLINGO, A., 1997. On the question of enhanced absorption of solar radiation by clouds. *QJR Meteorol Soc*, **123**, 419–434.

Gates, L., Henderson-Sellers, A., Boer, G., FOLLAND, C.K., Kitoh, A., Semmazzi, G., Smith, N. and Weaver, A. (with contributions by JOHNS, T.C. and TETT, S.), 1996. Climate models – evaluation. *In* Climate Change 1995. The Science of Climate Change. The Second Assessment Report of the IPCC Contribution of WGI. Eds J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell. Cambridge University Press.

Gerbig, C., Kley, D., Volz-Thomas, A., KENT, J., DEWEY, K.J. and MCKENNA, D.S., 1996. Fast response resonance fluorescence CO measurements aboard the C-130: instrument characterization and measurements made during the North Atlantic Regional Experiment 1993. *J Geophys Res*, **101** 29,229–29,238.

GREGORY, D. and Morris, D., 1996. The sensitivity of climate simulations to the specification of mixed phase clouds. *Clim Dyn*, **12**, 641–651.

Gyakum, J.R., Carrera, M., Zhang, D., Miller, S., Caveen, J., Benoit, R., Black, T., Buzzi, A., Chouinard, C., Fantini, M., Colloni, C., Katzfey, J.J., Kuo, Y., Lalaurette, F., Low-Nam, S., Mailhot, J., Malguzzi, P., McGregor, J.L., Nakamura, M., Tripoli, G. and WILSON, C., 1996. A regional model intercomparison using a case of explosive cyclogenesis. *Weather and Forecasting*, **11**, 521–543.

HARDAKER, P.J., 1996. Estimating Probable Maximum Precipitation (PMP) for the Evinos catchment in Greece using a Storm Model approach. *Meteorol Appl*, **3**, 137–145.

Hayman, G.D. and DERWENT, R.G., 1997. Atmospheric chemical reactivity and ozone-forming potentials of potential CFC replacements. *Environ Sci Technol*, **31**, 327–336.

HEWITT, C.D. and MITCHELL, J.F.B., 1996. GCM simulations of the climate of 6k BP: Mean changes and interdecadal variability. *J Clim*, **9**, 3505–3529.

HIGNETT, P. and TAYLOR, J.P., 1996. The radiative properties of inhomogeneous boundary layer cloud: Observations and modelling. QJR *Meteorol Soc*, **122**, 1341–1364.

HOBSON, J.M., WOOD, N. and MASON, P.J., 1996. A new finite-difference diffusion scheme. *J Comput Phys*, **125**, 16–25.

Houghton, J.T., Meira Filho, L.G., CALLANDER, B.A., Harris, N., Kattenberg, A., and MASKELL, K. (Eds), 1996. Climate Change 1995. The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Houghton, J.T., Meira Filho, L.G., GRIGGS, D.J. and MASKELL, K. (Eds) (with contribution by GREGORY, J.M.), 1997. Simple climate models used in the IPCC second assessment report. *IPCC Technical Paper 2*.

Houghton, J.T., Meira Filho, L.G., GRIGGS, D.J. and MASKELL, K. (Eds). 1997. Stabilisation of atmospheric greenhouse gases: Physical, biological and socio-economic implications. *IPCC Technical Paper 3*.

HUNT, J.C.R., TETT, S.F.B. and MITCHELL, J.F.B., 1996. Mathematical and physical basis of general circulation models of climate. Paper presented at the 3rd ICIAM Conference Hamburg, 3–7 July 1995. *Zeitschrift fur Angewande Mathematik and Mechanik*, **76**, Supplement 4, 501–508. In 'ICIAM/GAMM 95', Eds E. Kreuzer and O. Mahrenholtz.

Jenkin, M.E., Saunders, S.M., DERWENT, R.G. and Pilling, M.J., 1997. World wide web site of a Master Chemical Mechanism (MCM) for use in tropospheric chemistry models. *Atmos Environ*, **31**, 1249.

