The Met.Office

Scientific and Technical Review

1997/98

Exceling *in weather services*

Scientific and Technical Review 1997/98

The Met.Office

An Executive Agency of the Ministry of Defence

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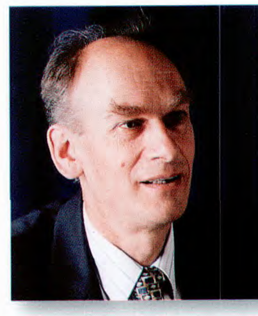
Chief Scientist's introduction



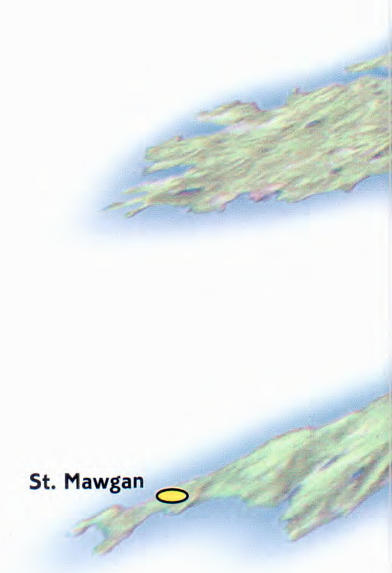
Paul Mason

The *Scientific and Technical Review* is a companion publication to the *Annual Report & Accounts 1997/98*. It covers in much greater depth our scientific and technical programmes, and their progress during the year. It is aimed mainly at scientists in other national meteorological services throughout the world, in the academic community and in commercial and research organisations.

Each year a few topics are presented in more detail. This year, larger contributions cover the Observations, Operation Services and Ocean Applications activities.

The Annual Report and Accounts provides our owners in MoD, Parliament, our customers, and our staff, with a review of our performance against our key targets and our main activities in 1997/98 (see inside of the back cover for details of how to obtain a copy or more information).

The *Chief Executive's review*, taken from the Annual Report and Accounts, gives a further introduction to the year's events, and provides an overview of the strategic issues faced by The Met. Office.

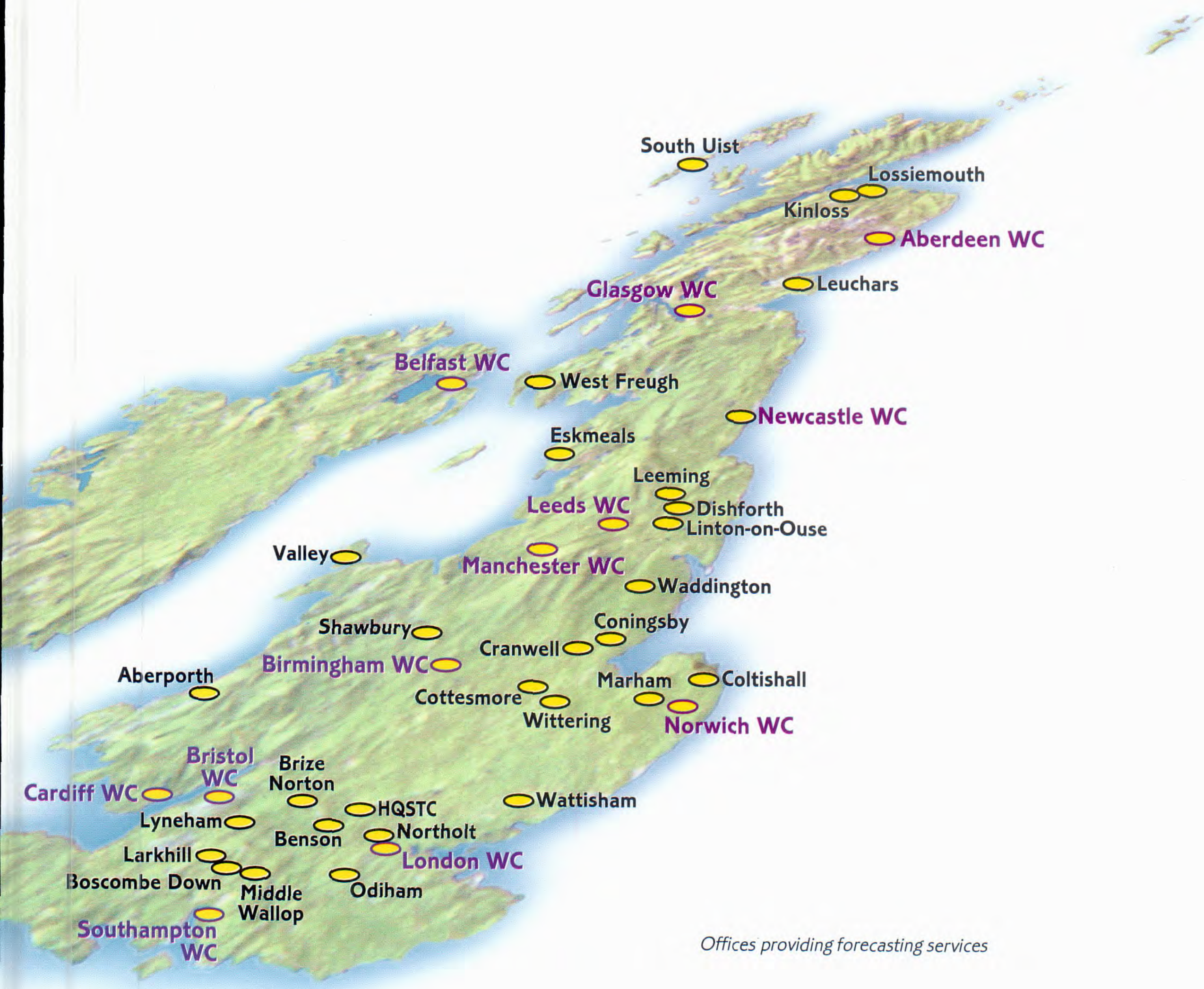


About The Met. Office

The Met. Office was formed in 1854 as a small department within the Board of Trade to provide meteorological and sea-current information to mariners. Early this century, The Met. Office started responding to new demands for weather services, most importantly in the field of aviation. This led to The Met. Office being taken under the auspices of the Air Ministry in 1920, later moving into the MoD.

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

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



Offices providing forecasting services

Chief Executive's Review

(taken from Annual Report and Accounts 1997/98)

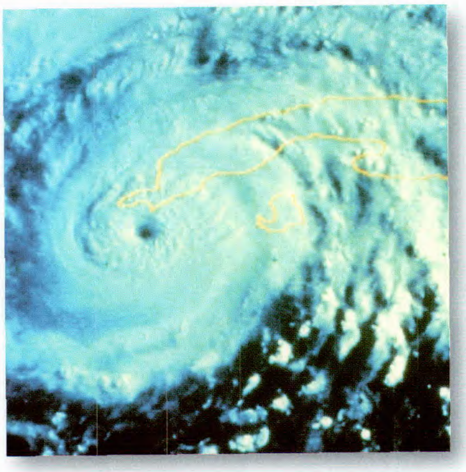
This is my first Annual Report and Accounts since my appointment as Chief Executive in August last year and I am delighted to report that, judged by the most demanding standards, 1997/98 has been a successful year for The Met. Office. We have met all but one of our key performance targets; we substantially exceeded the financial targets, and missed the global numerical weather prediction (NWP) target – a measure of our underlying improving accuracy – by only the narrowest of margins. At the same time, we have maintained a strong and diverse product range and have successfully created new markets for our services. But, most importantly, we have continued to provide our customers, in both the public and private sector, with increased value through a combination of improved service quality and greater efficiency.

Success built on science and people

The Met. Office continues to rank among the very best for the provision of weather services. Indeed, we are a benchmark for national meteorological services throughout Europe and the rest of the world. Through our Hadley Centre we have also gained an enviable international reputation for our work on climate change and climate prediction. But this position is neither easily won nor easily maintained – we have achieved it only through a strong science and technology base, supported by a healthy research and development programme, and the ability and dedication of our people. I am, therefore, pleased to take this opportunity to acknowledge the contribution made by all our staff to the success of The Met. Office, and to thank our Core customers in particular for the support they have continued to give to our Core programme.

An international player

As the UK's national meteorological service, The Met. Office has continued to represent the UK's international interests in meteorology, both in Europe and worldwide, through the World Meteorological Organization, a United Nations agency. With our long-established track record and our reputation for forward thinking, we have been able to influence the development of meteorology, especially in Europe,



Peter Ewins

and to help ensure the wider availability of data and products. We have, for example, been instrumental in developing European and global observing systems. And, through our climate research programme funded principally by the Department of the Environment, Transport and the Regions, we helped the UK government to play a leading role in the Third Conference of the Parties to the UN Framework Convention on Climate Change in Kyoto last December.

Capitalising on freedoms and flexibilities

The Met. Office became an Executive Agency in 1990 and has operated as a trading fund for two years. Under our parent department, the MoD, we have considerable freedom and flexibility to operate in a way that is best for The Met. Office and best for our stakeholders – our owners, our customers, our staff and, by no means least, the public. To take full advantage of these freedoms I have introduced a number of changes, both to our management structure and to the way we are organised. I have strengthened the role and responsibility of Directors, both individually and corporately, and increased substantially the extent and level of authority delegated to senior and middle managers. Responsibility for resources, service delivery and, where appropriate, revenue and profit now lies firmly where the decisions are best made. To ensure that managers are properly equipped for their new roles, we have held a successful series of development workshops.

Among the principal organisational changes are a clearer separation between business management and service delivery, the creation of a new Technical Services Division that brings together all our technical support capabilities, including our substantial IT infrastructure, and a greater focus on human resources, particularly on development and training.

Improving our Performance

As part of our commitment to continuous improvement, we have embarked on a new programme called *Improving our Performance*. This multi-pronged programme includes: a substantial simplification of our still rather bureaucratic processes and procedures, leading ultimately to ISO 9000 accreditation; the implementation of our commitment to *Investors in People*; the introduction of a new management information system covering both financial and non-financial information; improvements to our internal communications; and further improvements in programme and project management. Over the next three years, this programme will lead not only to greater efficiency but also to greater job satisfaction among our staff and to better value for money for our customers.

Investing for the future

Natural caution about the financial viability of The Met. Office in the run-up to trading fund led to an inevitable decline in investment – in people, in infrastructure, and in future products and services. However, we have demonstrated over the past two years that we can more than survive, and my aim now is to increase our investment in key areas where the business case is sound.

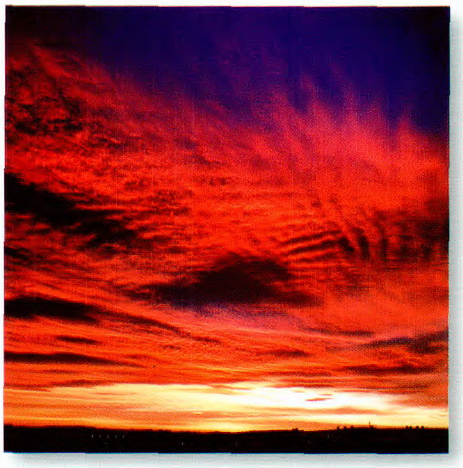
We have already made a good start with our observational network, the cornerstone of our weather forecasting services, and we have put plans firmly in place to update our IT infrastructure. We are also working to ensure that we are year 2000 compliant well before the start of the next millennium. The end of last year saw the commissioning of our new Cray T3E supercomputer which is now contributing directly to improvements in our NWP performance. And, of course, we are making a substantial investment in our human resources through selective recruitment and through *Investors in People*.

Services to commerce and industry

Finally, I should mention the internal review of our commercial services which, although not yet complete, has confirmed the importance and value of these services, both to The Met. Office and to our customers. There is no doubt that they enable The Met. Office to maintain and develop a broader and deeper range of capabilities than would otherwise be possible, to the benefit of all our customers. Commercial services also make a significant and increasing financial contribution to the Core programme, keeping down costs to our Core customers. Moreover, they provide real added value to commerce and industry, and many of them – for example our forecasting services to the major utilities and local authorities – are in the public interest.

Looking forward

The Met. Office has been in the business of providing meteorological services for over 140 years.
We deliver a world-class, value-added service to a wide range of loyal customers; we have an able and committed workforce, continually improving their knowledge and skills; and we have laid plans that will take us successfully into the next millennium.
1997/98 has been a good year for The Met. Office and I look forward to our continued success as we build for the future.



Observations

The observation programme provides the basic, common observational data used in the provision of services for The Met. Office's customers. This involves:

– operating and maintaining, within the framework of the World Weather Watch of the World Meteorological Organization (WMO), a surface-based observing system to measure relevant properties of the atmosphere (from the surface to about 25 km), UK land surfaces and adjacent ocean areas;

– contributing to the provision of a cost-effective global satellite observing system, in collaboration with other nations and, in particular, through membership of EUMETSAT;

– acquiring observations from other countries through participation in WMO programmes, including the exchange of observational data in accordance with international agreements; and

– archiving quality-controlled observations in a climatological database.

Observing networks

Requirement for measurement of radiation and sunshine

A practical network for measurement of solar and terrestrial broad-band radiation and bright sunshine has been proposed after user requirement studies. The three main requirements are to: monitor daily solar radiation and bright sunshine on a national and regional spatial scale; measure the surface radiation budget; provide high-accuracy measurements of broad-band radiation to support climate change research and to provide ground truth for satellite radiation measurements.

Measurements of global radiation at hourly intervals will be provided automatically from 54 stations, of which 20 are for climatology. Three stations (Lerwick, Camborne and Bracknell) will provide one-minute resolution data, including downward direct, diffuse and global short-wave solar radiation and downward atmospheric long-wave radiation.

Since standard Campbell–Stokes sunshine recorders are of limited accuracy, more-sophisticated instruments such as Kipp and Zonen Scientific Monitoring Stations (Fig. 1) will need to be installed at the 20 climatological stations.

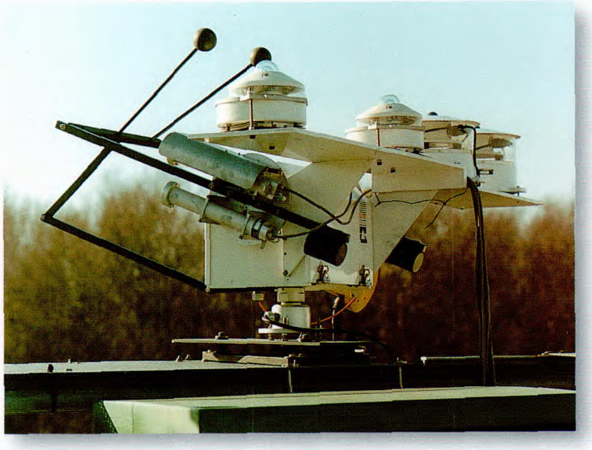


Figure 1. The Kipp and Zonen Scientific Solar Monitoring Station.

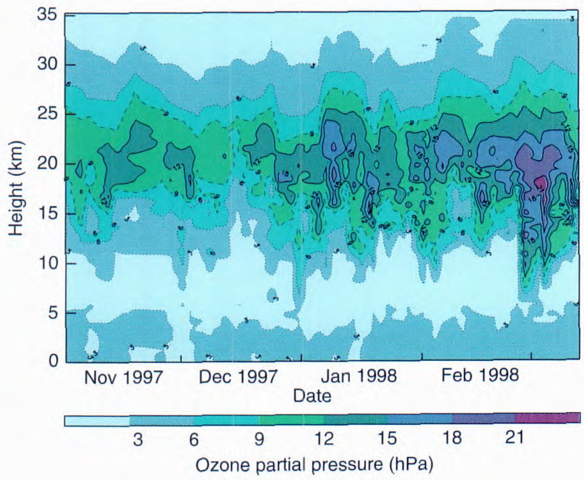


Figure 2. Ozone partial pressure cross-section for Lerwick based on nearly 50 ozone sonde ascents made during Winter 1997/98.

Ozone

Vertical profiles of ozone are measured at Lerwick with ozone sondes and a time sequence of observations is plotted in Fig. 2. Very low values of ozone were observed in mid-December when stratospheric temperatures were exceptionally low. High values of ozone concentration in mid-January followed a major mid-winter stratospheric warming event. At the end of January lower values were observed as the stratosphere cooled again. Daily measurements of total ozone were also made at Camborne and Lerwick with Dobson spectrophotometers. The low values of total ozone observed at Camborne in April 1997 were associated with above-normal values of ultraviolet radiation. This year no exceptional low values (i.e. an 'ozone hole') have been observed. Unlike previous years, the air in the high-altitude circulation, the so-called vortex, has not been very cold.

Upper-air data

The closure of the Omega navigation system in October 1997 caused a major problem for radiosonde wind measurements. More than 25% of the radiosonde systems in the WMO Global Observing System used Omega signals to track the radiosondes in flight and hence measure winds. Since 1994 a range of replacement upper-air sounding systems has been tested. The replacement radiosonde system installed at Gibraltar, the Falkland Islands and St Helena uses Global Positioning System (GPS) navigation signals received by the ascending radiosonde to determine its movement. During trials at Camborne, the GPS wind measurements were compared against winds derived from radar tracking and also from the UK operational radiosondes using LORAN-C, see Fig. 3.

In general the GPS measurements were of better accuracy than those obtained with Loran-C. However, unacceptably large wind anomalies were generated by the GPS wind systems on some occasions, and guidance has been issued on how to identify and eliminate this problem. The lack of regular temperature and relative humidity profiles from central England has been limiting short-term forecast accuracy of significant weather. To rectify this an automatic radiosonde launch system has been tested. Figure 4 shows a balloon shortly after launch during initial evaluation tests at Camborne in November 1997. Successful launches were obtained with mean surface winds up to about 18 m s^{-1}. The system will be installed at Watnall in 1998.

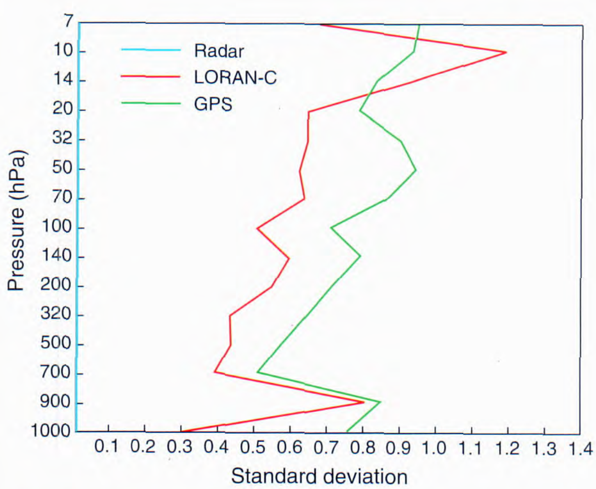


Figure 3. Results from comparing wind measurements are presented as a function of pressure (height), where the radar measurements have been used as a reference for the GPS and LORAN-C radiosonde winds.

Figure 4. Automatic radiosonde launcher under trial at Camborne.

Weather radar network

The 15 C-band weather radars that comprise the operational UK network have reliably provided rainfall data throughout the year, both as direct services to customers and as the primary rainfall data for the fully automated precipitation forecasting system called Nimrod.

Operational developments

Procedures have been developed for performance assessment. These include: the upgrading of hardware performance parameter monitoring; a statistical approach with monthly accumulations of data which give guidance on relative coverage performance for both detection and quantitative accuracy; and more frequent and regular assessment of magnetron spectrum performance. These have been refined to give early warning of gradual system degradation.

An off-line radar facility is being created as a trials test bed, both for new developments and repaired items before their introduction into the on-line network.

Research and development

A contract was completed with Deutsches Zentrum Für Luft- und Raumfahrt (DLR) in Germany supported by the European COST-75 programme. The project examined technical and meteorological effects on Doppler weather radar measurements, and reviewed methods for extracting meteorological

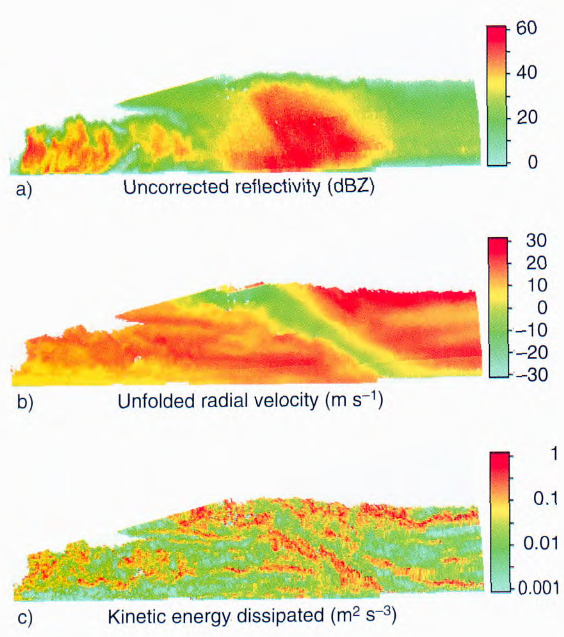
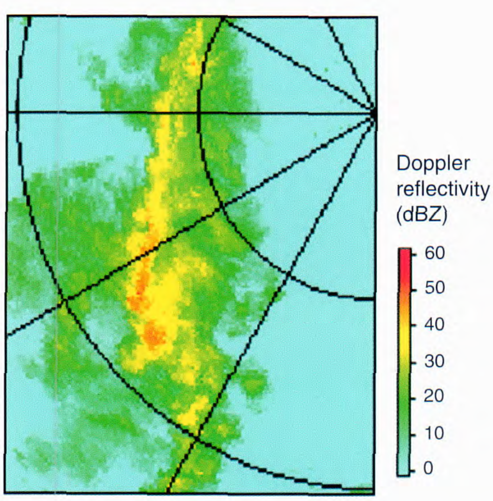


Figure 5. Range–height indicator scan of (a) reflectivity (precipitation intensity), (b) radial Doppler velocity and (c) energy dissipation rate (obtained from Doppler spectral width) at azimuth 32°. The range is 20–80 km and cloud top is approximately 13 km.

information from the radar return signals, in particular convergence and energy dissipation rate. An example of vertical radar measurements through a thunderstorm, collected by the DLR radar in Germany, is shown in Fig. 5. Here the precipitation intensity and Doppler radial velocity are shown, together with the derived values of energy dissipation rate. This has the potential to provide information about storm development and longevity.

Studies on both Doppler and polarisation-diversity weather radar are also being carried out as part of the DARTH project (Development of Advanced Radar Technology for application to Hydrometeorology), funded by the Commission of the European Communities. DARTH is co-ordinated by the University of Essex and has partners in Germany, Italy, Sweden and Spain. As part of this study, The Met. Office is identifying the benefits of the advanced radar techniques to operations, with a particular focus on applications in hydrometeorology. With the University of Salford, The Met. Office is investigating the impact of error characteristics in radar data on hydrological catchment modelling for flood events.

The GANDOLF system (Generating Advanced Nowcasts for Deployment in Operational Land-surface Flood forecasting) was developed in partnership with the Environment Agency as a real-time forecast system for heavy rainfall events. The development phase of this project has now been completed and it is now undergoing operational implementation. The system is also being used in a number of projects to provide a tool for analysing complex radar information, through classification of the image into differing stages of convective development. Figure 6 shows an example taken from radar data collected by the regional meteorological service in Bologna in Italy as part of the DARTH project.



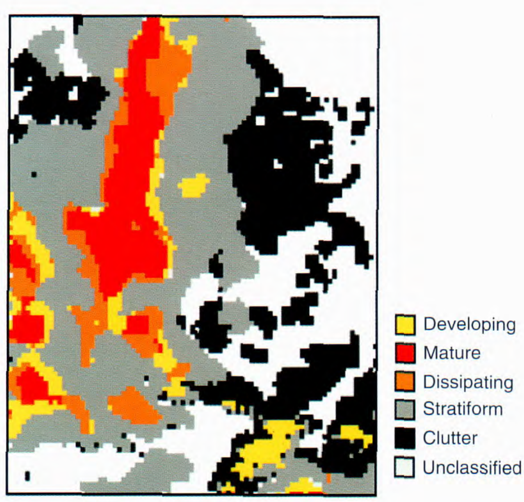


Figure 6. The reflectivity section (left) is taken from an Italian regional met. service radar at 1334 UTC on 12 May 1995. (Right) The GANDOLF analysis of this radar image.