JOHNS, T.C., Carnell, R.E., CROSSLEY, J.F., GREGORY, J.M., MITCHELL, J.F.B., SENIOR, C.A., TETT, S.F.B. and WOOD, R.A., 1997. The second Hadley Centre coupled ocean-atmosphere GCM: Model description, spinup and validation. *Clim Dyn*, **13**, 103–134.

JOHNSON, C.E. and DERWENT, R.G., 1996. Relative radiative forcing consequences of global emissions of hydrocarbons, carbon monoxide and NO_X from human activities estimated with a zonally-averaged two-dimensional model. *Clim Change*, **34**, 439–462.

JONES, A. and SLINGO, A., 1996, Predicting cloud-droplet effective radius and indirect sulphate aerosol forcing using a general circulation model. *QJR Meteorol Soc*, **122**, 1573–1595.

JONES, A. and SLINGO, A., 1997. Climate model studies of sulphate aerosols and clouds. *Philos Trans R Soc London*, **series B**, **352**, 221–229.

JONES, R.G., MURPHY, J.M., NOGUER, M. and KEEN, A.B. 1997. Simulation of climate change over Europe using a nested regional climate model. Part II: Comparison of driving and regional model responses to a doubling of carbon dioxide. *QJR Meteorol Soc*, **123**, 265–292.

Kattenberg, A. Giorgi, F., Grassl, H., Meehl, G.A., MITCHELL, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. and Wigley, T.M.L. (with contributions by COX, P.M., GREGORY, J.M., Horton, B., JOHNS, T., JONES, R.G., KEEN, A., MURPHY, J., NOGUER, M., SENIOR, C. and TETT, S.), 1996. Climate models – projections of future climate. In Climate Change

1995. The Science of Climate Change. The second assessment Report of the IPCC Contribution of WGI: Eds J.T. Houghton, L.G. Meirho Filho, B.A. CALLANDER, N. Harris, A. Kattenberg and K. MASKELL. Cambridge University Press.

Kemp, J.R. and THOMSON, D.J., 1996. Dispersion in stable boundary layers using large-eddy simulation. *Atmos Environ*, **30**, 2911–2923.

LEAN, J., BUNTON, C.B., Nobre, C.A. and ROWNTREE, P.R., 1996. The simulated impact of Amazonian deforestation on climate using measured ABRACOS vegetation characteristics. Proceedings of ABRACOS symposium. *In* Amazonian deforestation and climate. Eds J.H.C. Gash, C.A. Nobre, J.M. Roberts and R.L. Victoria. Chichester, Wiley.

Leonard, B.P., LOCK, A.P. and MACVEAN, M.K., 1996. Conservative explicit unrestricted-time-step multidimensional constancy-preserving advection schemes. *Mon Weather Rev*, **124**, 2588–2606.

LORENC, A.C., BARKER, D., BELL, R.S., MACPHERSON, B. and MAYCOCK, A.J., 1996. On the use of radiosonde humidity observations in mid-latitude NWP. *Meteorol Atmos Phys*, **60**, 3–17.

MACPHERSON, B., WRIGHT, B.W., HAND, W.H. and MAYCOCK, A.J., 1996. The impact of MOPS moisture data in the UK Meteorological Office data assimilation scheme. *Mon Weather Rev*, **124**, 1746–1766.

Manney, G.L., SWINBANK, R. and O'Neill, A., 1996. Stratospheric meteorological conditions for the 3–12 November 1994 ATMOS/ATLAS-3 measurements. *Geophys Res Lett*, **23**, 2409–2412.

Manney, G.L., SWINBANK, R., Massie, S.T., Gelman, M.E., Miller, A.J., Nagatani, R., O'Neill, A. and Zurek, R.W., 1996. Comparison of U.K. Meteorological Office and U.S National Meteorological Center stratospheric analyses during northern and southern winter. *J Geophys Res*, **101**, 10,311–10,334.

Marsh, R., ROBERTS, M.J., WOOD, R.A. and New, A.L., 1996. An intercomparison of a Bryan–Cox type ocean model and an isopycnic ocean model. Part II: The subtropical gyre and heat balances. *J Phys Oceanogr*, **26**, 1528–1551.

MARTIN, G.M., JOHNSON, D.W., Jonas, P.R., Rogers, D.P. and Brooks, I.M., 1997. Effects of airmass type on the interaction between cumulus clouds and warm stratocumulus clouds in the marine boundary layer. *QJR Meteorol Soc*, **123**, 849–882.

MARYON, R.H. and RYALL, D.B., 1996. Developments to the UK Nuclear Accident Response Model (NAME). Dept. of the Environment Commissioned Research for Radioactive Substances Division, Report DOE/RAS/96.011.

Metcalfe, S.E., DERWENT, R.G., Whyatt, J.D. and Dyke, H., 1996. Spatial variability in emissions reduction scenarios for sulphur and nitrogen in the UK. *Water, Air and Soil Pollut*, **85**, 2619–2624.

MIDDLETON, D.R., 1996. Physical models of air pollution for air quality reviews. *Clean Air*, **26**, 28–36.

MIDDLETON, D.R. and DERWENT, R.G., 1996. An empirical function for the ratio NO_2: NO_X. *Clean Air*, **26**, 57–60.

MILTON, S.F. and WILSON, C.A., 1996. The impact of parametrized subgrid-scale orographic forcing on systematic errors in a global NWP model. *Mon Weather Rev*, **124**, 2023–2045.

MITCHELL, J.F.B. and JOHNS, T.C., 1997. On the modification of greenhouse warming by sulphate aerosols. *J Clim*, **10**, 245–267.

MYLNE, K.R., Davidson, M.J. and THOMSON, D.J., 1996. Concentration fluctuation measurements in tracer plumes using high and low frequency response detectors. *Boundary Layer Meteorol*, **79**, 225–242.

Newman, P.A., Lait, L.R., Schoeberl, M.R., Seablom, M., Coy, L., Rood, R., SWINBANK, R., Proffit, M., Loewenstein, M., Podolske, J.R., Elkins, J.W., Boering, K., Webster, C.R., May, R.D., Fahay, D.W. and Dutton, G.S., 1996. Measurements of polar vortex air in the mid-latitudes. *J Geophys Res*, **101**, 12,879–12,891.

Nicholls, N., Gruza, G.V., Jouzel, J., Karl, T.R., Ogallo, L.A. and PARKER, D.E. (with contributions by FOLLAND, C.K. and WARD, M.N.), 1996. Observed climate variability and change. *In* Climate Change 1995. The Science of Climate Change. The Second Assessment Report of the IPCC: Contribution of WGI. Eds J.T. Houghton, L.G. Meira Filho, B.A. CALLANDER, N. Harris, A. Kattenberg and K. MASKELL. Cambridge University Press.

PANKIEWICZ, G.S., 1997. Neural network classification of convective air masses for a flood forecasting system. *Int J Remote Sensing*, **18**, 887–898.

PARKER, D.E., FOLLAND, C.K., Bevan, A., WARD, M.N., JACKSON, M. and MASKELL, K., 1996. Marine surface data for analysis of climatic fluctuations on interannual to century timescales. *In* Natural climate variability on decade-to-century timescales. National Research Council, Eds D.G. Martinson, K. Bryan, M. Ghil, M.M. Hall, T.R. Karl, E.S. Sarachik, S. Sorooshian and L.D. Talley. Washington DC, National Academy Press.

PARKER, D.E., HORTON, E.B., CULLUM, D.P.N. and FOLLAND, C.K., 1996. Global and regional climate in 1995. *Weather*, **51**, 202–210.

PARKER, D.E. and Jones, P.D. 1996. Global surface temperatures. *Nature*, **381**, 270.

PARKER, D.E., Wilson, H., Jones, P.D., Christy, J.R. and FOLLAND, C.K., 1996. The impact of Mount Pinatubo on worldwide temperatures. *Int J Climatol*, **16**, 487–497.

PARKER, D.E and FOLLAND, C.K., 1997. Correspondence on climatological reference periods. *Weather*, **52**, 26–27.

Polcher, J., Laval, K., Dumenil, L., LEAN, J. and ROWNTREE, P.R., 1996. Comparing three land surface schemes used in GCMs. *J Hydrol*, **180**, 373–394.