Lightning location system enhancement

The Met. Office has operated a Very Low Frequency (VLF) 'arrival time difference' (ATD) thunderstorm location system since 1986. This hardware is currently being upgraded and the software enhanced. Improvements will allow the system to operate automatically and increase the number of lightning strokes that may be processed per hour to between 10,000 and 12,000, improving the system's detection efficiency.

Lightning is a source of VLF radiation, and until now the received waveforms have only been used to locate the source of the radiation using a network of outstations and an ATD lightning location technique. However, each waveform contains information on the type of flash (cloud-to-ground, cloud-to-cloud), stroke polarity, stroke strength and the number of strokes per event that generated the radiation. Software is being developed to extract this information from received waveforms that originated from lightning located in the UK.

To improve the location accuracy of the system, a VLF propagation model is being developed. This will adjust waveform group velocities to take account of the earth ionosphere wave-guide depth and surface type along the path from source to receiver. By including detailed spectral attenuation models, the accuracy of the location assignment over the UK at the dawn/dusk terminator is expected to increase by about 25%. The model should also enable flash attribute information to be extracted from waveforms which were produced at greater distances from the outstation network.

New technology

Present weather (precipitation)

Some techniques for automatically reporting present weather have been explored. These have included comparative trials of instruments that use sensors to detect precipitation, and identify the type by its reflection and refraction effects in an optical beam. Such instruments are typically able to identify drizzle, rain and snow, and estimate the rate (slight, moderate or heavy) and cumulative amounts. Intercomparisons against human observers have been carried out at Eskdalemuir. Results show there are many instances where precipitation can be automatically detected and identified, although there can be problems with sensitivity at the start and end of these events.

Present weather (rain and hail identification)

Another new idea, currently subject to a feasibility study, is the use of acoustic techniques to identify precipitation type, in particular hail. Rapid advances in computing power now allow complex analyses of acoustic signals from a microphone in real time. Investigations are being made using various types of microphone and sensing surfaces, to see whether different types of precipitation produce acoustic signatures that can be recognised by a computer.

Closed-circuit television project

The development of closed-circuit television (CCTV) cameras to monitor the weather continued, with the aim of meeting two requirements. The first was to provide observational information in data-sparse areas and the second was to meet specific forecast requirements, such as providing cloud and visibility data in military low-flying areas. Cameras were installed at a range of sites across the UK for evaluation, Fig. 7.

The main aims of the evaluation were to determine: the potential usefulness of CCTV images to forecasters and observers; how well present weather (precipitation, fog/sky-obscuring events and thunderstorms), ground state, cloud type and amount could be identified; how information from CCTV cameras could be incorporated into automatic synoptic reports.

Precipitation was best detected by pointing the camera into the wind but the lighter types of rain and drizzle went undetected. Therefore, work has begun to enhance detectability of precipitation by illuminating the droplets. A total of 70% of fog events were reported using the camera, and the rest were reported as haze. The advantages of collocated CCTV and automatic weather stations (AWS), and of having a monitoring station in the same region, were highlighted when it came to identifying cloud type and amount.

The cloud height information from laser cloud-base recorders helped differentiate between similar-looking types, and a knowledge of the cloud affecting the region was helpful in distinguishing between multiple layers. For ground state, extremes such as snow, ice, flooding or cracked ground could be identified, however, distinguishing between more-subtle conditions, such as dry or wet ground, was not then possible.

Figure 7. Location of the CCTV cameras.

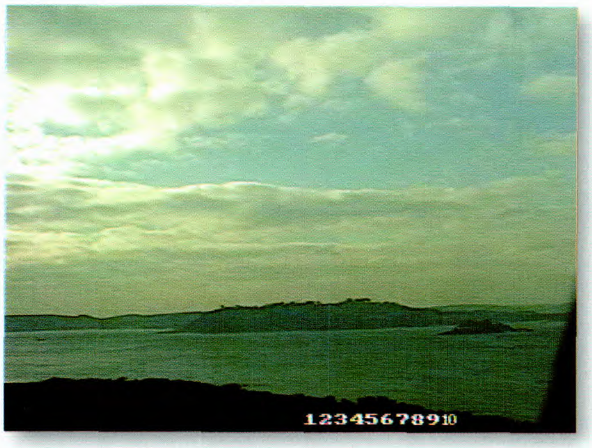


Figure 8. Example of the type of picture available from CCTV.

The visual information from the CCTV image can be added to the AWS report and transmitted to Bracknell in approximately 10 minutes. The main limitation of the existing system is that it can only be used during daylight hours, therefore infrared cameras and image intensifiers are under investigation to extend the use of CCTV into the night.

Mobile Semi-Automatic Met. Observing System (SAMOS)

Sometimes existing observing sites close on very short notice, often due to termination of tenancy. Timescales are typically too short to allow a standard permanent installation to be used at the replacement site. Such a case occurred with the closure of the Birmingham Airport observing office and equipping the replacement at Coleshill. A portable system was created where all the sensors and items required for installation could be transported together, with most connections in place, and then deployed on site in a short time (Fig. 9). The mobile system will provide wind speed and direction, pressure, wet-bulb and dry-bulb temperatures, humidity, grass and concrete temperatures, rainfall, cloud height and visibility. Data are transmitted from the system by cellphone.

Profiler radar systems

Wind profiler radar systems are able to measure upper winds at high temporal resolution (several times per hour if required) at similar vertical resolution to radiosonde upper-wind measurements. Profiler radars observing at frequencies close to 50 MHz are able to measure the wind from the Doppler shift in backscattered radiation from clear air at heights from 2 km to at least 20 km. Systems operating at frequencies close to 1 GHz are better suited for measurements in the lower layers of the atmosphere and can provide measurements from 100 m to about 3 km above the surface in dry conditions, and as high as 5–8 km when rain systems are passing over the radar. During 1997, a 1 GHz radar was installed at Camborne for evaluation testing. This system has been run remotely from Bracknell, with little direct intervention from staff at Camborne. Good quality measurements have been obtained for most of the period, but certain failures have highlighted the need for a larger range of operational spares and improvement in the capabilities of remote interrogation to diagnose

Figure 9. Mobile SAMOS system being installed at Coleshill.

system faults. Measurements from the system will be made directly available to users, once problems with communications and data archiving in Bracknell have been resolved, and will be used in scientific studies in collaboration with the University of Reading.

Profiler radar systems installed to date have been mainly for scientific research, but now systems are being introduced for operational purposes, such as wind monitoring at airports. Preparations for developing operational profilers and networking capabilities for the observations from the various radar sites in Europe are being implemented in the European COST-76 project. The UK provided the project management for the first profiler network experiment in Europe, CWINDE, when hourly measurements were collected from 11 locations across Europe during January to March 1997. The profiler measurements will also be provided to the FASTEX database in order to support scientific studies and the development of data assimilation schemes. The UK is responsible for quality control of the reported winds and was responsible for querying problems with the measurements.

Original data submitted to CWINDE had significant errors, but collaboration between the groups in the UK and France has allowed the errors to be identified. Software has now been developed in France to improve the quality of the operational measurements.

Use of GPS receivers to derive water vapour profiles

In co-operation with the Institute of Engineering Surveying and Space Geodesy (IESSG), University of Nottingham, a network of GPS receiver sites is being established for measuring integrated column water vapour amount. The total quantity of water vapour above each site is calculated by measuring the delay of the GPS signals received from each GPS satellite in view, over and above what would be expected from the geometry of the satellites and receiver, assuming no intervening medium. This requires the precise location of the receiver to be known and to be stable to an accuracy of a few centimetres. The first four receivers are at Camborne, Aberystwyth, Hemsby and Lerwick. Collaboration with other geodesic users of GPS receivers should provide a network of 12 sites in the UK.

Space-based observing

EUMETSAT programmes

The Meteosat programme of geostationary satellites at the Greenwich meridian continued with a successful launch of Meteosat 7 on 2 September 1997 and subsequent commissioning. It becomes operational in April 1998 with Meteosat 6 reverting to a standby role. Meteosat 7 will provide continuity of operations until MSG (Meteosat Second Generation) becomes operational in 2001. Meteosat 5 is being sent to 65° E to provide support to the Indian Ocean Experiment (INDOEX) commencing in late 1998.

The EUMETSAT Polar System (EPS) programme passed a major milestone in January 1998 when approvals were given by EUMETSAT and ESA to start building the spacecraft. Full programme approval remains subject to ratification in some EUMETSAT member states. MSG will ensure a continuity of polar-orbital data in conjunction with the USA from 2003 to 2017.

The instruments on the Meteorological Operations Satellite (METOP), the satellite part of EPS shown in Fig. 10, will produce high-resolution images, vertical temperature and humidity profiles, and temperatures of global land and ocean surfaces. Also on board will be instruments for monitoring ozone and wind flow over the oceans.

AMSU-B programme

In 1986 The Met. Office signed an agreement with NOAA to provide and support three flight models of the humidity sounder element of the Advanced Microwave Sounding Unit (AMSU-B), for NOAA's series of polar-orbiting satellites. The instruments, including an engineering model, were procured from British Aerospace and a facility was set up to test, calibrate and characterise them.

The calibration and test facility is based at the Defence Evaluation and Research Agency in Farnborough and includes precision calibration targets and instrument thermal control systems, as

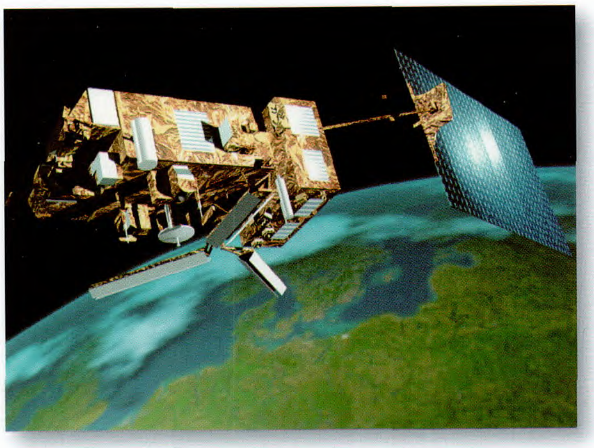


Figure 10. Artist's view of the new EUMETSAT Polar System (EPS) satellite.

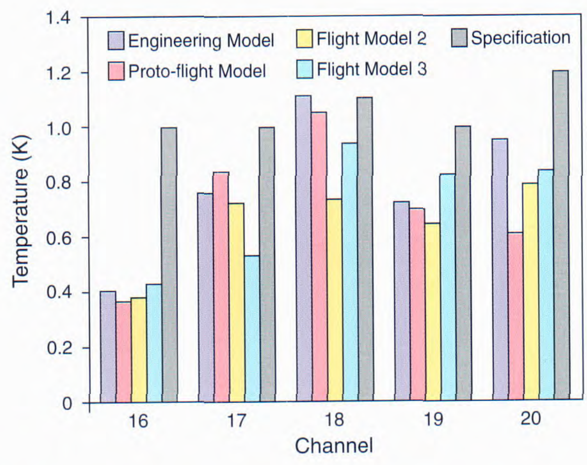


Figure 11. Radiometric sensitivity for all AMSU-B models.

well as associated data processing and logging hardware. This enabled a wide range of characterisation tests to be carried out on the AMSU-B instruments including linearity, temperature sensitivity, calibration accuracy and view dependency (Fig. 11). All the AMSU-B flight models have now been delivered to the polar orbiter launch contractor Lockheed Martin, and two have already undergone spacecraft-level thermal vacuum tests.

Commercial activities

Using the skills and experience gained from the AMSU-B project, The Met. Office has gained a number of commercial contracts to provide test, calibration and associated services for remote-sensing satellite instruments.

Characterisation of two instruments, the Microwave Humidity Sounder (MHS) engineering model for Matra Marconi Space and the Microwave Radiometer (MWR) for Italian company Alenia Spazio, were completed in the summer of 1997. Tests on the Multi-Imaging Microwave Radiometer demonstrator for Alenia and at least two flight models of MHS are in progress. Negotiations continue for a number of possible contracts including the calibration of the Humidity Sounder for Brazil (HSB), a version of the AMSU-B instrument.

The Met. Office also produces precision black-body calibration targets used in the characterisation of microwave instruments (Fig. 12a). Met. Office targets were used in the MWR calibration (Fig. 12b) and have been fitted to the Deimos radiometer which flies on the Met. Research Flight C-130. These targets have also been sold commercially.

Aircraft radiometer work

A number of airborne radiometer simulators have been developed for forthcoming meteorological satellite instruments. These instruments will provide

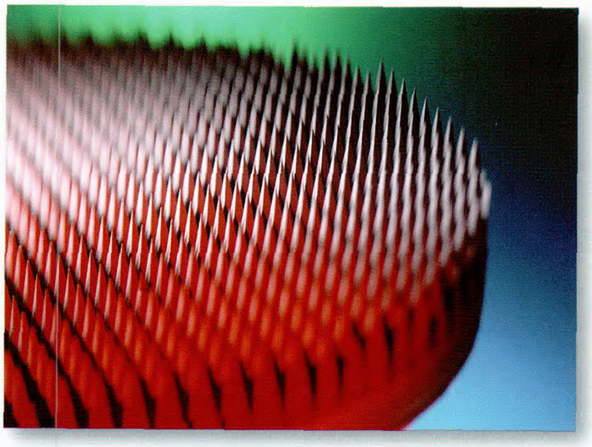


Figure 12a. Microwave calibration target.

Figure 12b. Met. Office staff fit targets to the MWR test rig.

improved temperature and humidity profiles for operational meteorology, leading to improvements in forecasting. Airborne simulators are used to test and improve knowledge of the relevant atmospheric spectroscopy, surface characteristics and radiative transfer models. This is a necessary precursor to the routine extraction of the required atmospheric data from the satellite radiance measurements.

To validate the radiative transfer models behind the retrievals of temperature and humidity from the next generation of satellite sounding instruments (such as AMSU-B) two microwave radiometers have been developed and flown extensively on the C-130 aircraft. Recent studies have concentrated on the measurement of emissivity at AMSU frequencies over a variety of surfaces. Data from a series of flights over snow and ice, semi-arid land and various crop surfaces have been used to develop a model for the prediction of the emissivity over a range of incidence angles and polarisations, providing a background for AMSU retrievals over these surfaces.

The Airborne Research Interferometer Evaluation System (ARIES) has been built as a simulator for a number of new infrared sounding satellite instruments, in particular the Infrared Atmospheric Sounding Interferometer (IASI). IASI is being developed by Centre National d'Etudes Spatiales in France for METOP. These new sounders offer higher spectral resolution and spectral coverage than previous sounders, with the potential of yielding both higher vertical resolution and accuracy in the temperature and humidity retrievals.

ARIES is mounted on the C-130 aircraft and measures infrared radiation in the wavelength range 3.3–16 µm. ARIES is capable of viewing both upwelling and downwelling radiation (and at angles off nadir), and its data will be used to provide infrared spectra for comparison with simulations from line-by-line radiative transfer models (e.g. GENLN2, GEISA). Such simulations require measurements of the atmospheric temperature and humidity profiles which are routinely available from the standard instrumentation on the C-130 aircraft.

Figure 13 shows ARIES observations from an aircraft run at an altitude of 100 ft, with the instrument observing straight upwards. A line-by-line radiative transfer simulation, based on the measured atmospheric profile, is included for comparison. This work is helping identification of areas of uncertainty in modelling and relevant atmospheric spectroscopy, prior to the launch of IASI. This includes infrared spectral features associated with CO_2, H_2O and other minor constituents, such as O_3, N_2O, CH_4 and CFCs.

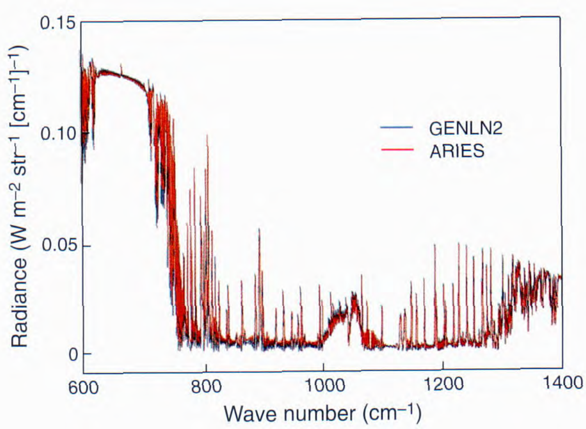


Figure 13. ARIES observed radiance spectra at altitude 100 ft looking in the zenith and a simulation using the GENLN2 line-by-line radiation code.

Operational Services

Project 2000

In March 1997 The Met. Office set up Project 2000 to minimise the potential risk to its services posed by the century date change, known as the 'millennium bug'. By June 1997, the magnitude of the task had been determined and a strategy developed to manage the issues. The Met. Office has approximately 20 million lines of critical code that need to be checked, spread across 4,000 individual systems using 50 different programming languages. Pilot projects were used to identify the practical issues to be resolved and the procedures to be followed. The Met. Office is also working closely with the World Meteorological Organization (WMO), other national meteorological services, customers and suppliers to ensure the whole business chain is secure.

To ensure that all business-critical systems are year 2000 compliant by the end of 1998, The Met. Office has started 73 separate compliance projects and has a central co-ordination team to provide general support and guidance. The creation of a full inventory of the systems, their code, interactions and interdependencies has been completed and the work of actually checking for, and fixing the 'bug' has begun. Each project must be completed and tested for compliance of individual systems by the end of 1998. Some will achieve this earlier. End-to-end testing of linked systems will begin in early 1999 to certify compliance of The Met. Office's services well before 2000.

Meteorological Database

The Office's major global 'real-time' data store, the Synoptic Data Bank (SDB), has been obsolete for some time, relying on architecture and software developed in the 1970s (then it was vital to use every available byte of computer space and machine performance). As a result, the SDB stores were inflexible and the software (mainly IBM Assembler) was increasingly difficult to maintain. Access methods are not now suited to modern screen-based users. Also, both the SDB and the long-term Synoptic Machinable Records software, which obtains reports from the SDB, were not year 2000 compliant.

A replacement system, the Meteorological Database (MetDB), has been developed so that the SDB and all 'downstream' systems can be decommissioned beginning in 1998. The MetDB is an in-house development, but uses international standard programming tools (Fortran) and storage formats (primarily BUFR). It is optimised for the high-performance storage and retrieval of 'synoptically ordered' data, meaning data from many places for the same time. The MetDB stores data from over 30 observation systems and message types. It can be readily expanded to store additional data types, and has been designed to store model-derived spot values alongside the 'raw' data elements.

Information is held on-line for 3–14 days (depending on data type), and then off-line for typically five years, although indefinite retention of cases of special meteorological interest is possible. In contrast to the SDB, users do not need to know whether the data they are interested in are held on- or off-line. In addition a multi-user Remote Procedure Call (rpc) feature is under test and will provide cross-platform connectivity to the MetDB.

The MetDB system has been successfully 'ported' to both HP-UX and IBM UNIX platforms, and is now a key component of the Thailand Operational Meteorological System.

MIDAS

While the MetDB is a solution to the storage of recent data, we have a similar problem with the long-term climatological data archive. Again, data structures and access software have become increasingly inadequate and unsupportable.

Typical retrievals from a climatological archive are more varied than those from a real-time database. Users need to be able to specify criteria, such as time and space bounds, or even data bounds, for example temperatures greater than 20 °C. A replacement system was chosen to allow such flexibility. The Met. Office Integrated Data-Archiving System (MIDAS) has been designed as a relational database, built on the Computer Associates IDMS relational database management system (RDBMS). This will allow user access via standard tools (Fortran, SQL, ODBC clients), providing great flexibility in the construction of retrieval applications. It has also been designed with portability in mind, so that it is not tied to a particular hardware or software platform. As a trial exercise, MIDAS has been successfully 'ported' to another RDBMS running on both the COSMOS MVS mainframe and a PC-based Windows NT system.

Weather Information Network

The Weather Information Network (WIN) is now the principal means for collecting UK observations and distributing data and products to outstations. The main contract was completed with Digital in October 1997, following extensive testing during the summer. With WIN being fully deployed in the UK, obsolete facilities were removed, allowing savings in running costs. For example in December 1997 the MOLFAX service was stopped, after 37 years of supporting the distribution of weather charts to forecasters around the UK by analogue fax. Charts in digital form are now included in the products delivered via WIN to computer systems at outstations, saving about £200,000 per year on the cost of the telephone circuits which were dedicated to MOLFAX.

Global Telecommunication System

Forecasting is critically dependent on the Global Telecommunication System (GTS), the network which connects the world's national met. services (NMSs) for real-time exchange of data and products. Although now computer-based, the GTS still has some outmoded characteristics.

At a series of meetings held during 1997, The Met. Office contributed to the detailed planning of two important developments: the renewal of the whole GTS network in Europe (a joint project involving the NMSs and the European Centre for Medium-range Weather Forecasts), and the definition of standards for using techniques derived from the Internet. In combination, these two developments will overcome many of the deficiencies in the existing GTS, not by developing special solutions for meteorology, but by using technology and services in common with other industries which operate international networks.

With formal ratification of the new standards by the WMO in 1998, and adherence to the procurement timetable for the new European network, benefits will be seen in Autumn 1999. Some GTS connections will be converted to use TCP/IP (Internet protocol for data transport) during 1998 in order to give assurance that the new standards and procedures are well-defined.

Cray T3E supercomputer

Operational forecasting in The Met. Office is underpinned by the routine running of the Unified Model (UM) on the supercomputer. Previous Met. Office supercomputers have used a parallel vector processor architecture, but in contrast the new Cray T3E has a massively parallel processor design that uses hundreds of processor elements (PEs). Each PE consists of small, relatively cheap but fast CPUs and local memory.

Given the different design of the T3E, a phased approach was adopted for its introduction. Not only was a large amount of work required to adapt the application programs, i.e. the models used for forecasting and research, to the new architecture, but also operational procedures needed to be modified.

The development T3E, installed in the previous year, was replaced in April 1997 by the production T3E with 696 PEs, Fig. 14. The machine was accepted in November 1997. Because the amount of work that the T3E was required to run was greater than anticipated, an upgrade to increase the number of PEs to 856 was carried out following the acceptance.

A parallel version of the operational weather forecasting suite was established on the T3E. The suite had to be proven to run correctly and within the strict schedule required so that products could be delivered to

Figure 14. The Cray T3E supercomputer.

customers in time. Also, a new higher-resolution version of the global forecast model was incorporated in the suite. The suite, including the higher-resolution model, was put into operation on 28 January 1998 (see *Development of the Forecasting System* in the *Numerical Weather Prediction* section).

The T3E has been used by a variety of research users, in particular, those from the Climate Research Division. The Cray Y-MP C90, the old supercomputer, was switched off on 13 February 1998.

General Purpose Computing Service

A General Purpose Computing Service is provided using an IBM mainframe computer. This service includes the important functions of pre- and post-processing of data for the supercomputer, including the management of observational and product databases; generation of products for customers from observations and model output; and the management of a very large data archive.

The volumes of data to be processed and archived have increased with the use of higher-resolution models on the T3E and the running of more research experiments. This means the requirement for processing capacity on the IBM mainframe computer has increased markedly. The computer was therefore upgraded in January 1998 from an IBM 9672 Model R73 to a Model R45. This machine has four processors, compared to the seven on the original machine. However, these new processors are much more powerful, so that the total processing capacity is greater by 50%.