Pyle, J.A., AUSTIN, J., Chipperfield, M.P., Cox, R.A., Farman, J.C., Gray, L.J., Harris, N.R.P., Jones, R.L., McCulloch, A., O'Neill, A., Penkett, S.A., Reeves, C.E., Roscoe, H.K., Shine, K.P., Toumi, R. and Webb, A.R., 1996. Stratospheric Ozone 1996. Sixth report of the United Kingdom Stratospheric Ozone Review Group. Department of Environment reference number 96DPL0020.

ROBERTS, C.M. and GORDON, C. 1997: Flux corrections in coupled models. *Mon Weather Rev*, **125**, 909–925.

ROBERTS, M.J., New, A.L., WOOD, R.A. and Marsh, R., 1996. An intercomparison of a Bryan–Cox type ocean model and an isopycnic ocean model. Part I: The sub-polar gyre and high-latitude processes. *J Phys Oceanogr*, **26**, 1495–1527.

ROULSTONE, I. and Sewell, M.J., 1996. Potential vorticities in semi-geostrophic theory. *QJR Meteorol Soc*, **122**, 983–992.

ROWELL, D.P., 1996: Response to comments by Sud and Lau: Further analysis of simulated interdecadal and interannual variability of summer rainfall over tropical north Africa. *QJR Meteorol Soc*, **122**, 1007–1013.

ROWNTREE, P.R., 1996, Global and regional patterns of climate change: recent predictions for the Arctic. *In* Proceedings of the Conference on Global Change and Arctic Terrestrial Ecosystems, Oppdal, Norway, August 1993. Springer-Verlag.

Rubtsov, V.N. and ROULSTONE, I., 1997. Examples of quaternionic and Kahler structures in hamiltonian models of nearly geostrophic flow. *J Phys A: Math Gen*, **30**, L63–L68.

Santer, B.D., Taylor, K.E., Wigley, T.M.L., JOHNS, T.C., Jones, P.D., Karoly, D.J., MITCHELL, J.F.B., Oort, A.H., Penner, J.E., Ramaswamy, V., Schwarzkopf, M.D., Stouffer, R.J. and TETT, S.F.B., 1996. A search for human influences on the thermal structure of the atmosphere. *Nature*, **382**, 39–46.

Santer, B.D., Taylor, K.E., Wigley, T.M.L., JOHNS, T.C., Jones, P.D., Karoly, D.J., MITCHELL, J.F.B., Oort A.H., Penner, J.E., Ramaswamy, V., Schwarzkopf, M.D., Stouffer, R.J., TETT, S.F.B., Boyle, J.S. and PARKER, D.E., 1996. Human effect on global climate. *Nature*, **384**, 524.

Sear, C.B., Tadesse, T., Bettany, B., BUDGEN, P., Copley, V. and GRIGGS, D.J., 1996. The presentation of weather information via the media in Ethiopia. *Meteorol Appl*, **3**, 295–300.

SENIOR, C.A. and MITCHELL, J.F.B., 1996. Cloud feedbacks in the UKMO Unified Model. *In* Climate sensitivity to radiative perturbations: Physical mechanisms and their validation. Ed H. Le Treut. NATO ASI Series 1: *Global Environmental Change*, Vol. 34. Springer Verlag.

SHUTTS, G.J., 1997. Operational lee wave forecasting. *Meteorol Appl*, **4**, 23–35.

Simmonds, P.G., DERWENT, R.G., McCulloch, A., O'Doherty, S. and Gaudry, A., 1996. Long-term trends in concentrations of halocarbons and radiatively active trace gases in Atlantic and European air masses monitored at Mace Head, Ireland from 1987–1994. *Atmos Environ*, **30**, 4041–4063.

SLINGO, A., 1996. Assessing the treatment of radiation in climate models. *Ambio*, **26**, 52–57.

SLINGO, A. and WEBB, M.J., 1997. The spectral signature of global warming. *QJR Meteorol Soc*, **123**, 293–307.