NT and Nimbus

The general desktop working environment within The Met. Office uses either UNIX workstations, X-terminals or PCs running Windows 3.1.
A detailed study recommended that long-term PC costs could be minimised by not introducing Windows 95 and moving straight to Windows NT. Another study investigated whether outstations should move from their mixed VMS and Windows 3.1 environment to UNIX or NT for the next generation of outstation display and product generation systems (Nimbus). NT was found to be the most appropriate platform for Nimbus. Using the same platform for both systems will simplify their support.

Two projects have now been established to implement these proposals. The bulk of the desktop NT systems will be installed early in 1999, by this time the new Nimbus system will have been demonstrated, with roll-out during 1998–2000 (see *Nimbus* in the *Services and Business* section).

National Meteorological Centre

Changes in guidance

Guidance for forecasting centres around the UK is produced by the Chief Forecaster at the National Meteorological Centre (NMC) in Bracknell. This was reorganised following the setting up of the Commercial, National and Aviation Central Production Units (CPUs) as part of the Forecast Rationalisation project.

Production of aviation forecast maps for defence customers (formerly done at HQ Strike Command, RAF High Wycombe) transferred to the Aviation CPU and all the prognostic charts for T+12 and T+36 moved to the Guidance Centre within the NMC. These charts are now constructed on-screen where raw numerical weather prediction fields can be 'corrected' at the discretion of the Chief Forecaster.

Text-based guidance products covering the first 36 hours of the forecast were also restructured. These products, formerly the Synoptic Reviews (SRs), Parts One, Two and Three and the Supplementary SR were replaced by more-timely products which moved away from the detailed description of UK weather of Part One, towards a more model-oriented approach. They also concentrate on model assessment and discussion of the dynamical and physical drivers of the evolution. There will be greater emphasis on levels of confidence and uncertainty, especially in relation to hazardous weather. The main Guidance Centre text products originated by the Chief Forecaster are: model assessment and emphasis; hazards and uncertainties; synoptic evolution; preliminary medium-range assessment.

New five-cities forecast

From 1 April 1997, the NMC started production of forecasts for five cities in the UK for publication on The Met. Office's World Wide Web site as part of the Public Met. Service. The cities are London, Manchester, Glasgow, Cardiff and Belfast, and the forecasts cover a period of three days. Maximum and minimum temperature, wind speed and direction, weather and precipitation are provided.

Skill scores have been calculated since the service started for temperature, wind and precipitation forecasts by comparing them against persistence forecasts. Since July the temperature forecasts have also been compared with those published in the *Washington Post*.

The scores are analysed within the NMC each month and their results are fed back to the forecasters together with guidance on how to improve the skill of the forecasts. A Site-Specific Forecast Index has been created from the skill scores with the intention that it will be used as a key performance target once its behaviour is understood.

Forecasting Systems

Radarnet

The Radarnet system receives data from the UK and European weather radar networks. The volume of data received and processed by Radarnet is set to increase in order to meet user requirements for improved accuracy of surface precipitation estimates and also higher spatial and temporal resolution. The mesoscale model, with its new enlarged domain, should also benefit from the assimilation of additional radar data from France and the Low Countries.

To be able to process the extra data, the current Radarnet system which uses low-power VAX workstations is being replaced by a pair of Hewlett-Packard file servers.

The NWP system

The implementation of the high-resolution global model in the operational suite (see *Cray T3E supercomputer*) was just the first step in revolutionising the numerical weather prediction (NWP) schedule to better satisfy customers' requirements. A high-resolution version of the mesoscale model, extending over a larger domain, will soon be introduced. This will run in parallel with an early run of the global model, receiving its boundary conditions as the forecast proceeds. It is also planned to run medium-range forecasts from start times of 0600 and 1800 UTC, instead of 0000 and 1200 UTC.

Horace

The Horace workstation system is now in full operational use at the NMC, HQ Strike Command and the Fleet Weather and Oceanographic Centre at Northwood. New facilities were introduced during the year to visualise flexibly, overlay and, where appropriate, animate every type of meteorological data including observations, NWP fields and satellite and radar imagery.

Much new development has focused on the specific requirements of commercial contracts with the Royal Navy and Thailand. Innovative software to monitor the existence or content of specific data on the system and to trigger automatic actions or alerts is nearing completion.

Forecast rationalisation

During November 1997 the NMC took over the aviation guidance role of HQ Strike Command. This change in responsibilities was the culmination of the Forecast Rationalisation project, and could not have taken place without the rapid development of a number of production applications on the Horace workstation system. These allow a set of key graphical forecast products to be produced on screen, replacing labour-intensive manual methods and resulting in better quality products. The systems necessary to achieve this include:

a) the On-Screen Field Modification application, allowing raw NWP fields to be modified in a dynamically consistent way prior to inclusion in graphical products;
b) a graphical production editor, allowing the drawing of weather symbols on contoured fields, and the merging of text and labels with pictures;
c) an extension to the high-level civil aviation significant weather chart system, generating low-level and military charts.

Forecasting Products

Forecasting Products R&D branch is working on several major projects which contribute to the automation of forecasting in The Met. Office, and also a large number of commercially funded projects involving the development of innovative applications of meteorological research to specific customer needs.

Within these two areas, expertise has been established in a variety of disciplines, bringing together meteorology and customer operations, notably in the areas of defence, civil aviation and flood warning.

Nimrod

The Nimrod project was completed at the end of 1997 after nearly six years' development. It now provides fine-resolution analyses and six-hour forecasts of precipitation, cloud, visibility, and related variables to forecasters and to external customers directly.

New hardware was installed to improve the timeliness of the main products, especially the half-hourly precipitation forecasts which are now available within the target 15 minutes on over 95% of occasions. Minor changes to the precipitation forecast scheme improved the retention of small-scale detail, resulting in better scores at T+1 and qualitative improvements to the pattern later in the forecast. Current relative errors in hourly forecast accumulations are shown in Fig. 15 as a function of lead time.

Improvement of visibility analysis was brought about through synergetic use of satellite imagery and surface instrument observations. The satellite image is first analysed into two categories: fog/low cloud, and clear/other cloud. Nearby matching observations are then used to define the visibility distribution within each category. Finally, using a weight based on distance to the nearest observation, the result is combined with a forecast first-guess, see Fig. 16. The detail over land is considerably better than that achievable using only surface observations, but there are still some weaknesses over the sea when no nearby observational data are available.

Forecasting for specific sites

The Site-Specific Forecast Model (SSFM) is a one-dimensional configuration of the UM which has been enhanced to account for many of the features of the terrain surrounding a specific point. It is intended to improve all aspects of local forecasts that are affected by local topography and land use.
The main focus of work has been on the upstream

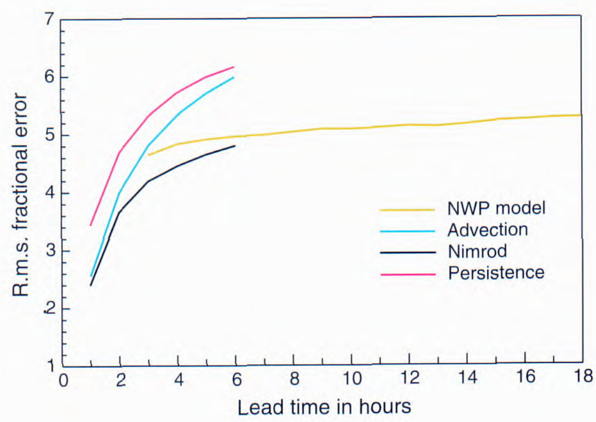


Figure 15. Performance of the precipitation component of Nimrod measured using a r.m.s. fractional error computed for 15 km resolution hourly accumulations over the period March 1997 to February 1998. The persistence forecast uses the accumulation in the past hour as its baseline. The mesoscale model is not available before T+3.

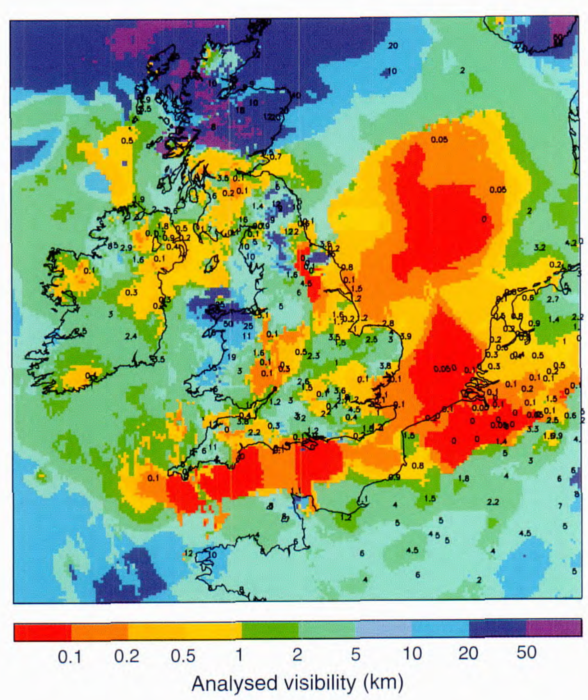


Figure 16. A Nimrod visibility analysis using the scheme introduced operationally in December 1997. Values are plotted at the surface observation locations. This case, for 11 March 1997, shows the benefit of using satellite imagery to define the areas for which the observations are representative.

Source Area Model (SAM), based on the use of a blending height in aggregating surface fluxes from different surfaces, see Fig. 17. The surface vegetation is represented by the coloured patchwork taken from 25 m resolution data from the Institute of Terrestrial Ecology. The degree to which a patch of vegetation affects the target site is given by an upwind weighting function, represented by the ellipse in the figure, whose scale depends on wind speed, stability and target height. (This is based on the 'tile' surface exchanges scheme, currently under trial in the UM, in which surface exchanges are computed for several surface vegetation types and then aggregated.) Figures 18a and 18b show the r.m.s. difference between observed screen temperature at Glasgow Airport and that forecast for each surface type and for the combination diagnosed by the SAM over the period November 1997 to January 1998.

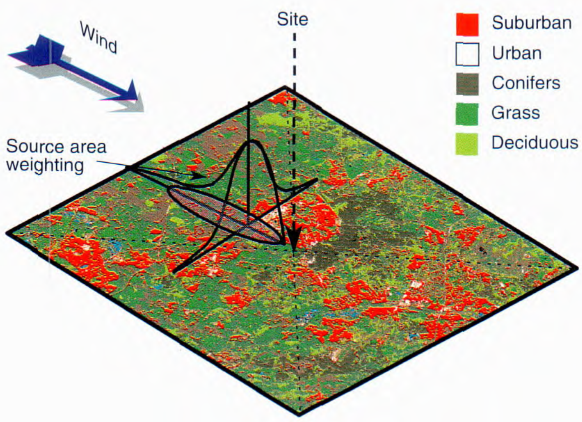


Figure 17. Representation of local surface characteristics using the SAM. The map shows surface types in a 20 km square at 25 m resolution. The ellipse represents the upwind areas influencing the target point. The source area weighting curve is derived using the concept of a blending height. Forecasts are carried out for each surface type and then blended using the weights diagnosed by the SAM.

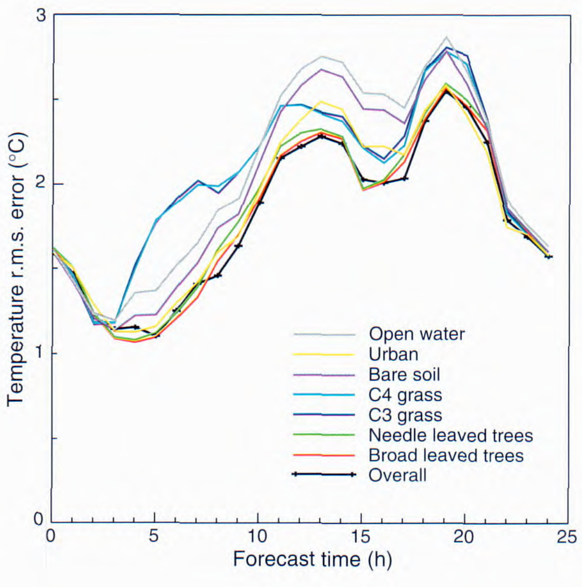


Figure 18a. Performance of the SSFM at Glasgow Airport, November 1997 to January 1998 as a function of forecast length from noon. Screen temperature r.m.s. errors are plotted for each land type, and also for the combination using the SAM. The latter is as good as the best of the types at almost all times, but note that the best forecast is over different surface types at different times.

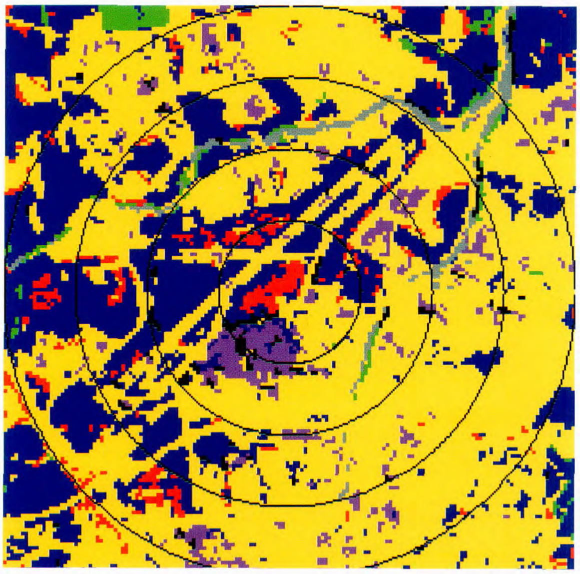


Figure 18b. Distribution of land types in the 4 km square around Glasgow airport. The colours match those used in the graphs in Fig. 18a.

Other developments have included use of: a blocking and flow perturbation model to adjust air characteristics advected over a site for orography differences from the mean of the surrounding country; a parametrization of the effects of drainage flows; and a modified surface exchange scheme to allow for the urban 'canopy' representing mainly the radiative influence of tall buildings.

An example of the model's capability in fog prediction is shown in Fig. 19 from a case in October 1996. In reality a shallow layer of fog less than 10 m deep developed in the Bracknell area, dissipating at 0830. The high resolution of the SSFM enabled it to represent the growth and decay of the fog realistically, clearing it about an hour earlier than the large-scale model.

Work started on implementing the model operationally, aiming first to provide improved input to temperature forecasts, including road surface temperatures, and to Terminal Aerodrome Forecasts (TAFs). A trial carried out from October 1997 to January 1998 suggests that resulting temperatures and TAFs compare well with manual forecasts. A new workstation will host a database containing the information required to drive the model, its results and also results obtained using Kalman filter statistical diagnosis. The model itself will run on the supercomputer, and is expected to generate forecasts for up to a thousand sites worldwide.

Convection diagnosis

UM forecasts contain a lot of information on atmospheric structure that is relevant to the forecasting of thunderstorms. Currently such forecasts are only available from the UM as a by-product of the deep convection parametrization, which was designed mainly to maintain model stability and to represent the heat, moisture and momentum fluxes generated by tropical convection. A new convection diagnosis procedure is being developed to use the more-detailed information, together with fine-scale surface forcing, to generate probabilistic forecasts of the occurrence, size and intensity of thunderstorms.

A method has been devised for estimating the closeness of atmospheric temperature and humidity profiles to convective instability. These measures were then related to probabilistic representations of the range of potential forcing due to surface heating,

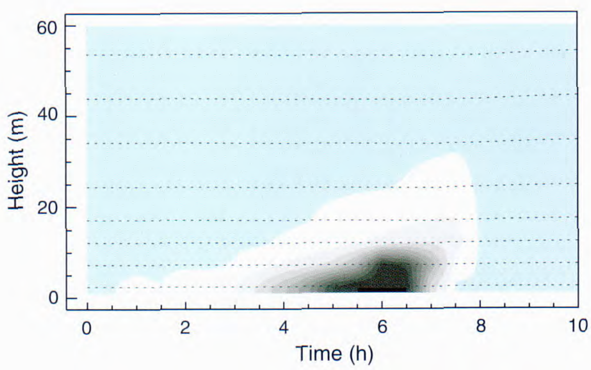


Figure 19. Fog density as a function of height and time at Bracknell for a SSFM forecast starting at midnight, 17 October 1996, when shallow fog of about 10 m deep formed. The dashed lines indicate the model's vertical resolution.

moistening or lifting in order to generate a probability of initiation of convection. Figure 20c shows such a probability map for the comparison with the verifying radar rain rates (Fig. 20b). The UM convective precipitation output was significantly underdone (Fig. 20a), corresponding to a probability threshold of about 80% when a 60% threshold would have provided the optimum forecast.

Information from empirical and climatological studies, mainly in the USA and France, has been used to extend the UM parametrization of mean rain rate (Fig. 20d) to define other characteristics such as shower duration (Fig. 20e) or lightning risk. In each case, the values shown have the probability of occurrence shown in Fig. 20c. A trial of the usefulness of these products is planned for Summer 1998.

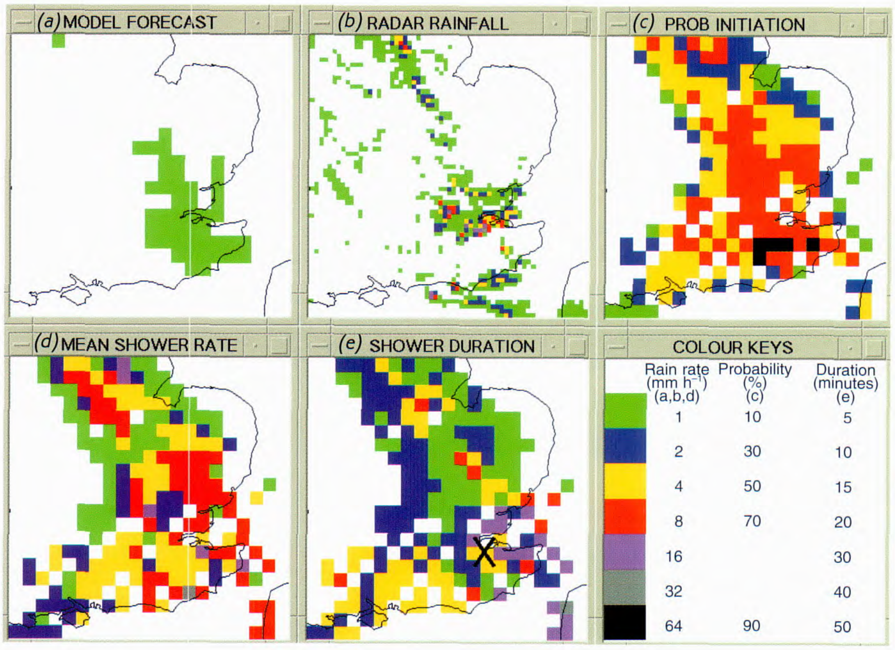
As well as perturbing the surface temperature and humidity, results have been computed using the Nimrod forecasts, with correspondingly reduced uncertainty, to predict areas most likely to develop thunderstorms in the next three hours. On several occasions these have been very successful and it is hoped to pursue this further within the GANDOLF project (see *Thunderstorm nowcasting*).

Upper-air wind forecasts for civil aviation

Aviation wind prediction work included: verification using route-integrated equivalent headwinds (RIEHW); retuning the bias correction for jet-level winds; and testing of an alternative post-processing technique to the bias correction.

The RIEHW error has been established as a quality measure which represents the important characteristics of wind forecasts as they affect the fuel-loading decisions of commercial airlines. It has been demonstrated that, for flights at fixed air speed, it is proportional to the relative flight time error.

Figure 20. Enhanced diagnosis of convection from a 12-hour forecast of the mesoscale model for 23 June 1997. Apart from the radar actual, all images have 15 km resolution. (a) Mean rain rates currently output. (b) Verifying radar rain rates (5 km resolution). (c) Probability of shower initiation. (d) Given shower initiation, the mean shower rate. (e) Given shower initiation, its mean duration at a point. The cross indicates the location of an observed thunderstorm.



A routine computation technique has been used to validate operational changes to the UM during the year. Figure 21 shows results from several North Atlantic flights in the early part of Winter 1997/98 which shows flight times generally within 1% of those predicted.

One disadvantage of this technique is that it can only be applied reliably during the recent past, when there have been enough automated aircraft reports to allow accurate computation of the actual RIEHWs. An alternative is to use a high-resolution analysis as truth and to use pre-defined tracks. Figure 22 shows errors computed for flights at 200 hPa across the central portion of the North Atlantic following either the great circle or the 'optimum' route. The results are presented as 12-month running means of monthly results. They show a steady reduction in flight time error, and also that the relative error in the optimum

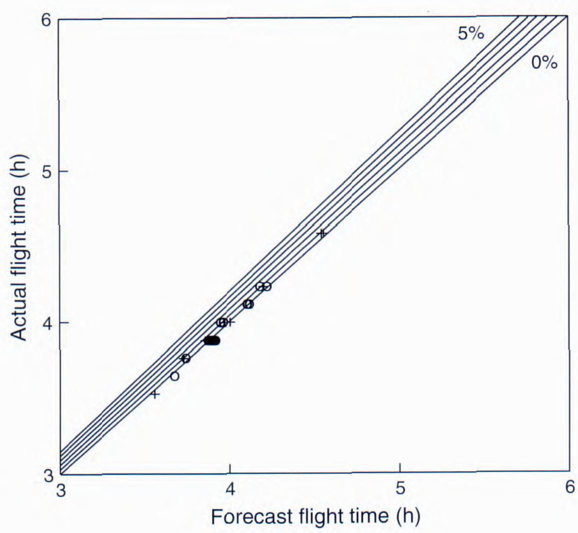


Figure 21. Comparison of actual and forecast flight times for ASDAR-equipped North Atlantic flights between 10° and 60° W during Winter 1997/98. Crosses indicate westbound flights and circles eastbound. The diagonal lines indicate percentage errors in forecast flight times. Contingency fuel is carried to allow for such an excess, often at the 5% level.

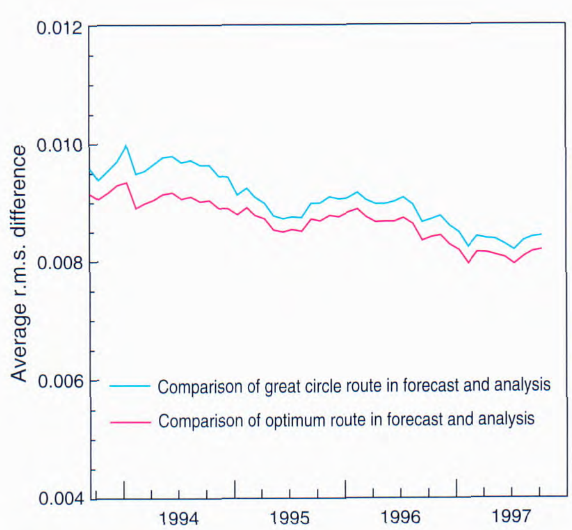


Figure 22. Twelve-month running means of RIEHW r.m.s. error across the North Atlantic, estimated along a great circle route and a forecast 'optimum' route at 200 hPa, comparing the forecast with a high-resolution analysis.

route is lower than that in the great circle (see *Optimum routeing*).

The RIEHW r.m.s. error was used as the main criterion when reassessing the bias correction which is applied operationally to aviation winds. An alternative approach using a spectral enhancement was investigated and found to be most effective when only the larger scales were enhanced. Overall there was a small benefit, but this was not significant enough to justify operational introduction. A further study showed that the existing 4% enhancement remained optimum when the high-resolution version of the global UM was introduced in January 1998. It also identified a bias in meridional wind over tropical Africa in winter, for which a correction was applied pending further investigation within the UM.

Clear air turbulence (CAT)

Investigations of CAT focused on two separate generation mechanisms. In the classical shear generated turbulence, effort was concentrated on developing an archive of UM diagnostic variables associated with automated aircraft reports of turbulence. Although subject to measurement errors, mainly during aircraft manoeuvres, these have several advantages including a physically derived intensity scale, and null reports. As well as the current data, a historical archive has been recovered for the FASTEX experimental period in early 1997. Work has now started on screening CAT predictors computed from the UM variables. Figure 23 shows four such predictors for the occasion in December 1997 on which severe

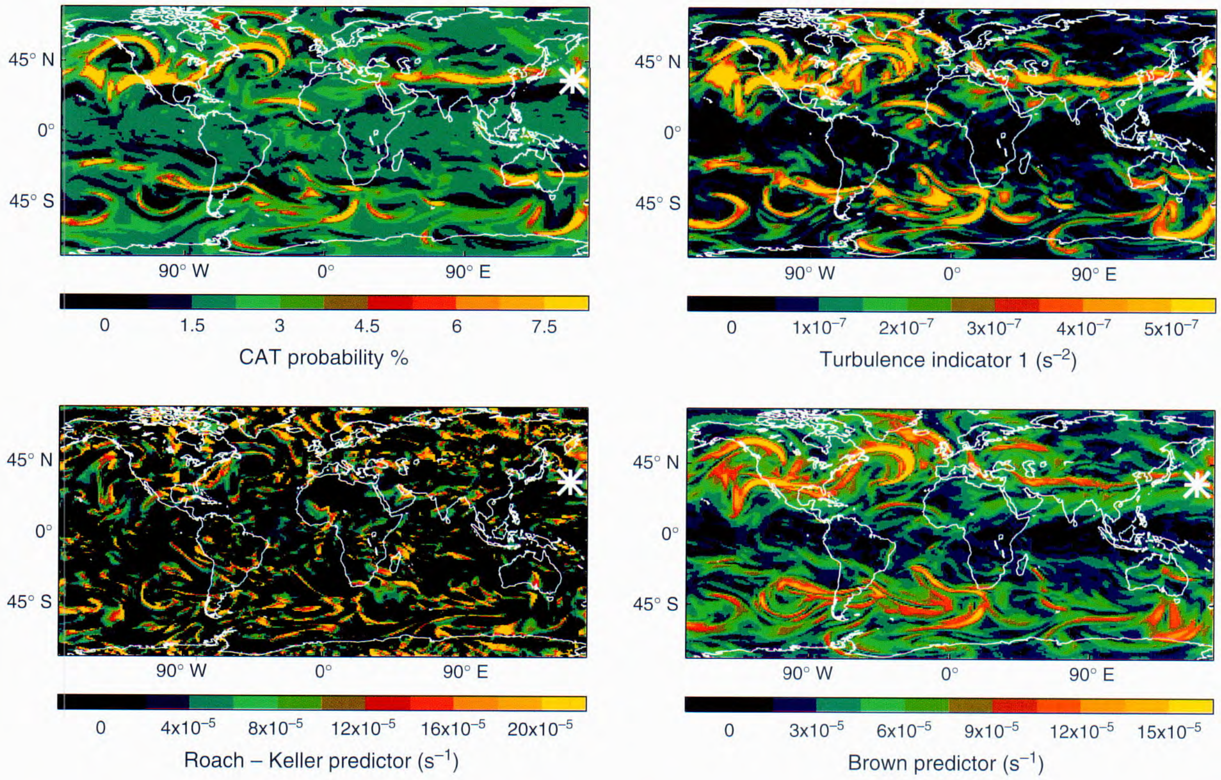


Figure 23. Four predictors of shear-induced clear air turbulence derived from UM output, and compared at 250 hPa for 1200 UTC, 28 December 1997. The asterisk marks the location of a fatal turbulence encounter at about this time.

turbulence affected an airliner east of Japan, resulting in the death of a passenger.

The second approach is aimed at mountain-induced turbulence. A relationship is being sought between the UM gravity wave stress and reports of CAT in mountainous regions. Results suggest that the relationship may be strong enough to provide useful predictions. Figure 24 shows these results, the darker colouring indicating higher levels of stress and white asterisks showing locations of reported turbulence.

Optimum routeing

In addition to using upper-air wind forecasts for determining fuel loading (see *Upper-air wind forecasts for civil aviation*) airlines also calculate the minimum time track which exploits tailwinds and avoids headwinds. This is normally done by specifying a large number of possible routes and calculating the time taken to fly each. In contrast, The Met. Office technique obtains the solution by direct integration of the relevant differential

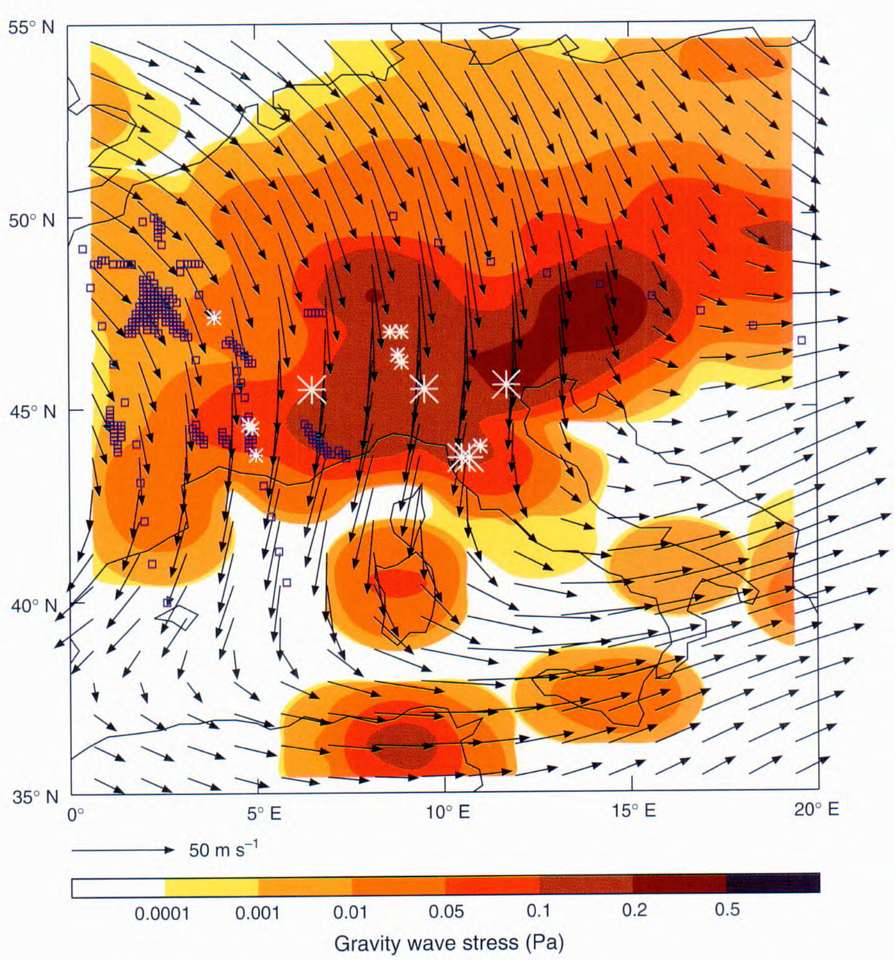


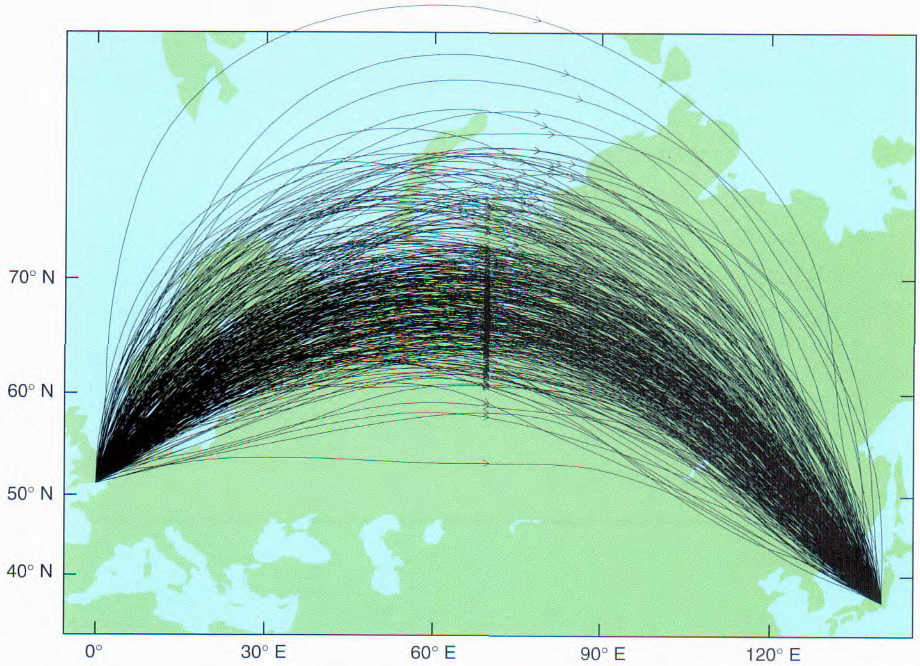
Figure 24. UM gravity wave stress and wind at 300 hPa on 27 February 1997 in comparison with aircraft reports of clear air turbulence (white asterisks) and of no turbulence (blue boxes). The size of the asterisk indicates whether the report was of light or moderate turbulence.

equations. This approach is particularly beneficial where a set of pre-defined routes does not currently exist, such as over Russia. Figure 25 shows the minimum time tracks from London to Tokyo calculated every day for a year.

Wake vortices

Avoidance of wing-tip vortices cast off by large jet aircraft provides a major restriction to runway capacity at major airports. A crosswind can shift the vortices out of the path of subsequent aircraft. However, there is a lack of information about the reliability with which the crosswind can be predicted, and about conditions under which vortex encounters occur. Work has started on analysing data obtained from a fast-response anemometer array at Memphis Airport, USA, to investigate the use of real-time techniques for predicting the crosswind a few minutes ahead. Figure 26 shows a sequence of two-minute predictions using a simple ARIMA (auto-regressive integrated moving average) model which

Figure 25. Least-time routes from London to Tokyo, computed for every day of one year using the optimum route generation facility.



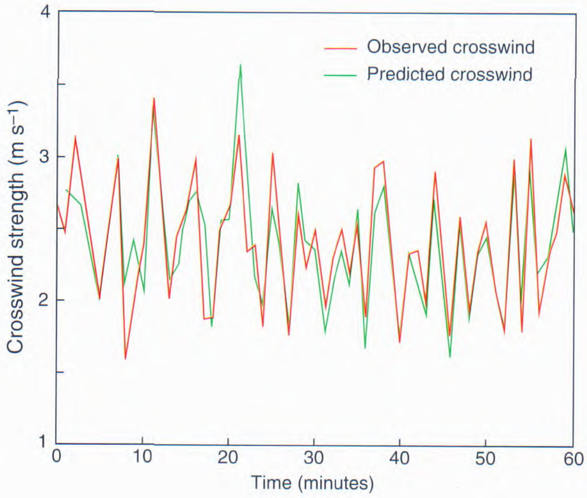


Figure 26. Hour-long time-series of crosswind at Memphis Airport, USA. The red line joins one-minute average observations. The green line joins two two-minute forecasts obtained using an ARIMA prediction scheme.

is more skilful at predicting than using either persistence or the mean. Work has also been undertaken on vortex encounters in a European collaborative project to develop a database of associated meteorological conditions.

Air traffic management

Contributions have been made to several European projects on future air traffic management systems. A common feature of these is their dependence on the accuracy with which aircraft trajectories can be predicted. Such predictions are required for typically two to three hours ahead within Europe and depend critically on the accuracy of the meteorological forecast, especially wind. The Met. Office provided meteorological scenarios for testing, and assessed error magnitudes. This used routine data from the UM, and also the WAFTAGE upper-air nowcasting model, a four-dimensional optimum interpolation scheme which extrapolates the information contained in aircraft reports forward in time.

Aircraft icing

Classical aircraft icing from supercooled cloud droplets has been studied as part of a European collaborative project (EURICE) to assemble a database of observations now containing 35,000 nautical miles of microphysical data. EURICE aims to review aircraft design standards established without the benefits of recent observational capabilities. Figure 27 shows part of the analysis, which highlights the current design standard missing the large liquid water contents at high altitude.

Further work was also undertaken on the problem of icing from supercooled rain and drizzle. A study to relate its occurrence to UM profiles in order to obtain a global climatology achieved limited success, due mainly to the model's limited vertical resolution. Work on predicting freezing rain and drizzle at the surface (see also *Nimrod*), indicates that the resolution of the mesoscale model provides significantly more realism.

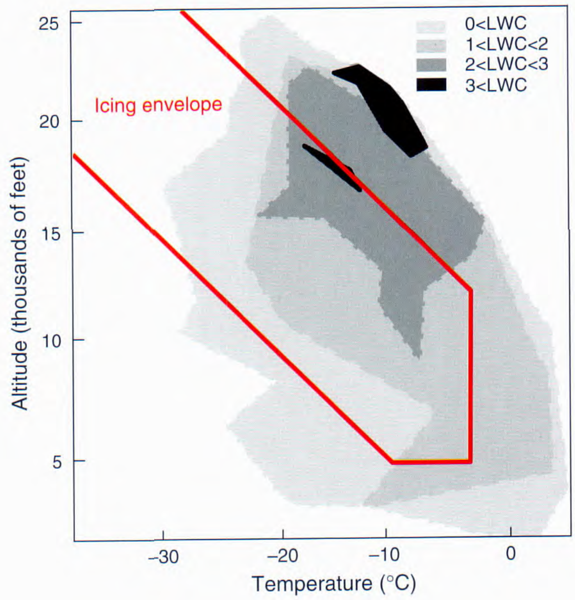


Figure 27. Analysis of cloud liquid water content as a function of temperature (vertical axis) and height for all observations up to 50 µm drop size and 5.21 nautical miles extent. The superimposed red line shows the current design icing envelope for icing in convective clouds.

Forecast advice from NMC was used to assist a flight campaign seeking observations of supercooled drizzle. Successful encounters were achieved on more than half of the flights.

Thunderstorm nowcasting

The final report was completed on the GANDOLF project. This was a collaboration with the Environment Agency (Thames Region) to develop and test a thunderstorm life-cycle model to improve quantitative precipitation forecasts up to three hours ahead. During the summer of 1997, another trial of the system confirmed earlier results, that in critical flash-flood situations the model offered a substantial improvement over existing techniques.

A further test of the system was afforded by the Devon floods on 7 August 1997. Figure 28 shows one-hour forecasts from 1830 UTC, compared with the radar actual for 1930 UTC. Whereas the Nimrod forecast (Fig. 28b) has successfully predicted the overall movement and intensity of the rain area, the GANDOLF forecast (Fig. 28a) made a good attempt at predicting the detailed precipitation structure, including individual rainfall maxima and the area of lighter rain between. Although GANDOLF is capable of initiating new cells in the neighbourhood of existing ones, it is unable to develop new areas of convection. It is planned to combine it with the convection diagnosis technique (see *Convection diagnosis*), and then to integrate both into Nimrod, to provide a higher quality of thunderstorm forecast than currently achieved.

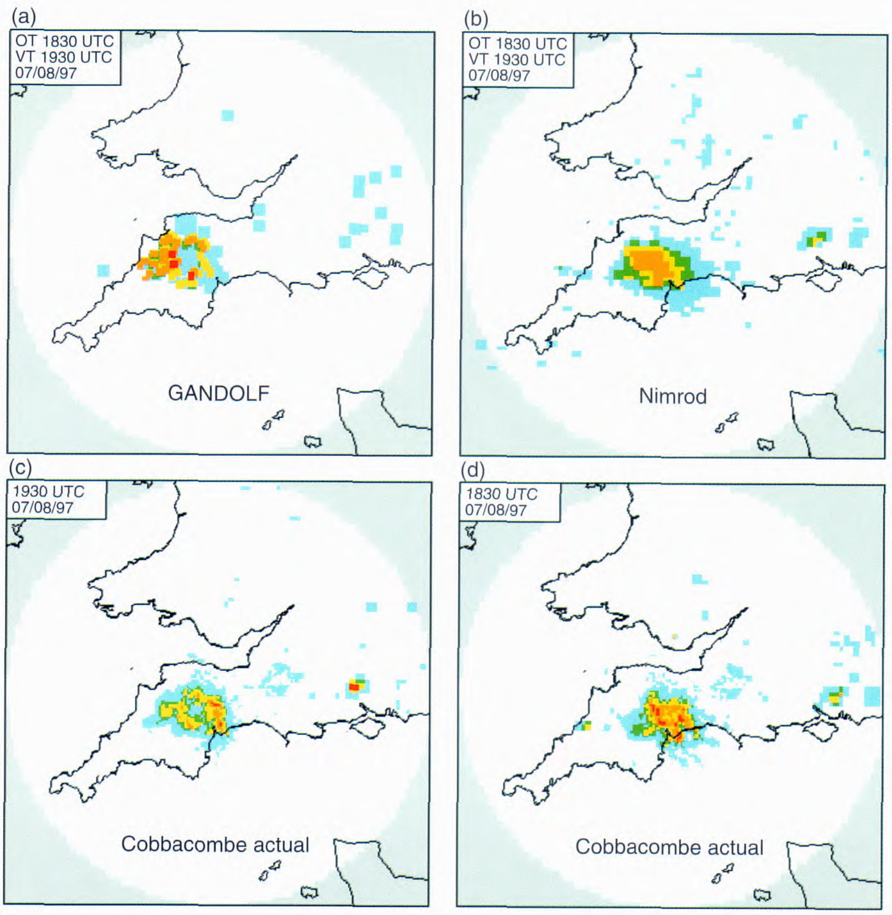


Figure 28. Rainfall nowcast for 1930 UTC, 7 August 1997, when flash floods affected parts of south Devon. (a) One-hour prediction using the GANDOLF model. (b) One-hour prediction using the current Nimrod algorithms. (c) Radar actual for the forecast time. (d) Radar actual one hour earlier.

Lightning strikes on helicopters

Helicopters are susceptible to damage from lightning strikes, and several such strikes have been recorded in the northern North Sea in winter. In some cases there has been no obvious thunderstorm activity in the area at the time. An investigation started on atmospheric conditions associated with these strikes. In particular, it is desirable to know whether the processes are the same as those associated with natural lightning strikes, or whether processes related to the presence of the helicopter are involved. Figure 29 shows the UM convective precipitation rate distribution on the occasion of one such strike (marked by a black diamond). On this occasion, the atmospheric structure was clearly conducive to natural lightning and several ground flashes were recorded by the operational lightning detection system.

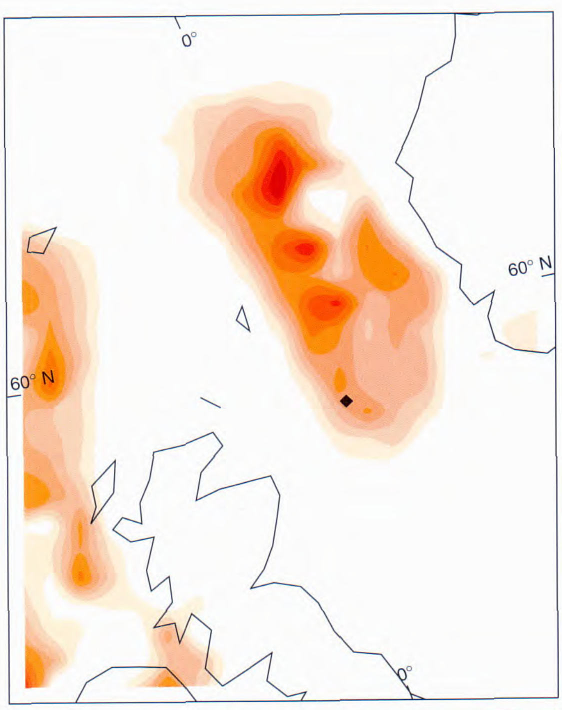


Figure 29. UM convective rainfall rate for 1200 UTC, 19 January 1995. The black diamond marks the location of a helicopter lightning strike.

Battlefield meteorological support

A relocatable nowcasting system is under development to be used on the battlefield. Local observations will be used to make rapid updates to remotely provided mesoscale model forecasts. The system, called CMETS (Computerised Meteorological System), comprises three main parts: a linear flow model to adjust the boundary layer wind and pressure for local orography; the WAFTAGE model, originally developed for civil air traffic management (see *Air traffic management*); and Nimrod. Nimrod was modified to work without weather radar input, and to accept SSMI satellite-derived precipitation estimates as an alternative data source. Figure 30 shows an example of low-level winds produced by the linear flow model in the vicinity of Glasgow Airport. The nowcasting system provides the basis for a suite of operational advisory products, currently covering ballistics and radar.

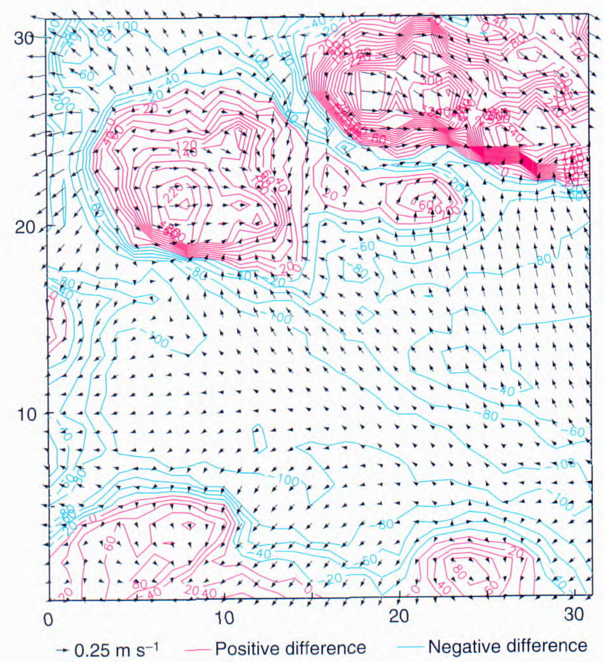


Figure 30. Diagnosed 10 m wind perturbations in a 30 x 30 km area around Glasgow Airport, deduced using the linear flow model component of CMETS. The mean wind was north-westerly and the stability was neutral. The arrows show the direction and fractional magnitude of the increments and the contours show the perturbation land height with a 20 m interval.

Services and Business

Services and Business (S&B) Division comprises those groups with responsibility for managing and delivering services to the following areas: Ministry of Defence; Civil Aviation Authority; Public Met. Service; and commercial customers.

Customer requirements are diverse, but science and technology usually have a role to play somewhere in the production and distribution of these services.

Technology

There have been a number of significant developments in the technology that supports the production and distribution of products and services. These developments are concerned with increasing the efficiency of the production processes and improving the quality of the end products. Many of these changes are related to The Met. Office's approach to solving year 2000 problems. An underlying principle of this work is the move to Windows NT as the basic PC operating system.

Commercial MIST

MIST (Meteorological Information Self-briefing Terminal) is being widely used in the control room environment where it gives managers ready access to weather information, even allowing important decisions to be made in remote locations using a GSM phone and laptop computer. The number of MIST customers has increased through the year to over 100.

Development of MIST continues under the joint venture with Matra Marconi Space (MMS). The PC-based display system is now a full 32-bit application running under either Windows 95 or NT. This allows customers in a networked NT environment to distribute weather information to a greater number of staff. The host system at Bracknell, holding the database and handling dial-in access via either the public switched telephone network or ISDN, continues to perform well.

Nimbus

Nimbus is a major project in which it is planned to replace all the hardware in the Weather Centres and Defence sites by a single system. This system will comprise a Local Area Network (LAN) hosting PCs running NT. These LANs will connect to the Weather Information Network (WIN) which in turn will provide data transfer capabilities between the production units and Bracknell. It will also provide many of the basic connections to systems for distributing products and services to customers.

Figure 31. The MIST control room environment.

The various meteorological display and production applications currently in use are being 'ported' to the new NT environment.