Slingo, J.M., Sperber, K.R., Boyle, J.S., Ebisuzaki, W., Ceron, J-P., Dix, M., Dugas, B., Fyfe, J., GREGORY, D., Gueremy, J-F., Hack, J., Harzallah, A., INNESS, P., Kitoh, A., Lau, WK-M., McAvaney, B., Madden, R., Matthews, A., Palmer, T.N., Park, C-K., Randall, D. and Renno, N., 1996. Intraseasonal oscillations in 15 atmospheric GCMs: Results from an AMIP diagnostic subproject. *Clim Dyn*, **12**, 325–357.

STEVENSON, D.S., COLLINS, W.J., JOHNSON, C.E. and DERWENT, R.G., 1997. The impact of aircraft nitrogen oxide emissions on tropospheric ozone studied with a 3D Lagrangian chemistry model including fully diurnal chemistry. *Atmos Environ*, **31**, 1837–1850.

TAYLOR, J.P., EDWARDS, J.M., GLEW, M.D., HIGNETT, P. and SLINGO, A., 1996. Studies with a flexible new radiation code. II: Comparisons with aircraft shortwave observations. *QJR Meteorol Soc*, **122**, 839–861.

THOMSON, D.J., 1996. The second-order moment structure of dispersing plumes and puffs. *J Fluid Mech*, **320**, 305–329.

THURLOW, M.S., Brooks, B.J., Lucas, P.G.J, Ardron, M.R., Bhattacharjee, J.K. and Woodcraft, A.L., 1996. Convective instability in rotating liquid 3He-4He mixtures. J *Fluid Mech*, **313**, 381–407.

WARD, M.N. and Hoskins, B.J., 1996. Near-surface wind over the global ocean 1949–1988. *J Clim*, **9**, 1877–1895.

Webb, A., Gardiner, B., Driscoll, C., AUSTIN, J., Arlett, C., Raven, J., Lowe, D., Paul, N., McLeod, A., Diffy, B., Young, A., Hillerton, J.E., Gardiner, D., Bentham, G. and Bramwell, P., 1996. The potential effects of ozone depletion in the United Kingdom, Report by the United Kingdom UVB Measurements and Impacts Review Group. London, The Stationery Office.

White, A.A., 1997. Plato, polyhedra and weather forecasting. *In* Mathematics masterclasses: stretching the imagination, Ed M.J. Sewell. Oxford University Press.

ADAS	Agricultural Development and Advisory Service
ADEOS	Advanced Earth Observation Satellite (Japan)
ADMS	Atmospheric Dispersion Modelling System
AFS	Aeronautical Fixed Service
AFTN	Aeronautical Fixed Telecommunication Network
AMDAR	Aircraft Meteorological Data And Reporting
AMSU	Advanced Microwave Sounding Unit
AOGCM	Atmosphere–Ocean General Circulation Model
APR	Atmospheric Processes Research
ARIES	Airborne Research Interferometer Evaluation System
ASDAR	Aircraft to Satellite Data Relay
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
bps	Bits per second
CAMOS	Computer Aided Meteorological Observing System
CASE	Co-operative Awards in Sciences of the Environment
CFC	Chlorofluorocarbon
CFO	Central Forecasting Office
CGAM	Centre for Global Atmospheric Modelling
CMETS	Computerized Meteorological System
COST	Co-operation in Science and Technology
CPU	Central Production Unit
CWINDE	COST Wind Initiative Network Demonstration
DARPA	Defense Advanced Research Projects Agency (US)
DARTH	Development of Advanced Radar Technology for application to Hydrometeorology
DERA	Defence Evaluation and Research Agency
DMS	Dimethyl sulphide
DoE	Department of the Environment
DPSN	Defence Packet Switched Network
ECMWF	European Centre for Medium-range Weather Forecasts
EGOWS	European Group on Operational Workstation Systems
ENSO	El Niño Southern Oscillation
EPS	EUMETSAT Polar System
ERBE	Earth Radiation Budget Experiment
ERS	European Remote-sensing Satellite
EU	European Union
EUCREM	European Cloud Resolving Models
FASTEX	Fronts and Atlantic Storm Track Experiment
FOAM	Forecasting Ocean–Atmosphere Model
FWOC	Royal Navy's Fleet Weather Oceanographic Centre
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-surface Flood forecasting
GCC	Global Collecting Centre
GCM	General Circulation Model
GIS	Geographic Information System
GISST	Global sea-Ice and Sea-Surface Temperature
GMS	Geostationary Meteorological Satellite (Japan)
GPS	Global Positioning System
GTS	Global Telecommunication System
HQSTC	Headquarters Strike Command
HRDI	High Resolution Doppler Imager
HTML	Hypertext mark-up language
IASI	Infrared Atmospheric Sounding Interferometer
ICAO	International Civil Aviation Organization
ILAS	Improved Limb Atmospheric Spectrometer
IPCC	Intergovernmental Panel on Climate Change
ISDN	Integrated Services Digital Network
IT	Information technology
IWP	International Weather Productions (a Met. Office business unit)
JCMM	Joint Centre for Mesoscale Meteorology
LAM	Limited Area Model
LCBR	Laser cloud-base recorder
LES	Large Eddy Simulation
MCS	Mesoscale Convective System