The user requirement for meteorological display software has already been met. This application has built on software developed in collaboration with MMS for the commercial MIST project. It has also incorporated many of the ideas and concepts used in Horace (see *Horace* in the *Operational Services* section). Observational data are stored locally on the LAN server in a commercial relational database management system (RDBMS). This also allows access by the production software, easing many of the problems with the current systems. Production applications are based on standard PC packages. The first full Nimbus installations are planned for Autumn 1998 (a version of the display software is to be deployed to the Falkland Islands in early 1998). The same software will also form the basis of the new NATO Automated Meteorological Information System (NAMIS).

MOMIDS

The Met. Office Military Information Distribution System (MOMIDS) installation programme is continuing. MOMIDS is a PC-based display system designed to meet the need for more-decentralised briefing, particularly of aircrew. PCs installed in the squadrons give users access to 'standard' meteorological data. Ultimately the local station forecaster will also input specific briefing information, either text or graphics, into the system using Nimbus.

MIDAS

Nearly all The Met. Office's point climate data has been moved to an RDBMS on the mainframe computer system (see *MIDAS* in the *Operational Services* section). Migration of all the batch applications away from the current bespoke data archives to MIDAS is almost complete and has helped solve a year 2000 problem, removing vast amounts of 'legacy' code. Moving to an RDBMS also allows new working practices to develop. Users on any Met. Office system including Nimbus now have interactive access to the full climate archive. There are still some performance issues to be addressed but this way of working is expected to grow. It is a good example of how data access is 'freed up' and non-specialists are given more processing and analysis facilities through the use of standard PC packages.

Science

Other sections of this Review describe current research, which will ultimately find an outlet in the service provision area. Here are some of the more unusual services provided during the year and the science behind them.

Increased accuracy

Many current production systems use input information derived directly from the numerical weather prediction (NWP) model output. If forecasters regard this 'first-guess' forecast as inaccurate they can modify it, otherwise they accept it and leave the production system to generate and distribute the customer outputs.

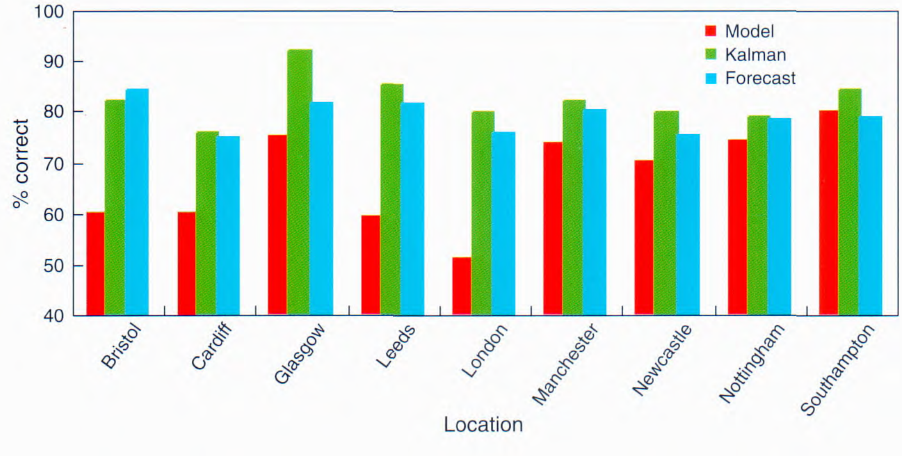
Much work is being done throughout The Met. Office to increase the accuracy of the NWP process and hence the first-guess forecast. However, it is possible to provide simple post-processing to the NWP output so as to enhance accuracy. Figure 32 shows the results of a recent trial where simple Kalman filtering is applied to first-guess temperature forecasts. It shows the percentage of occasions when the forecast temperature is within 2 °C of the observed, the criterion set by the customer, and demonstrates a major improvement in accuracy achieved at minimal cost.

Marine safety

Following two significant marine disasters in Europe – *Herald of Free Enterprise* (Zeebrugge 1987) and *Estonia* (Baltic 1994) – marine safety bodies wanted to develop a clearer classification system for passenger vessels. It has been agreed that such a safety classification scheme should partly depend on the wave climate in which a vessel is expected to operate. The responsible body in the UK, the Marine Safety Agency, commissioned The Met. Office's Marine Consultancy Service to study wave climate in waters around the UK, and to provide up-to-date quantitative guidance on wave conditions which would be used in the safety classification process.

Two data sources were used: the conventional observations of wave height made by vessels under way, and 'hindcast' wave data generated at three-hourly intervals over the last decade by The Met. Office's European Waters Wave Model. The model's spatial resolution (25 km) allowed local detail to be seen in many areas, which would not have been possible from ship data alone.

Figure 32. Accuracy of temperature forecasts (percentage of errors less than 2 °C) for various locations throughout the UK for February 1998. Each set of bars shows the accuracy of the forecast taken direct from NWP, NWP plus Kalman filtering and forecast actually issued to the customer.



Agriculture

The Global Agroclimate, Land-use, Elevation and Soils database (GALES) is being used as a site-selection facility for finding areas that match a given set of environmental criteria. It was developed in collaboration with the Agricultural Development and Advisory Service. GALES holds high-resolution information on climate, soil, vegetation, altitude and land use. Data can be accessed quickly and viewed easily through a customised Geographic Information System (GIS), see Fig. 33.

Contrails

Aircraft condensation trails (contrails) form behind aircraft when the air in the aircraft's wake is sufficiently moist that, when cooled, clouds of ice crystals are formed. The ability to forecast when and where contrails are likely to occur is important, particularly for military customers.

Met. Office contrail forecasting techniques have changed little since the early 1940s. Recent research has indicated that these older techniques may not give accurate forecasts of contrail formation from modern aircraft. Such aircraft use more-efficient engines than were available fifty years ago.

A contrail observation trial investigated the accuracy of The Met. Office's forecasts when applied to modern aircraft. During the one-year trial, which started in September 1996, RAF pilots at four stations in the UK were asked to report whenever they noticed contrails forming behind their aircraft. The pilots noted the position and height of the aircraft at the time that contrails were observed. Forecasts of contrail height were then performed using both old and new forecasting techniques.

The technique currently used by Met. Office forecasters correctly predicted the formation of over 60% of all contrails reported. In addition, results showed that the techniques developed specifically for new aircraft engines did not perform any better than Met. Office forecasts.

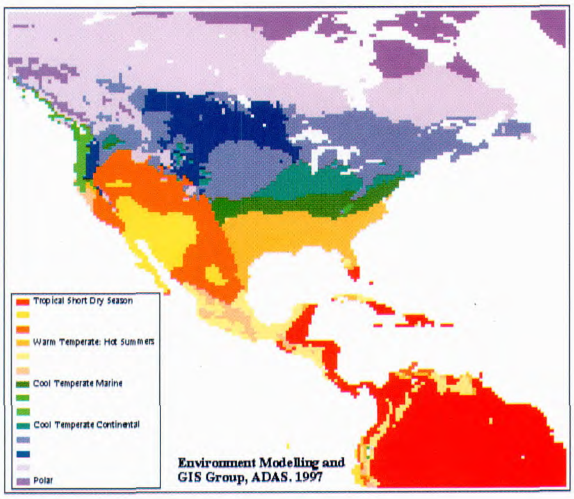


Figure 33. A GALES climate display for North and part of South America.

Prediction of radar coverage

The Electromagnetic Environment Modelling System (EEMS) is being developed by the Maritime Warfare Centre for the Royal Navy. EEMS will be used to predict radar coverage. Unlike previous models used by the Navy, EEMS is able to model radar propagation along a path where the meteorological conditions vary. The Met. Office has developed a meteorological data processor which takes output from the mesoscale model and converts it into the form used by EEMS. It is necessary to interpolate between model grid points in order to define the meteorological environment along the radar's path. To choose the best method for interpolation in spatially variable environments, such as coastal regions, an understanding of the structure of these environments is needed. Last year the Met. Research Flight C-130 aircraft was used to investigate the environment of coastal regions. Flights were made over the Swedish coast as part of a European experiment (see Fig. 34), with two further flights over the Sussex and Northumbria coasts.

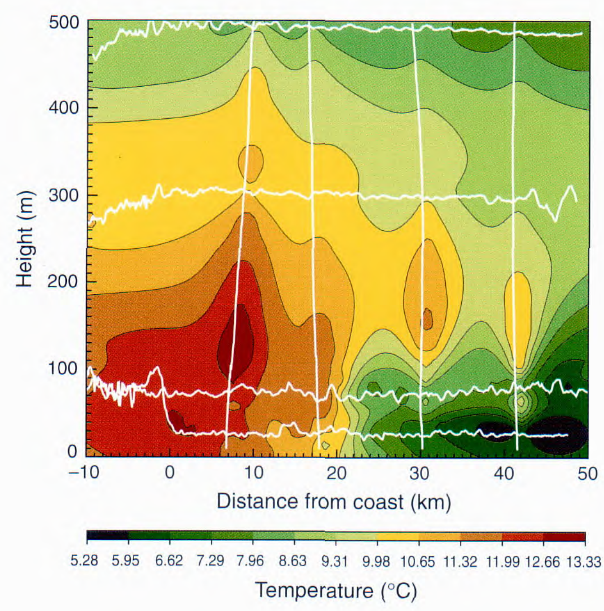
Figure 34. The temperature structure measured off the Swedish coast in May 1997. The white traces show the altitude of the C-130 aircraft on different experiment runs. The advection of warm air from the land over the relatively cold sea can be seen.

Air quality forecasting

Air quality is of growing concern throughout the UK as local authorities prepare their air quality reviews, required by the Environment Act of 1995. These authorities are responsible for meeting stringent new guidelines on pollution levels. Air quality forecasts can play a major role in identifying problematic conditions in advance. They allow the use of process management and other techniques to ensure emissions are reduced at these times.

Air quality forecasts are now being used to encourage people to take public transport when days of poor air quality are expected. The Met. Office has been working with Hampshire County Council in developing a regional forecast system which will identify areas at risk. This system will also indicate major contributors to the problem, such as traffic, industry or sources in other parts of the country.

Such information is crucial to effective emissions control. The system has been developed from The Met. Office's Nuclear Accident Model. Detailed local traffic flow and power consumption data are fed



into the model, along with estimates from other parts of the country and western Europe. Estimates of hourly emissions are integrated over a period of up to five days ahead, producing hourly maps of levels of many of the main pollutants.

The Department of the Environment, Transport and the Regions has also shown interest in the system, and it is soon to be tested against the current method for producing national air quality bulletins.

Wind storm damage

In the UK, insurance losses from wind damage can be a major part of the total insured losses. A wind storm model has been set up for the reinsurance industry to assess the likely losses for a variety of storm situations. The model consists of an ideal representation of the most severe wind storms in the UK in recent years. It allows estimates of the surface wind to be made at any point in the UK, for any storm track, by taking into account the storm intensity, the local topography and surface roughness. The winds are combined with data on the housing stock (age, type of house, etc.) in the area affected by the storm and an estimate is made of the total damage inflicted.

Some checks on the wind estimates were made against independent data which included the storms of 24 December 1997 and 4 January 1998. Reasonable agreement was found, though each storm had individual characteristics which were difficult to capture using this simple model.

Pipe fracturing

Water authorities are concerned about loss caused by pipe fractures. Pipe bursts can be related to air and soil temperatures on timescales of a few days. Bursts tend to be worst in cold spells lasting for three days or more. Damage is not caused by direct freezing of water in the pipe, but seems to be due to a combination of water temperature of the supply (from surface reservoirs) and the soil and water temperature patterns at the depth of the pipe. A trial forecast service has been set up to permit more-effective deployment of fault-tracing crews.

Numerical Weather Prediction

The Numerical Weather Prediction development programme is improving the capability of The Met. Office's computer modelling system for operational forecasting. The models are also designed for climate prediction and other environmental research, and are made available for use by UK universities.

The computer code is freely exchanged internationally, and the complete system 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 benefit to Met. Office customers.

The Unified Model (UM) is used for operational short-range forecasts, both globally and in a high-resolution configuration over the UK. It has been used in a joint experiment with the European Centre for Medium-range Weather Forecasts for medium-range ensemble forecasts. It is also used for monthly probabilistic forecasts made on behalf of specific customer groups, and for experimental seasonal forecasts.

Forecast performance

The overall performance of the global forecast model is shown in Fig. 35. This is a composite measure of performance 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 Met. Office customers. 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 variability caused by changes in atmospheric behaviour.

The model is also used to forecast weather parameters, such as cloud and precipitation, primarily for the UK. From June 1998, precipitation forecasts up to 36 hours ahead will be obtained from a mesoscale version of the model covering the UK and immediately surrounding areas with a 12 km grid. This will also give predictions of other parameters such as cloud and fog. The quality of these predictions is illustrated in Fig. 36.

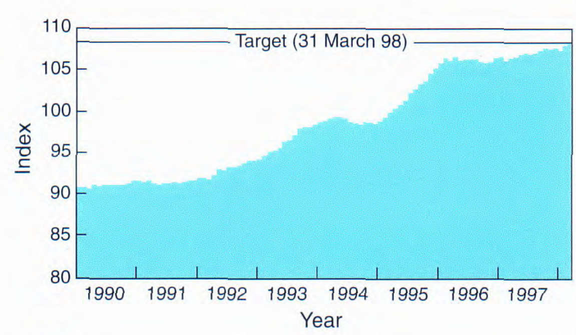


Figure 35. Global NWP skill score index from 1990 to 31 March 1998.

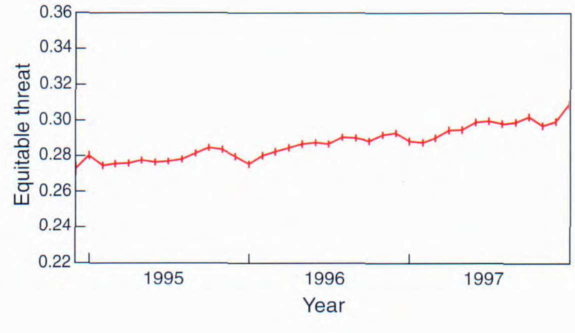
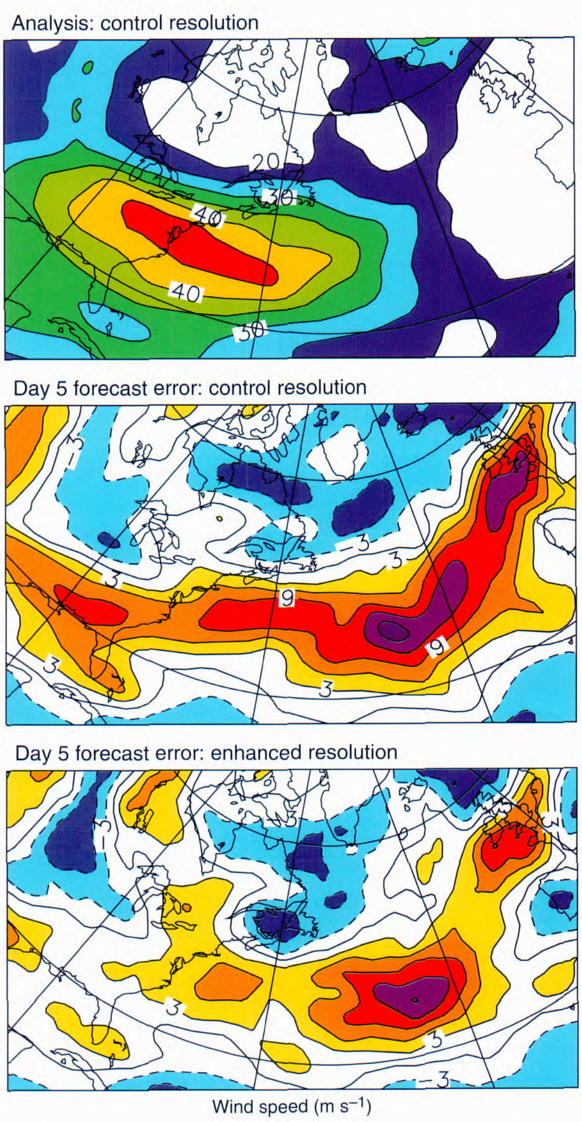


Figure 36. Time-series of monthly equitable threat scores for precipitation using the mesoscale model at various forecast ranges. The score is an average of the three separate scores using thresholds of 0.2, 1.0 and 4.0 mm h^{-1}. The verification is against representative UK observing stations.

The accuracy of precipitation forecasts is calculated using an 'equitable threat score' which measures the success at forecasting precipitation rates above a given threshold, weighted according to the frequency of such events. The diagram is a composite of the scores for three thresholds representing light, moderate and heavy precipitation. It shows a steady improving trend over the last four years, with some fluctuations caused by anomalous weather conditions. This trend is due to a combination of improvements in the larger-scale forecast driving the boundary conditions, in the use of data and in the mesoscale model itself.



Development of the forecasting system

Higher-resolution global model

In January 1998 a higher-resolution version of the UM was introduced operationally on the Cray T3E. The number of vertical levels was increased from 19 to 30 with a concentration of the new levels near the tropopause. The horizontal resolution was increased by 30%, which equates to a change in grid spacing from 90 km to 60 km in mid-latitudes.

The enhanced resolution has provided a number of benefits. Long-standing systematic errors in the global model have been reduced, such as the extratropical westerly wind bias (Fig. 37) and the excessive cooling

Figure 37. Winds at 250 hPa (isotachs) over the Atlantic region for January 1997, showing typical westerly wind bias in the global model and the reduction in the bias with enhanced resolution.

and moistening at the tropopause. The additional vertical resolution near the tropopause has improved jet-level wind forecasts and the extra horizontal resolution gives better definition of fronts and precipitation. In general the model is more energetic with deeper low pressure systems in both the extratropics and Tropics. During trials in January 1997 the enhanced resolution provided more accurate forecasts of mean sea-level pressure in the northern hemisphere on 71% of occasions at day 2.

Provision of improved regional forecasts

The extra power of the Cray T3E will also be exploited in providing better short-range detailed forecasts for the UK. The domain of the mesoscale model which provides detailed UK forecasts will be enlarged in 1998. The operational forecast suite will be rescheduled, so that products from the existing regional model are replaced by products from early runs of the enhanced global model, with a similar data cut-off of two hours. Tests showed that the higher-resolution (60 km) global model had r.m.s. errors 5–10% lower than the existing regional model, see Fig. 38.

This was mostly due to the replacement of 'out-of-date' lateral boundary forcing since the boundary values for the regional model were provided by a previous global run with a nominal data time of up to 12 hours earlier. If the lateral boundary forcing is taken from a contemporary global model run there is a similar reduction in error, see Fig. 39.

The early global runs will also provide the lateral boundary forcing for the new mesoscale model which will run in parallel with it, allowing mesoscale forecasts to be produced at the same time as Limited Area Model forecasts are currently produced. This is essential if they are to be used in operational short-range forecast guidance.

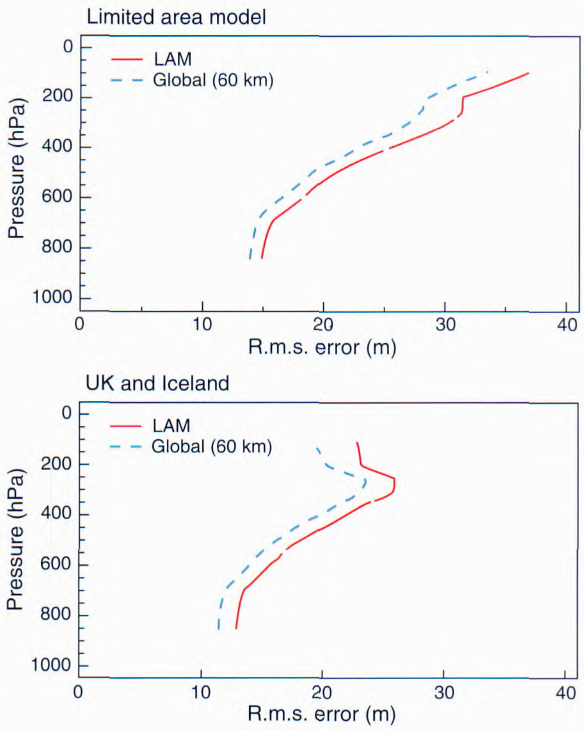


Figure 38. Vertical profiles of r.m.s errors for height at T+36 compared to radiosonde observations.

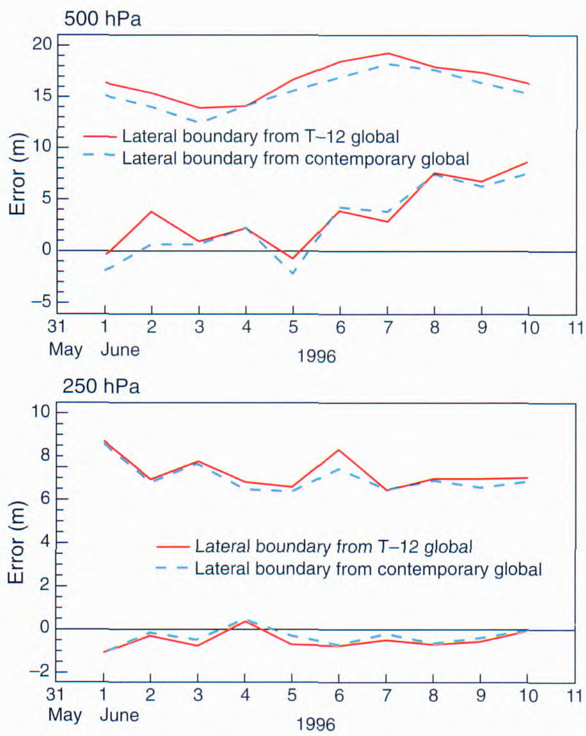


Figure 39. Time-series of r.m.s and bias errors for 500 hPa height and 250 hPa wind over 10 days.

New methods of assimilating data

Observations of the state of the atmosphere at any given time are incomplete. They are not uniformly spread in the horizontal and vertical and not all observing systems measure all the required elements of pressure, temperature, wind, humidity and cloud. Initial conditions for all model forecasts are produced from data assimilation which combines a short-period model forecast with observations. The aim is to produce the model state, consistent with the observed state of the atmosphere, which produces the most accurate forecast.

A new data assimilation scheme (3DVAR) has been developed. This uses variational methods to find the best fit to the observational data by a model field. This procedure allows for specified observational and model errors, and applies further constraints to impose balance in the resulting analysis fields. Information from the observations is spread horizontally, vertically and between different model variables through specification of the three-dimensional structure of model errors and definition of analysis variables. The 3DVAR scheme is being tested using observations processed in the same way as for the current operational analysis correction scheme. The results from a one-week trial of continuous assimilation are already comparable to those of current scheme, see Fig. 40.

The 3DVAR scheme has been converted to run in massively parallel processor mode on the Cray T3E. Work is also continuing on a limited area version,

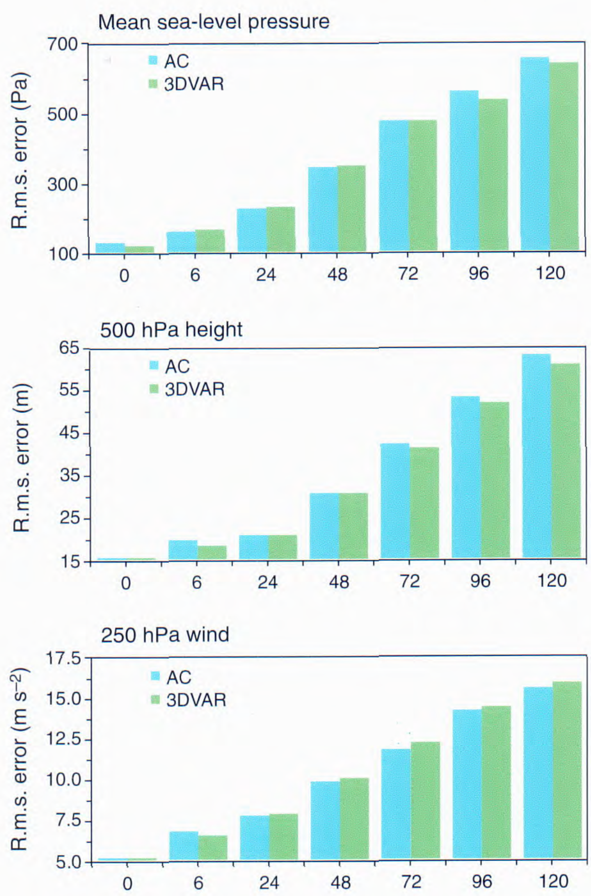


Figure 40. Comparison of r.m.s. errors, with respect to observations in the northern hemisphere extratropics, for seven global analyses and forecasts run using the new 3DVAR analysis and the operational analysis correction (AC) scheme.

improvements to the specification of model errors and their structure and the extension to 4DVAR (allowing further improvements to the analysis by exploiting information on the time evolution of observations).

The design of the new scheme makes it easier to include new observation types into the assimilation. Observations do not need to be converted to model-like variables before they can be used. This is an advantage for observations such as satellite radiances. Using all observations in one analysis means that the influence of satellite radiances on model temperatures and humidities is automatically constrained to be consistent with information from other observations types, such as radiosondes and aircraft data. Work has started to include direct use of satellite radiances in the 3DVAR scheme.

New data sources

The UM develops systematic errors through a lack of adequate observations, and these are particularly marked in the water vapour field. As a source parameter for the formation of cloud and precipitation, water vapour is an important variable in the hydrological cycle. Total column water vapour estimates are derived from brightness temperatures measured by the Special Sensor Microwave Imager (SSMI). Over oceans these have been shown to give accuracies similar to those of radiosonde measurements. With daily global coverage, these data (not currently assimilated into the model) can be used to validate the model and identify areas where it is deficient. Figure 41 shows regions where there is potential for improvements in the analysis of water vapour, which should feed through into improved forecasts. The SSMI observations have recently become available in near-real-time, which is a prerequisite for use in operational forecasts.

Although the model is generally in good agreement with observations, there are differences in the Tropics, which appear too dry, and in stratocumulus regions to the west of the southern continents, which appear too wet.

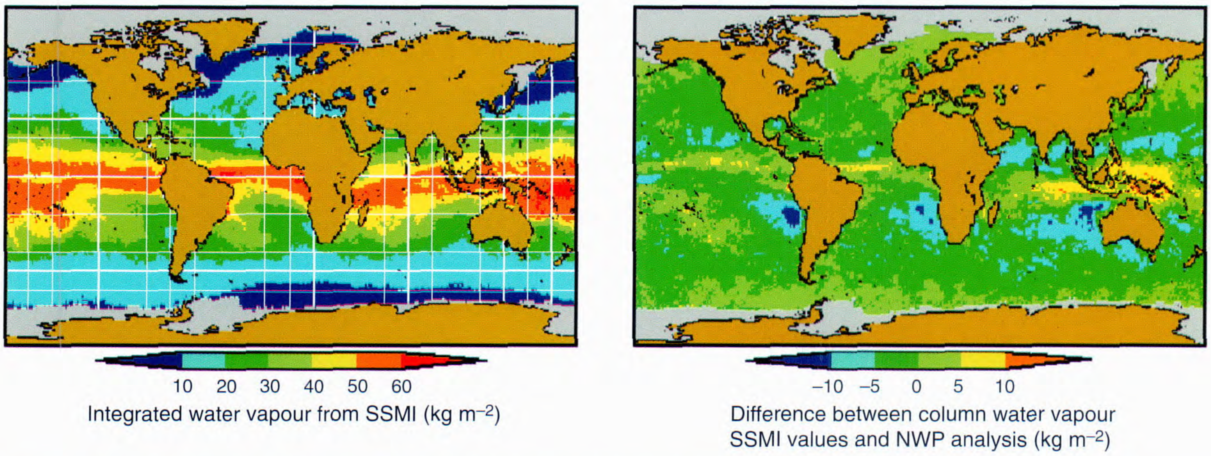


Figure 41. The total integrated water vapour field retrieved from SSMI observations through 1DVAR (left), and the difference between the observations and the UM analysis (right).

Representation of precipitation and cloud

The large-scale precipitation scheme has a significant influence on the water content of a cloud. A new scheme describes transfers between the major water quantities in the atmosphere: water vapour; liquid water droplets; raindrops; and ice crystals (for example, snow). The transfer terms are derived directly from basic cloud physics equations. This new scheme requires the specification of properties of ice and raindrops, such as fall speeds as a function of particle diameter, from observations. The scheme does not estimate the ice content as a function of temperature and total water content. Ice grows and decays in the model using the cloud physics equations. This allows a better representation of a cloud because the model retains a knowledge of its history.

Typical UK winter stratocumulus clouds consist of a well-defined layer of liquid water capped by a temperature inversion. Figure 42 shows model predictions of a stratocumulus cloud using two different schemes.

The new scheme (left) shows a well-defined liquid stratocumulus deck. Water content increases towards cloud top. A small amount of ice falls through the cloud, increasing as it falls. Ice particles grow by vapour diffusion and riming as they collide with water droplets in the liquid cloud. Although the temperatures are below freezing, the majority of the cloud remains liquid. The predicted structure agrees well with observations.

In contrast, the old precipitation scheme (right) shows a very different structure. The cloud decks are more spread in the vertical and the bases follow the 0 °C isotherm. This does not agree with the observations of this cloud. The proportions of ice and liquid are diagnosed as a function of temperature, with more ice at colder temperatures. The wrongly diagnosed ice falls, resulting in a downward flux of moisture. Hence the height of the cloud gradually reduces. Fog is produced where the surface temperature is below freezing, such as between longitudes 4° W and 1° E. This is a common model error.

In summary, the prediction of ice based on physical transfer processes models the behaviour of real clouds more accurately than using a simple temperature-based function to determine proportions of liquid and ice.

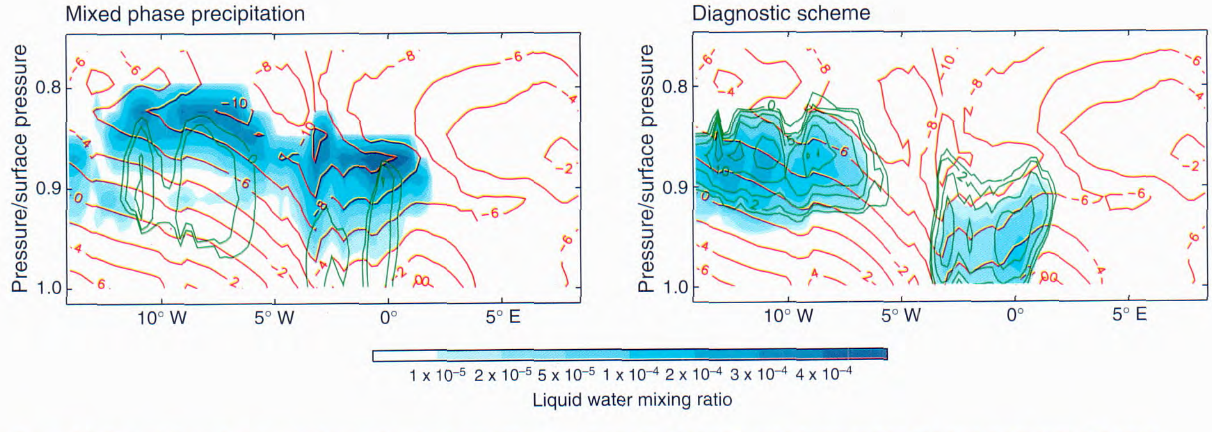


Figure 42. A simulation of winter stratocumulus cloud using the new scheme (left) and the old scheme (right). The blue areas show the liquid water mixing ratio. The green contours show the ice mixing ratio ($x10^{-5}$) and the red contours the temperature (°C).

Atmospheric Processes Research

Many important atmospheric phenomena exist at a scale too small to be resolved on a forecast model grid (such as individual cumulus clouds) yet their thermal and dynamical impact may be too large to ignore. These processes have to be represented (or 'parametrized') in terms of other forecast model variables and the quality of the resulting forecasts may be expected to improve with the accuracy of this representation.

These phenomena often involve some very complex processes (for example, radiative transfer through a field of cumulus clouds) and require an understanding of the underlying physics. Atmospheric Processes Research (APR) combine observational, numerical modelling and theoretical studies to improve the representation of these processes through greater understanding.

Observational research in The Met. Office centres around the instrumented C-130 aircraft of the Meteorological Research Flight (MRF), Farnborough, and a tethered kite-balloon system based at the Meteorological Research Unit (MRU), Cardington (Fig. 43). In addition to its research function, MRU makes routine ascents for the National Meteorological Centre using both radiosondes and the kite-balloon – the latter providing detailed profile data up to heights of 1.5 km. Observational field campaigns are very expensive and it is often necessary to participate in major international collaborative projects to obtain the required data sets (such as the Mesoscale Alpine Programme).

Two numerical codes are used for simulating atmospheric flows: the model for topographic flow problems called 'Blasius', and the Large Eddy Model for convection and boundary-layer studies. For many purposes their output is sufficiently realistic to be treated as surrogate observational data. Nevertheless, observations provide an essential 'reality check' even if they cannot match the spatial and temporal description of model fields.

Figure 43. Helium-filled kite balloon at Cardington. It is capable of lifting up to ten turbulence probes to an altitude of over 1.5 km.

Boundary-layer studies

Modelling cloud-top entrainment processes

The parametrization of entrainment is a major issue for numerical weather prediction and climate models, which is only just beginning to be seriously addressed. Large eddy model simulations have shown a parameter 'D' to be important in determining the nature of entrainment into cloudy boundary layers. This parameter is related to the maximum negative buoyancy which can be generated by mixing clear and cloudy air at cloud top, and is inversely proportional to a bulk moist Richardson Number for the inversion. If D is small, the entrainment process appears to be an intrinsically small-scale one and the entrainment interface is relatively flat. The role of the larger eddies is to carry the negatively buoyant mixtures generated by entrainment away from the entrainment zone. When D is large, vigorous eddies develop rapidly, growing to scales comparable with the cloud depth. They engulf large pockets of clear air, leading to large-amplitude convolutions of the entrainment interface. These features are shown in Fig. 44, with the instantaneous fields of a passive scalar for two different values of the D parameter.

Topographic effects

In the Unified Model (UM), which has grid boxes several tens of kilometres square in its global configuration, it is important to correctly represent the effects of variations in the surface that are much smaller than the grid size (such as changes from grass to forests or buildings, etc.). Currently, such effects are represented by an enhanced surface roughness. The basis for this parametrization has been validated using high-resolution models that can explicitly represent such small-scale effects but which use a simple

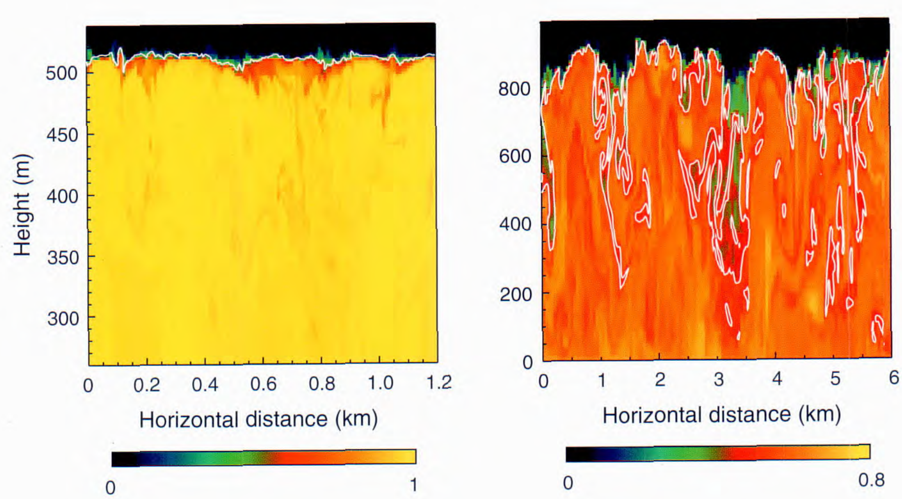


Figure 44. Vertical cross-sections of a passive scalar S from simulations with small D (left panel) and large D (right panel). Initially S is set to 1 in the boundary layer and 0 elsewhere. The white contour is S = 0.5, which initially lies in the centre of the inversion. Note the large difference in the axis scaling between the two panels.

parametrization to represent the turbulence. Large eddy simulations explicitly model these turbulent motions but require large computing power, and so have not previously been applied to this situation. The introduction of the Cray T3E supercomputer has allowed such simulations to be attempted.

Using 1,280 x 64 x 64 grid points, a simulation has been performed of flow over a change in surface roughness, from forest to open water, and then back to forest again. Figure 45 shows the perturbations to the wind induced by the changes in surface characteristics. The mean flow response agrees with results from the simpler turbulence models (not shown here) and supports the UM parametrization scheme currently used.

Deep convection

An improved 'double-moment' microphysical scheme, which explicitly predicts number concentration (as well as total mass) of snow, ice and 'graupel' (snow grains) has recently been developed for the Large Eddy Model. This increases the versatility of the scheme by removing the need to define parameters to diagnose precipitating particle sizes, which vary from case to case. It has been validated against multi-parameter radar observations of a variety of convective cases in southern England. Figure 46 shows the impact of the double-moment scheme on simulation of convection in an Arctic cold-air outbreak. Here 'single-moment' snow evaporated much too rapidly because the effect of evaporation on mean diameter is misrepresented. In contrast, the simulation using the double-moment scheme produced cloud fractions and humidity profiles close to the observed clouds.

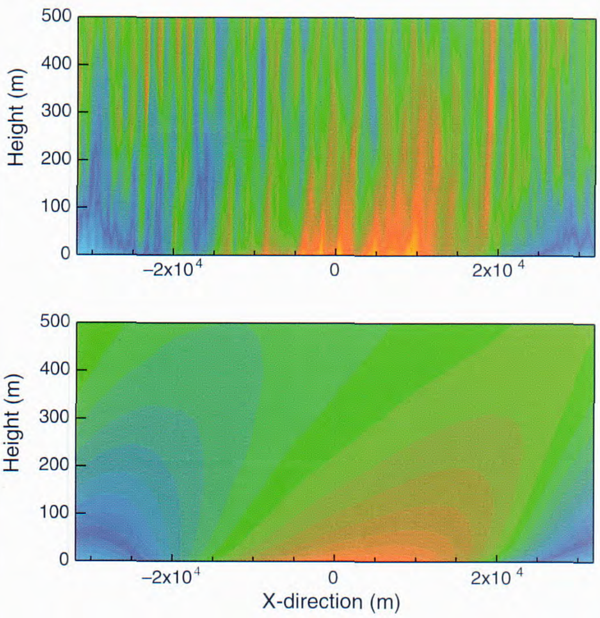


Figure 45. Top, an instantaneous 'snapshot' of the perturbations to wind speed caused by changes in surface roughness, demonstrating the turbulent nature of the flow; below is the time-averaged mean flow response. The flow is driven by a wind aloft of speed 10 $m\ s^{-1}$.

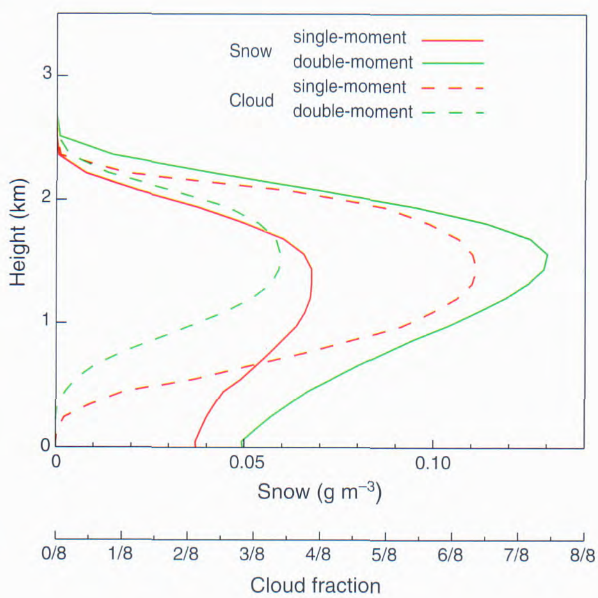


Figure 46. Impact on snow mass concentration and cloud fraction of improved (double-moment) microphysics representation in a 20-hour simulation of Arctic convection.

Frontal and cyclone dynamics

Results from FASTEX

The Fronts and Atlantic Storm Track Experiment (FASTEX) took place in early 1997. Over a two-month period the mesoscale structure of North Atlantic weather systems was intensively studied using five research aircraft – four from the USA and the MRF C-130 – in conjunction with a network of ship, radiosonde and satellite observations. An initial survey of the data obtained has identified periods of outstanding meteorological interest. The mesoscale structure within numerical forecasts for the FASTEX period is now being compared with the detailed observations. This work aims to identify forecast model weaknesses and ways of overcoming them.

Objective frontal analysis

Fronts are boundaries where two air masses of different density, and so different temperature, come together. They are important not only because of the associated changes of weather, but also because they are regions where entirely new weather systems may grow. Building on earlier work on the objective location of fronts, a method of identifying new weather systems in their very early stages has been developed. This method, which can be applied to real or simulated data, uses objective criteria which capture the essence of a human analyst's judgement in a self-consistent fashion (Fig. 47).

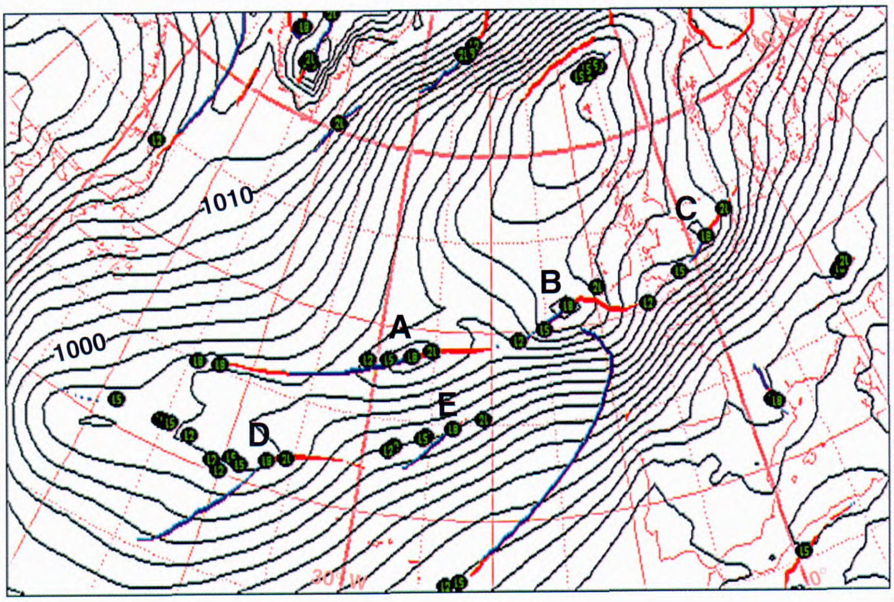


Figure 47. Black dots show objectively identified frontal waves at 12, 15, 18 and 21 UTC on 8 October 1997 (UTC time in green). Objective warm (red) and cold (blue) fronts, and isobars are for 18 UTC. At least five cyclonic features, labelled A to E, can be clearly tracked through the period. Feature E could not be identified using traditional methods, nor did it appear on UKMO hand-drawn analyses. Lows A, B and C together produced 50 mm of rain in parts of southern Britain, while A led to gales over the North Sea on the 10th as it deepened rapidly.

Cloud physics

Atmospheric aerosol particles have a potentially important impact on climate. They affect the Earth's radiation budget, both directly by scattering or absorbing solar radiation, and indirectly by acting as cloud condensation nuclei which govern the microphysics of clouds – influencing their albedo and lifetime. In June and July 1997 the MRF C-130 participated in the EU-funded Aerosol Characterisation Experiment (ACE-2) near the Canary Islands. This investigated the characteristics of European anthropogenic aerosol in the subtropical marine boundary layer.

One of the major components of ACE-2 was a Lagrangian experiment, where an attempt was made to follow a parcel of polluted air for two days from off the coast of Portugal as it was advected south-westwards in the trade winds. The air parcel was tracked using tracers and up to three constant-level balloons. Figure 48a shows the track of the C-130 as it followed the balloons during one of the Lagrangian experiments involving three flights. The aircraft was equipped with instrumentation to measure the physical and chemical characteristics of the cloud and aerosol particles and the thermodynamic and dynamic structure of the marine boundary layer and lower free troposphere. In all, three successful Lagrangian experiments were carried out; two in highly polluted air masses. In each case the evolution of the aerosol was quite different, depending significantly on the structure of the boundary layer and whether extensive stratocumulus clouds were present.

Figure 48b shows how aerosol concentrations increased by a factor of three in the boundary layer over a period of 30 hours. In this case, there were only very small amounts of broken stratocumulus but, due to relatively large subsidence in the free troposphere, the boundary layer depth decreased from 1,500 m to 900 m in the same period. These experiments, along with complementary small-scale model simulations, are being used to improve our understanding of the important processes influencing the evolution of aerosol characteristics over the sea, and in particular, the effect of clouds.

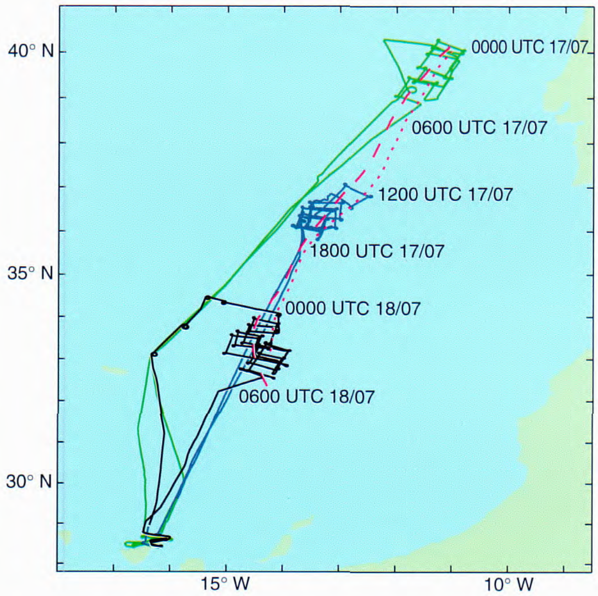


Figure 48a. Flight tracks of the C-130 aircraft on three separate flights (black, green and blue lines) during a Lagrangian experiment carried out between Portugal and the Canary Islands. The air parcel was followed using two constant-level balloons whose altitudes were actively controlled and their GPS tracks are indicated in red.

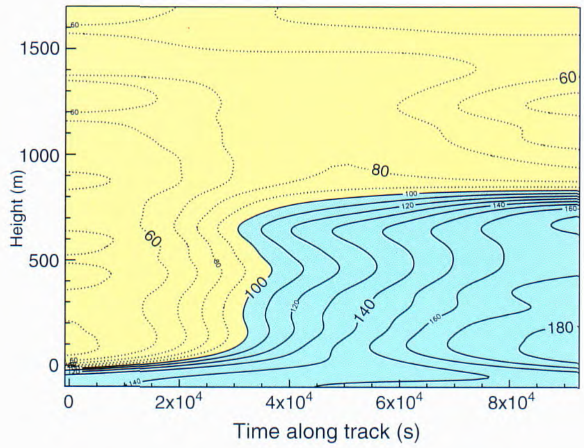


Figure 48b. Contour plot of the time evolution of aerosol concentration (cm^{-3}) in the size range 0.1–3.0 μm diameter during one of the Lagrangian experiments.

Atmospheric chemistry

Atmospheric chemical processes are involved in: driving the production of photochemical ozone during sunny, anticyclonic weather; the acidification of rain and its environmental impact on soil and freshwater ecosystems; and the build-up of greenhouse gases and aerosols in the troposphere.