METARs	Meteorological Airfield Reports
MIDAS	Met. Office Integrated Data Archive System
MIST	Meteorological Information Self-briefing Terminal
MLS	Microwave Limb Sounder
MMU	Mobile Meteorological Unit
MOMIDS	Meteorological Office Military Information Distribution System
MORECS	Met. Office Rainfall and Evaporation Calculation System
MOSES	Met. Office Surface Exchanges Scheme
MPP	Massively parallel processor
MSA	Marine Safety Agency
MSG	Meteosat Second Generation
MST	Mesosphere-Stratosphere-Troposphere
MSU	Microwave Sounder Unit
NAME	Nuclear Accident Model
NAVAID	Navigation Aid
NERC	Natural Environment Research Council
NHC	National Hurricane Center (US)
NMC	National Meteorological Centre
NMSs	National meteorological services
NOAA	National Oceanic and Atmospheric Administration (US)
NVGs	Night-vision goggles
NWP	Numerical weather prediction
OCP	Outstation Communications Processor
ODAs	Operational decision aids
ODS	Outstation Display System
OPUS	Outstation Production Unified System
PE	Parabolic equation or processor element
PMS	Public Meteorological Service
POL	Proudman Oceanographic Laboratory (UK)
PSTN	Public Switched Telephone Network
PVP	Parallel vector processor
RAFC	Regional Area Forecast Centre
RDBMS	Relational Database Management System
r.m.s.	Root-mean-square
RSMC	Regional Specialized Meteorological Centre
S&B	Services and Business
SA	*Sulphate aerosol*
SADIS	Satellite Distribution System
SAFIRE	Scanning Airborne Filter Radiometer
SAMOS	Semi-Automatic Met. Observing System
SBL	Stable boundary layer
SIGWX	Significant weather
s.m.d.	Soil moisture deficit
SQL	Structured Query Language
SSMI	Special Sensor Microwave Imager
SST	Sea-surface temperature
SSU	Stratospheric Sounder Unit
STOCHEM	A Lagrangian chemistry model
STOW	Synthetic Theater of War (US)
STWS	Storm Tide Warning Service
TACIA	Testing Atmospheric Chemistry in Anticyclones
TAFs	Terminal Aerodrome Forecasts
TARFOX	Tropospheric Aerosol Radiative Forcing Experiment
TCP/IP	Transmission Control Protocol/Internet Protocol
TDAs	Tactical decision aids
TIROS	Television Infrared Observational Satellite (US)
TOVS	TIROS Operational Vertical Sounder
TRIFFID	Top-down Representation of Interactive Foliage and Flora Including Dynamics
UARS	Upper Atmosphere Research Satellite (US)
UM	Unified Model
UMUI	UM User Interface
UTC	Universal Time Co-ordinated
VCP	Voluntary Co-operation Programme
WAFC	World Area Forecast Centre
WAFS	World Area Forecast System
WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe
WAM	Wave model
WIN	Weather Information Network
WMO	World Meteorological Organization
WWW	World Weather Watch or World Wide Web

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