The global three-dimensional Lagrangian chemistry model (STOCHEM) now links together the chemical reactions involved in regional-scale problems of ozone and acid rain formation with the global-scale build-up of greenhouse gases and aerosols (Fig. 49). European ozone levels are influenced by NO_x and carbon monoxide emissions in North America, and increasingly by emissions in Asia. Furthermore, the concentration of oxidants which convert sulphur dioxide into the acidic sulphur compounds deposited in acid rain is also expected to grow as the build-up of greenhouse gases continues into the next century.

Now there is a growing interest in the relationship between policy actions required within Europe to control ozone and acid rain and those policy actions required ultimately on a global scale to control the build-up of the greenhouse gases and aerosols.

Tropospheric observations

There has been an expansion of chemistry instrumentation fitted to the MRF C-130, achieved through a range of collaborations including ACSOE (Atmospheric Chemistry in the Oceanic Environment), funded by the Natural Environment Research Council. The C-130 (Fig. 50) was sent twice to the Azores as part of the ACSOE project. In the second campaign, flights were co-ordinated with other international chemistry measuring projects taking place in the Atlantic: the NOAA P-3 aircraft operating from Newfoundland and the DLR

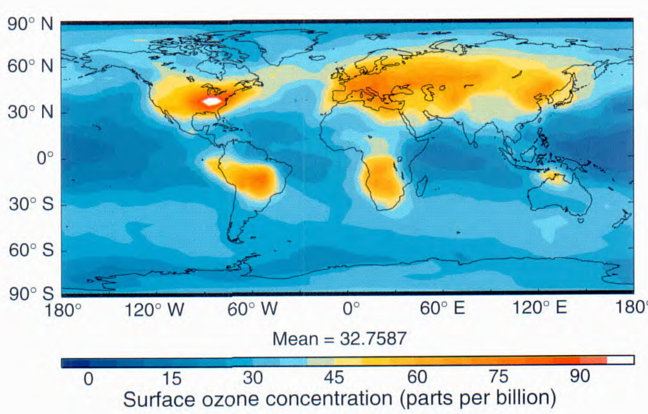


Figure 49. Time-averaged field of surface ozone concentration calculated with the STOCHEM model for July 1992.

Figure 50. The C-130 at 50 feet above sea level in the mid-Atlantic photographed from the NOAA P-3 aircraft after wing-tip intercomparisons.

Falcon aircraft operating from Shannon. Comparison exercises with both aircraft were carried out by flying in formation and initial results show good agreement of the chemical sensors.

In August and September, the C-130 took part in the European TACIA (Testing Atmospheric Chemistry in Anticyclones) programme. This programme investigated the chemical processes occurring in polluted plumes emerging from Europe and the UK. The aircraft flew in anticyclonic conditions (prevailing through much of the period) and measured strongly polluted plumes capped by strong inversions. The reactive compound nitric oxide, which is primarily emitted from car exhausts, was found at levels of tens of ppb (parts per billion) during these flights, roughly three orders of magnitude above typical background levels found in the mid-Atlantic. On one occasion, over the English Channel, ozone concentrations greater than 130 ppb were measured (the World Health Organization one-hour guideline is 76–100 ppb).

Figure 51a shows the back trajectories of the air sampled and Fig. 51b shows vertical sections through a plume of ozone measured in the South West Approaches last September. The concentrations of ozone are low in the layer nearest the sea surface.

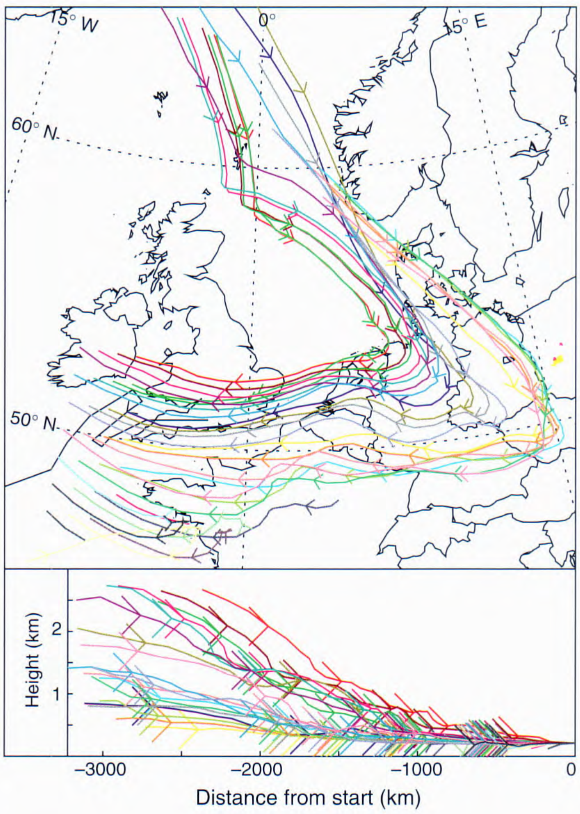


Figure 51a. Back trajectories showing the recent origin of the air sampled in Fig. 51b. The track of the aircraft is indicated by the line in the SW Approaches. Arrows on the trajectory lines represent 24 hours duration.

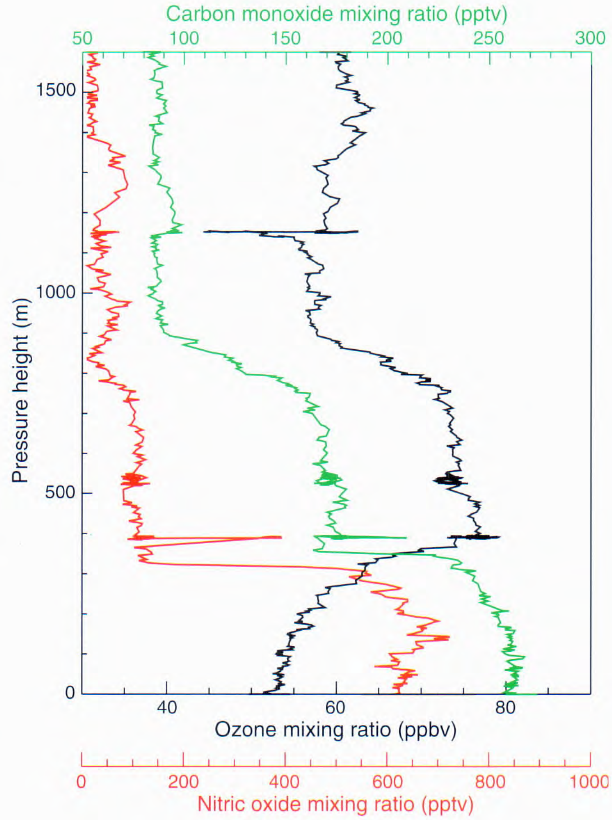


Figure 51b. Profiles of nitric oxide, ozone and carbon monoxide measured in SW Approaches (with acknowledgement to all TACIA groups).

This layer had the highest concentrations of primary pollutants and has undergone little photochemical processing.

The ozone has been removed due to its reaction with nitric oxide. Above the marine boundary layer, greater photochemical processing has occurred and the ozone concentration is larger. The region of high ozone is capped by a strong inversion, above which the ozone concentration is found to be near the background value.

Stratospheric chemistry, dynamics and transport

The impacts of atmospheric dynamics on stratospheric ozone, and ozone changes on climate, have continued to receive attention. The UM is being used to simulate the changes in the stratospheric climate from 1989 to 2050 using projected greenhouse gas concentrations. The model has so far reached the year 2009 and shows – even during this short time – the expected increase in tropospheric temperatures and decrease in stratospheric temperatures. The results from this simulation will be used to provide initial conditions for fully coupled chemistry–climate simulations of 16 months duration. The total ozone results for the period 1 July 1994 to 30 June 1995 (months 4–16 of the integration) are shown in Fig. 52 in a comparison with satellite data. The results generally compare well with the satellite data, but show higher ozone values in the northern spring and slightly lower values during the ozone hole in the southern hemisphere spring.

Atmospheric dispersion

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

For short-range dispersion, work has concentrated on converting recent research on the behaviour of fluctuations in concentrations into a form suitable for practical applications, and on further development of ADMS. In addition, a version of ADMS, tailored for emergency response in the event of accidental releases of hazardous substances, has completed trials and will be introduced operationally during 1998. Theoretical ideas on the differences between rural and urban meteorology await sound observational support. A major programme of urban meteorological observations has started with this in view. A new dry and aqueous-phase sulphur chemistry has been added to NAME to assess its potential for forecasting acid episodes. The model has also been used to investigate the European sources and transports of radiatively active trace gases using the long observational record at Mace Head, County Galway.

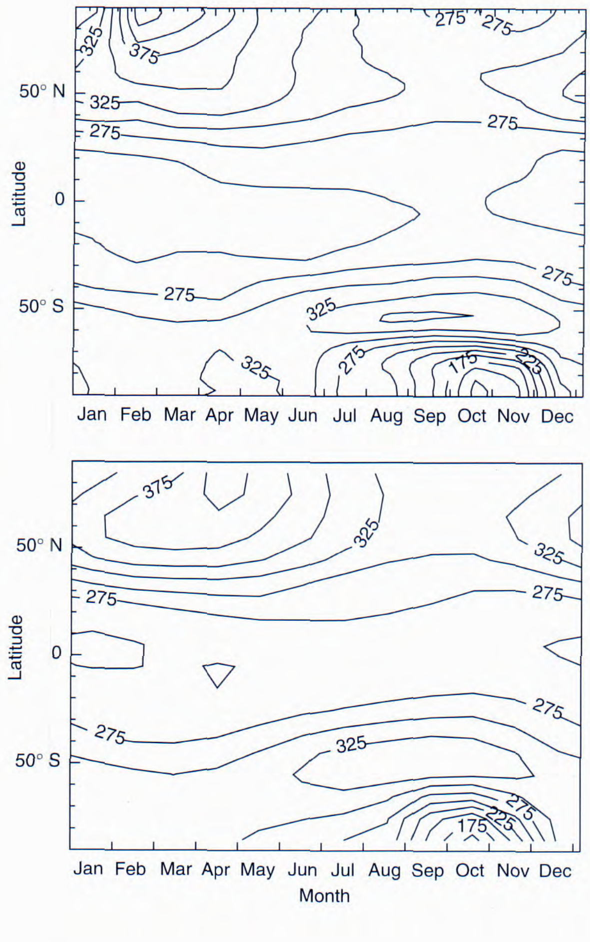


Figure 52. Monthly averaged total ozone (Dobson Units) from the coupled chemistry–climate model for the period July 1994 to June 1995 (top). Monthly averaged total ozone from the TIROS Operational Vertical Sounder averaged for the period 1990 to 1995 (bottom).

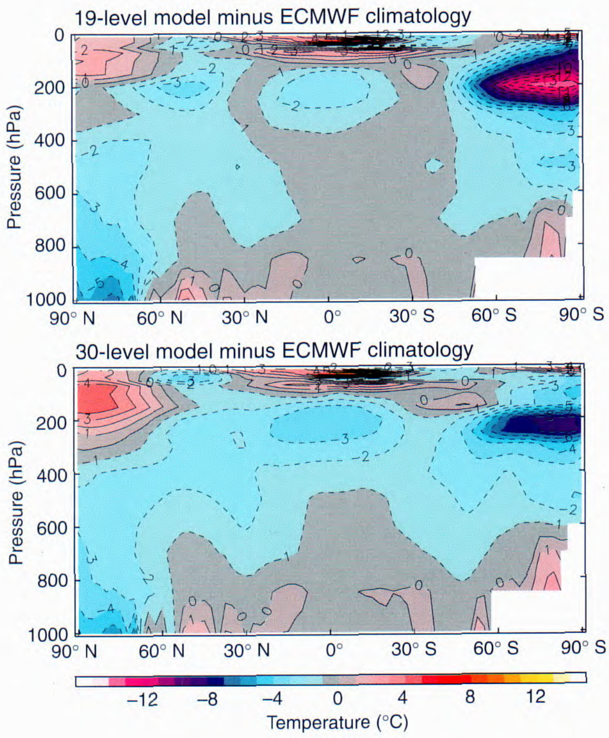
Climate Research

Climate change and variability

There was renewed political activity aimed at tackling climate change last year, with the Kyoto Protocol being agreed in December 1997, under the UN Framework Convention on Climate Change. The Met. Office's research in this area is carried out at the Hadley Centre for Climate Prediction and Research.

The main aims of this are to: understand the processes which control climate; develop climate models which represent these processes; use the models to predict climate change over the next decades; monitor climate variability and trends; and use observations and model simulations to detect climate change and to attribute this to influences such as human activity.

Much of the Hadley Centre's output is used by the Department of the Environment, Transport and the Regions, so that UK policy can be based on the best scientific understanding.



Development of the climate model

The most important tool for climate simulations and predictions is the climate model; this is based on The Met. Office's Unified Model (UM). A significant part of the research programme is directed towards improving the physical parametrizations used in the UM. For both climate and numerical weather prediction (NWP) applications, the correct simulation of clouds is of high importance. The new cloud microphysics scheme provides a major step forward in this area (see *Representation of precipitation and cloud* in the *Numerical Weather Prediction* section).

Other work includes a representation of the radiative effects of the anvil outflow regions from deep convection and a new cloud area parametrization scheme. The latter uses the resolved vertical gradients to infer the moisture contents of three sub-layers within each model layer. This scheme can detect thin cloud layers which would otherwise not be predicted, which is especially beneficial in increasing cloud amounts in the regions of

Figure 53. Latitude–pressure cross-sections of zonal mean temperature averaged over December to February from 10 years of integrations forced with observed SSTs, compared with the ECMWF reanalysis climatology:(top) standard 19-level integration, and (bottom) parallel 30-level integration.

subtropical stratocumulus. Data from the International Satellite Cloud Climatology Project also demonstrated the improvements in the simulated amount of low cloud with moderate optical thickness produced by the scheme over the northern Pacific Ocean. When the scheme was introduced into the coupled ocean–atmosphere model, the amount of cloud was increased, leading to a reduction in errors in sea-surface temperatures (SSTs) in this region.

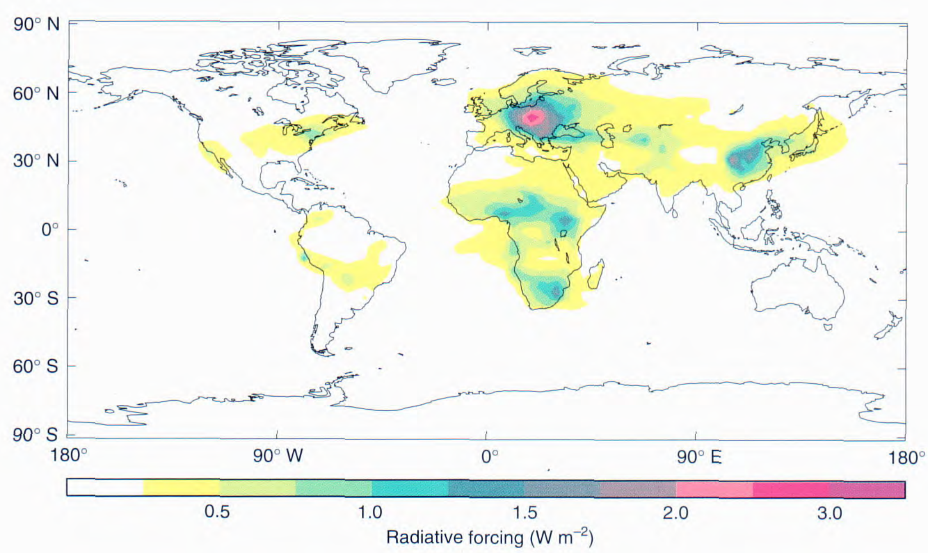
The effect of increasing the vertical resolution of the climate model has also been investigated. The standard atmosphere climate model (HadAM3, the third Hadley atmosphere model) has 19 vertical levels. This was increased to 30 levels, as used in the operational forecast model, which improved the resolution of the tropopause. The resulting representation of dynamical processes in this region reduced dramatically the systematic errors in the upper troposphere for basic fields such as wind, temperature and humidity. Figure 53 shows the reductions in temperature errors when HadAM3 is run with 30 instead of 19 levels. With 19 levels, the model temperatures are as much as 14 °C lower than analysed at 200 hPa over the summer pole. In contrast, with 30 levels, errors are no more than 8 °C.

Aerosols and climate

The distribution and direct radiative effect of anthropogenic sulphate aerosol have been simulated by the UM, using estimated historical sulphur dioxide emissions and *forecasted* future emissions, for a variety of epochs between 1860 and 2100. Black carbon aerosol, which warms the climate system by absorbing solar radiation, has been modelled using mid-1980s emissions from fossil-fuel combustion and biomass burning. Figure 54 shows the annual-mean direct short-wave radiative forcing due to the black carbon aerosol. Wind-blown dust aerosol may also be important, so a method of representing the production of dust particles from arid land surfaces has been devised and used in experiments to simulate the dust distribution.

Studies of the indirect effects of anthropogenic aerosols have investigated the connection between aerosol concentration and the efficiency of precipitation formation, using the new cloud microphysics scheme. Anthropogenic particles may extend the lifetime of liquid clouds by suppressing drizzle formation. This would cause a cooling of the climate, which could be as significant as the other indirect effect, due to the enhancement of cloud albedo, studied previously.

Figure 54. Annual-mean direct short-wave radiative forcing due to black carbon aerosol.



Carbon cycle

Work has begun on developing a coupled climate–carbon cycle model. This will consist of the Hadley Centre's land and ocean carbon cycle models (TRIFFID and HadOCC respectively) along with the ocean–atmosphere climate model. The terrestrial component, TRIFFID, is to be driven by an improved version of the Met. Office Surface Exchange Scheme (MOSES). This takes account of sub-grid land-surface heterogeneity by carrying out surface flux calculations for up to nine surface types within each grid box. An improved model of snow albedo and patchy snow is also included.

Simulations have highlighted the impact of MOSES on the climate sensitivity to doubling concentrations of atmospheric carbon dioxide (CO_2). An enhanced warming of the land surface is related to the inclusion of CO_2-induced stomatal closure within MOSES, which tends to suppress transpiration at high CO_2 levels reducing cloud cover and increasing surface warming. Figure 55 shows the impact of this direct physiological effect on the climate when atmospheric CO_2 concentrations are doubled. The reduced surface evaporation is especially evident in Fig. 55(top) over the tropical forests of Africa and South America. There is a corresponding increase in screen-level temperatures especially over the Amazon basin, and also in the high latitudes as a result of

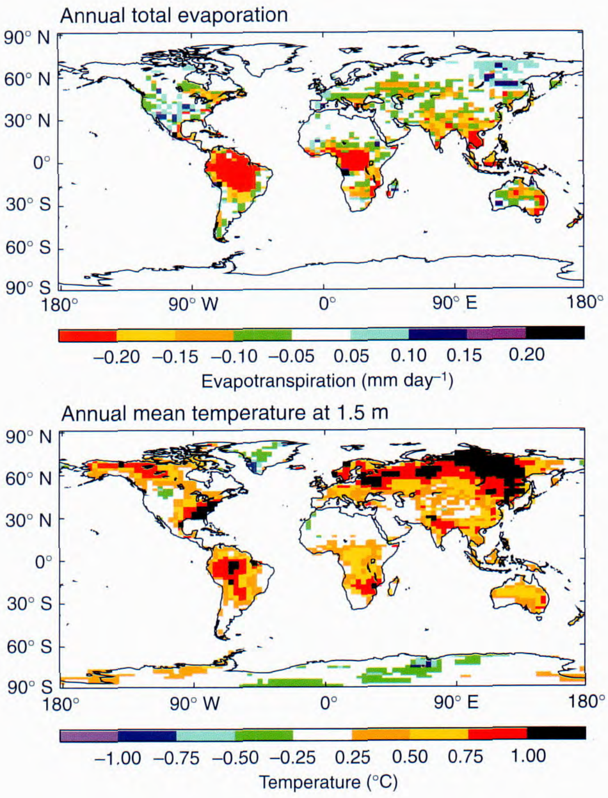


Figure 55. Impact of CO_2-induced stomatal closure on the climate over land when atmospheric CO_2 concentrations are doubled: (top) change in evapotranspiration; (bottom) change in screen-level temperature. The results are from simulations with HadAM3 including MOSES with and without the direct CO_2 effect on vegetation.

snow-albedo feedback acting on the general warming over land, see Fig. 55(bottom).

Atmospheric chemistry

The Lagrangian tropospheric chemistry model, STOCHEM, is being used to predict tropospheric ozone for radiation forcing calculations, and also tropospheric oxidant concentrations used in sulphate aerosol level predictions. Climatologies derived from present-day and double CO_2 simulations of the climate model were used in recent experiments with STOCHEM together with future emission scenarios from the Inter-governmental Panel on Climate Change (IPCC).

The model results indicate that the predicted rises in atmospheric temperature and humidity have a significant effect on the modelled chemistry. Figure 56 shows the changes to ozone in the lower troposphere resulting from IPCC IS92a scenario emissions from model simulations, with and without the inclusion of the appropriate climatic changes. The changes to ozone in the emissions-only case show increases over the entire globe, whereas there are decreases over ocean areas when the effects of the climate change are included. This shows that model predictions of future tropospheric ozone concentrations from emissions changes are significantly overestimated if climatic changes are not considered.

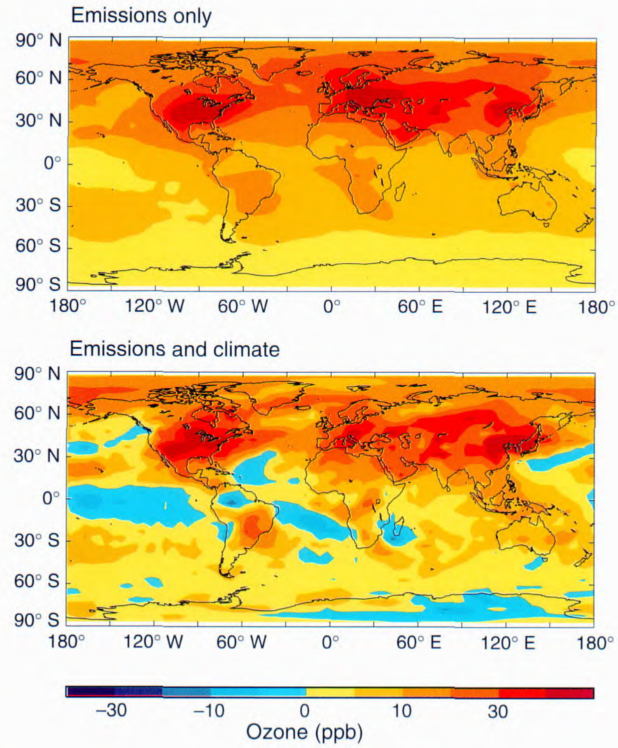


Figure 56. Changes to ozone concentration in the lower troposphere by the year 2100 (top) without and (bottom) with the inclusion of climate change.

Prediction of climate change

One of the main criticisms of climate models to date has been that they require arbitrary, unphysical fluxes of heat and water between the ocean and the atmosphere to maintain a realistic simulation of climate. Over the last two years, the latest climate model, HadCM3 (the third Hadley coupled model) has been developed. This gives a credible simulation of present climate with negligible long-term drift without any artificial fluxes (Fig. 57). The errors in simulated SST are generally small, except in part of the North Pacific Ocean, western subtropical coasts and areas around Antarctica (Fig. 58). The new model allows the explicit representation of all the main gases which have a strong climatic effect, and the conversion of sulphur emissions to aerosol concentrations along with their radiative impact.

When driven by the changes in greenhouse gas concentrations, both in the recent past and into the future under a non-intervention emissions scenario, the predicted temperature changes over the next century are very similar to those estimated in a similar experiment with the previous climate model (HadCM2) which required flux adjustments (Fig. 57). The broad character of the geographical patterns of the changes is also similar to that in the previous model, with greater warming over the land than over the sea, and little warming over the northern North Atlantic and Southern Oceans where the thermal inertia is large (Fig. 59). However, the new results are more credible because of the improved representation of physical processes which removes the need for artificial flux adjustments.

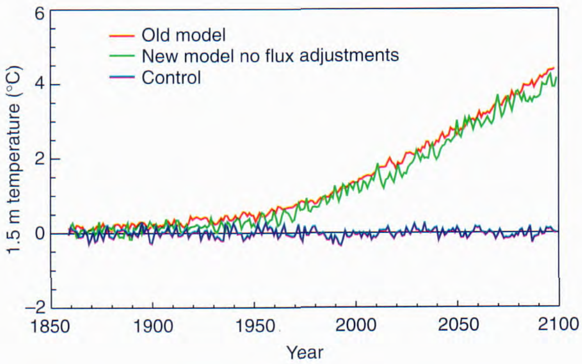


Figure 57. Time-series of global-mean annual surface air temperature response, relative to a control run, in a transient climate simulation using the new coupled model without flux adjustments forced with expected increases in greenhouses gases. This is compared with an ensemble average of four similar runs using the previous flux-adjusted model. The control run of the new coupled model shows little long-term drift over the course of the experiment.

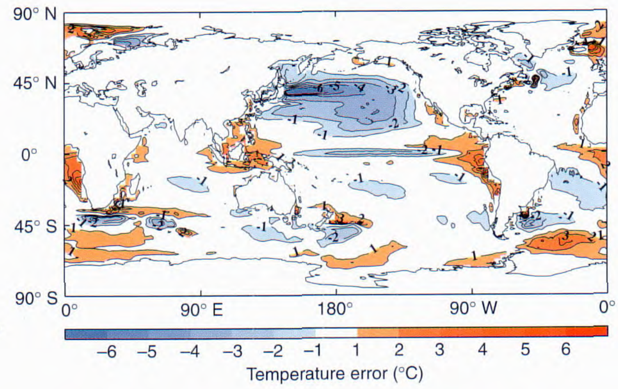


Figure 58. SST error pattern over a decade, 100 years into the control run of the new coupled climate model which does not require flux adjustments. Much of the ocean has temperature errors less than 1 °C compared to the observed climatology; areas with errors greater than 1 °C are coloured.

One of the issues facing policymakers is the effectiveness of scenarios which stabilise emissions. A recent model experiment showed that a scenario which leads to a stabilisation of CO_2 levels at 550 ppm by the end of the next century reduces the global mean warming between the present day and 2100 by about 2 °C, from the 3 °C which would result from a non-intervention (IPCC IS92a) scenario, see Fig. 60(top). The changes in sea level due to thermal expansion are also reduced, but the sea level is still increasing at 6 cm per century at 2250, with little sign of remission, see Fig. 60(bottom).

The melting of glaciers and ice sheets also contributes to increases in sea level. The amount depends on the local warming and its seasonal distribution – any given warming is more effective in summer than winter. The contribution from glaciers and Greenland in the non-intervention scenario is shown in Fig. 61. (Note that changes in Antarctica will probably make a negative

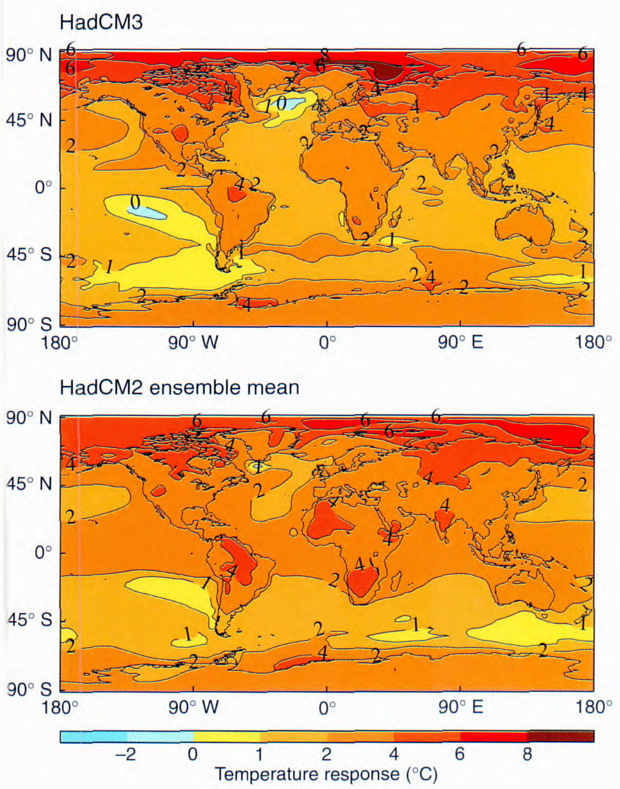


Figure 59. Comparison of surface air temperature response for the decade 2040–50 in similar greenhouse-gas-forced simulations with (top) the new coupled model and (bottom) the previous coupled model without flux adjustment. The response is computed with respect to early industrial conditions as simulated in the respective control experiments.

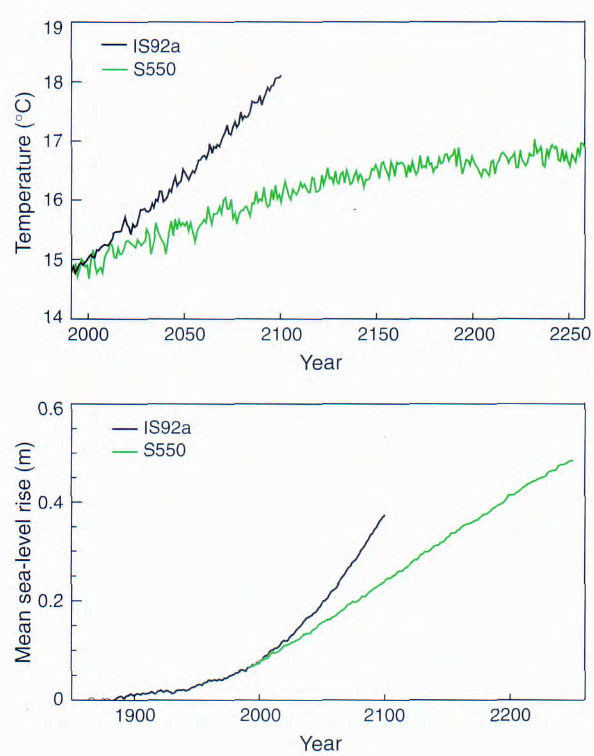


Figure 60. Global-mean near-surface temperature (top) and sea-level rise with only changes due to thermal expansion included (bottom), from the flux-adjusted coupled model under different assumptions about how greenhouse gases will change. The IS92a emissions scenario (black) estimates what might happen in the absence of any controls, while the S550 scenario (green) assumes strong measures are taken which succeed in stabilising greenhouse gas concentrations by 2100 at levels which would otherwise be reached in 2040.

contribution to sea-level rise; snowfall will increase there, but the temperature will still be so low that melting will remain very small.)

Whereas it is relatively simple to evaluate a model's ability to simulate current climate, demonstrating an accurate simulation of climate change is more complicated. One approach is to reproduce climate over the period of the instrumental record, but this is difficult as changes are obscured by natural variability (see *Detection and attribution of climate change*). Another way is to simulate recent palaeoclimates when there was a larger climate change than over the last hundred years, but sufficiently recent to allow a credible reconstruction of the past climate. Simulations of the mid-Holocene, about 6,000 years ago, are improved when the ocean temperatures are calculated with a full dynamical ocean model rather than being prescribed at present-day values. The moistening of the Sahara is much more pronounced (Fig. 62), in agreement with reconstructed data.

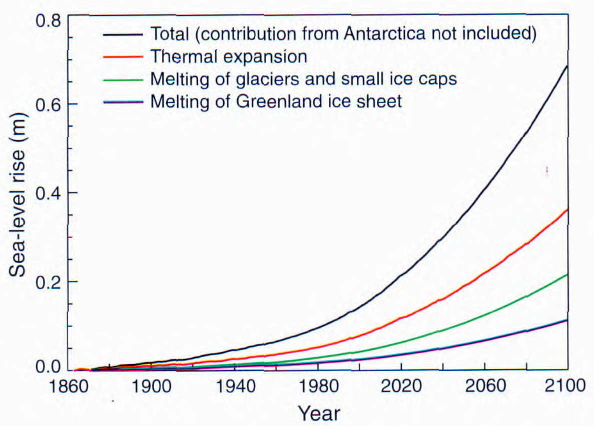


Figure 61. Components of global-average sea-level rise calculated from the flux-adjusted coupled model for the recent past and the next century under the non-intervention emissions scenario. The largest term derives from the expansion of ocean water as it warms up. The melting of mountain glaciers, mostly in high northern latitudes, contributes about half as much. Melting of the Greenland ice-sheet is less important, and there is a negative contribution (not shown) from increased accumulation of snow on the Antarctic ice-sheet.

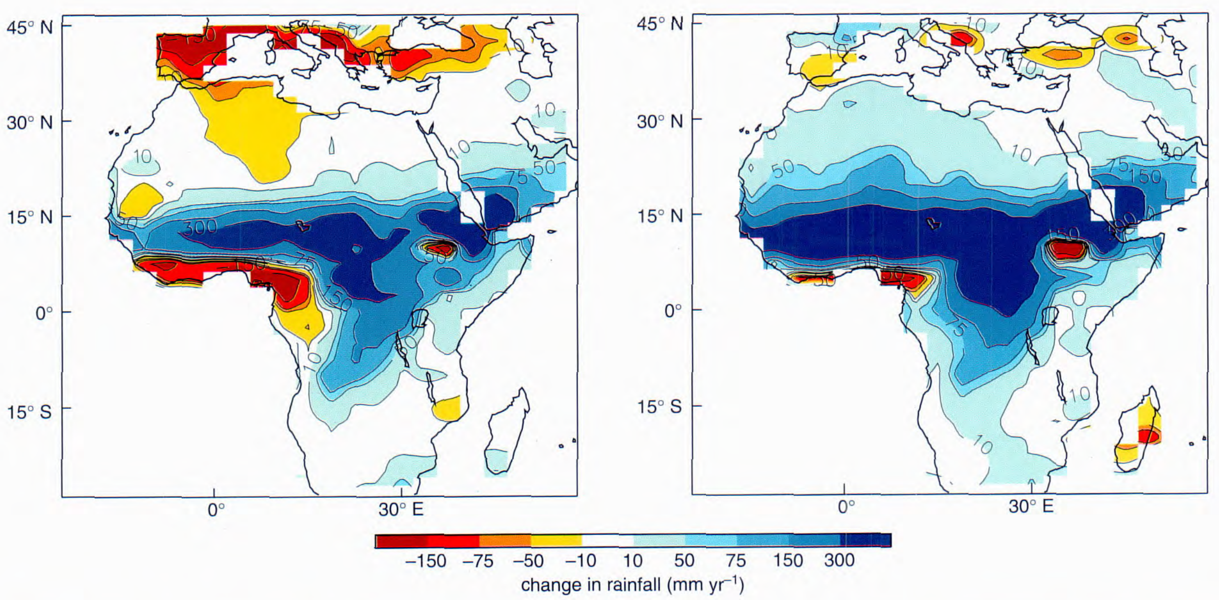


Figure 62. Change in precipitation rates for the mid-Holocene compared to the present day for June, July and August: (left) HadAM2 atmospheric model with present-day SSTs, and (right) HadCM2 flux-adjusted coupled model and computed SSTs.

Detection and attribution of climate change

Detecting climate change involves showing that the recent change is unusual. For attribution, the change must be shown to be due to a particular cause or causes. There are many factors, natural and human, which can lead to changes in global-mean temperature. However, each factor may lead to a characteristic temporal and spatial pattern of the response. Taking advantage of this, the spatial and temporal patterns of recent climate change can be partitioned. The patterns can then be estimated by simulating the response to each factor, and then fitting them to observations using standard linear regression techniques. This powerful technique takes into account the structure of natural variability and gives statistical estimates of the contribution from different factors.

Figure 63 shows estimates of the change in global mean temperature over recent 50-year periods due to greenhouse gases plus sulphate aerosols (anthropogenic effects) and variations in solar activity obtained by such a method. There is a 90% probability that the contribution from each factor lies within the band. Note that anthropogenic effects are very likely to contribute to warming over the recent period, but there is a significant contribution from solar variations early in this century. The accuracy of the approach is likely to be sensitive to the simulation of the response patterns and of natural variability, both of which are a priority for future improvement.

Last year an atmospheric version of the UM was used to detect anthropogenic influences, forced with the observed history of sea-surface temperature (SST) and sea-ice extent. This confirmed that the atmospheric model has substantially less climate noise compared to the coupled model (Fig. 64). Coupled model noise results partly from SST variations uncorrelated with those in the real world. Offsetting this, signals due to SST changes in the atmospheric model must be subtracted before an anthropogenic signal can be found using this technique. However, the reduction in SST signal in the stratosphere or uppermost troposphere is small. Modelled warming of the global land-surface temperature for the whole year is statistically significant when the impact of

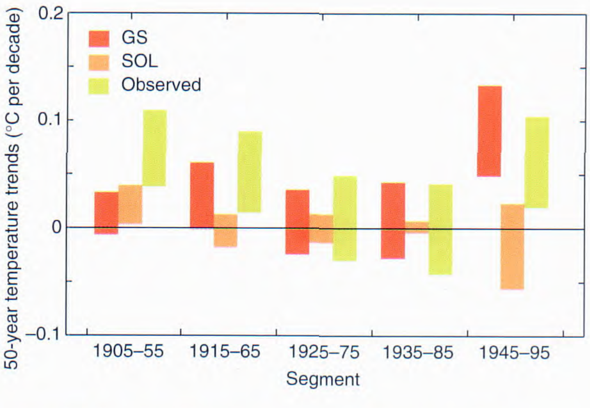


Figure 63. The estimated temperature trends (°C per decade) for successive 50-year periods due to different factors that could have changed climate: Greenhouse gases plus sulphate aerosols (red bars) and solar irradiance changes (orange bars). Each bar covers the 5–95% uncertainty range centred on the best estimate. Where the bars do not include zero then the effect of that factor on climate has been detected. Uncertainty ranges were estimated from a control simulation. The observed trends (green bars) are also shown within a 5–95% uncertainty range.

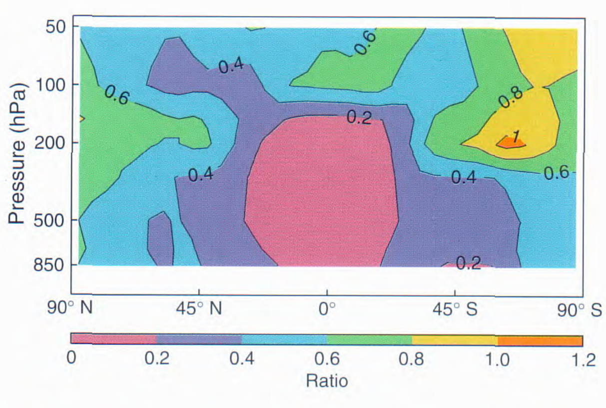


Figure 64. Ratios of the standard deviation of climatic noise in the atmospheric compared to the coupled model. Values are for eight-year averages of zonal mean temperature at levels between 850 hPa and 50 hPa.

increasing greenhouse gases is compared to the influence of SSTs alone (found by a powerful statistical method called the General Linear Model). However, northern hemisphere land-surface temperature increases are not well simulated in the winter half year. A new analysis confirms that much of the failure to simulate more than 0.2 °C of the strong observed winter warming of 0.7 °C is due to inadequate simulation of the increase in westerly wind flow over Eurasia between 1950 and 1994. It is unclear whether this change can be simulated, because it is a natural unforced change.

Climate variability

Atmospheric models forced by observed SST and sea-ice variations are being used to study climate variability. Collaboratively with the University of Reading, the interannual variations in African easterly wave activity over north-west Africa in the model have been studied. Substantial interannual variations occur in the frequency of these synoptic disturbances, which move westward across tropical North Africa during the rainy season and may be important because most Atlantic hurricanes develop from African easterly waves. Regional-scale causes of variations in easterly wave activity in the model have been studied for summer, see Fig. 65. Easterly wave activity is enhanced by stronger convective heating near the Guinea coast, which is measured using the seasonal rainfall total. Further north over the Sahel and southern Sahara, the strength of the easterly flow in and to the north of the mid-tropospheric African easterly jet (shown at 700 hPa) is correlated positively with wave activity. Finally, the low-level north-easterly flow at 950 hPa (not shown) across the eastern Sahara is suspected to interact with the mountainous Hoggar area in the southern Sahara, so that stronger flow gives rise to enhanced wave activity to the south-west.

Large-scale patterns of variation of ocean surface temperature have been reported on decadal to century timescales. One of these is similar to the pattern associated with the El Niño Southern Oscillation but with distinct differences in the Pacific. This pattern has been confirmed in both SST and ocean-surface air temperatures and placed in the context of global warming and other patterns of

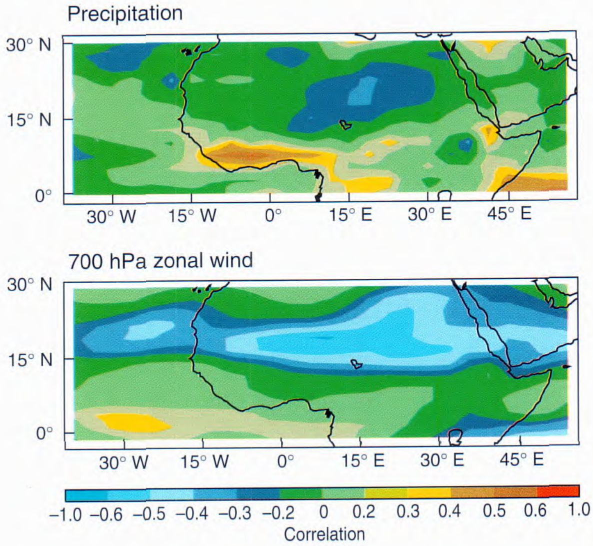


Figure 65. Patterns of correlations between seasonal African easterly wave activity averaged over tropical north-west Africa with (top) local seasonal rainfall, and (bottom) 700 hPa zonal wind (where correlations with easterly flow are negative).

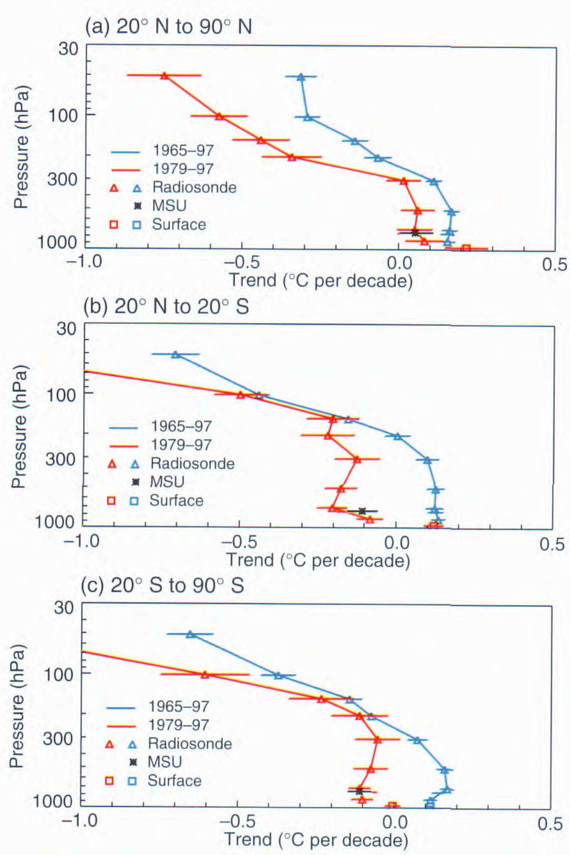
ocean-surface temperature variation since the 1870s. These patterns are being related to rainfall and atmospheric circulation. When several of the patterns are taken together, they reproduce very well the prominent decadal to multi-decadal variations in southern African rainfall since 1900.

Climate monitoring

An important tool in the detection and attribution of climate change is the data set on temperatures in the free troposphere. Monthly radiosonde temperature data have been further adjusted to compensate for instrumental and other discontinuities and biases since 1979. These data were blended with monthly US National Center for Environmental Prediction (NCEP) reanalysis temperature fields for 1958–97. This gives a more complete global coverage than available from the radiosonde data alone, but with few of the biases seen in the reanalysis.

Trends in the new temperature data are compared in Fig. 66 with those calculated for the troposphere from satellite Microwave Sounding Unit (MSU) data, together with values for the surface using SSTs and land surface air temperatures. For 1979–97, the period of availability of MSU data, the middle and upper troposphere cool relative to the surface, both in the extratropical zones of each hemisphere and in the Tropics. The agreement between MSU trends, and radiosonde trends weighted according to the MSU vertical measurement profile, is excellent. Trends in radiosonde temperatures at the 850 hPa level are intermediate between those of the MSU and the

Figure 66. Linear trends of temperature anomalies from radiosondes, MSU retrievals, and surface data for the three regions (a) 20°–90° N, (b) 20° N–20° S and (c) 90° S–20 °S. Error bars show 95% confidence limits.



surface, indicating real recent changes in the vertical thermal structure of the atmosphere. Global MSU temperature trends (slight cooling) and surface trends (marked warming) appear to be genuinely different. The stratosphere cools in all zones. The longer period 1965–97 shows warming trends throughout the troposphere and weaker cooling trends in the stratosphere than in 1979–97 in each zone.

New statistical methods are being developed to enhance the Global sea-Ice and Sea-Surface Temperature (GISST) data set and to quantify uncertainties in global and regional average temperature anomalies since the mid-nineteenth century. The techniques involve optimal estimates of temperature patterns where data are sparse, and several advanced analysis methods which are still being refined.

With a continuation of global warming, there is a new interest in determining how unusual current climate is relative to the recent past. This has led to a new emphasis on analysing extremes on scales ranging from daily, such as for frost or heavy rainfall, to a few years for average temperature or rainfall. To provide a rigorous assessment of the rarity of monthly to annual anomalies of temperature, data for the ocean and land surface analysed at the Hadley Centre and the University of East Anglia for a 1961–90 base period have been fitted to an appropriate mathematical distribution. A global field of annual surface temperature anomaly percentiles for 1997 is shown in Fig. 67a. In 1997, more than 75% of grid boxes are warmer than the median temperature experienced in 1961–90, while 18% are in the 'extremely warm category'. Based on statistics for 1961–90, only 2% would be expected in this category (Fig. 67b). Not surprisingly, the distribution of worldwide anomalies in Fig. 67b is different from that in 1961–90. It is too early to assess whether variability about the current warmer averages has changed but the more accurate data sets being developed may allow this to be studied soon.

Globally, 1997 was the warmest year so far recorded, being an estimated 0.43 °C higher than the 1961–90 average. The previous warmest year, 1995,

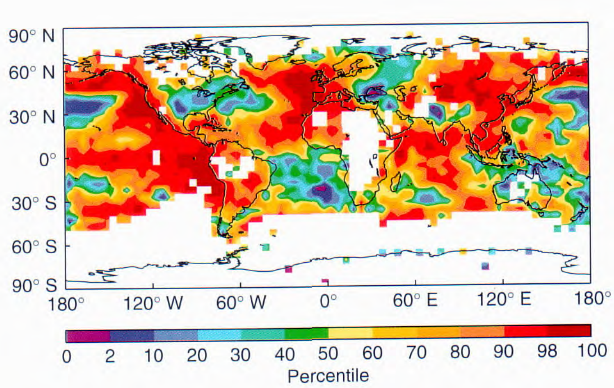


Figure 67a. Surface temperature anomaly percentiles for 1997 with respect to 1961–90.

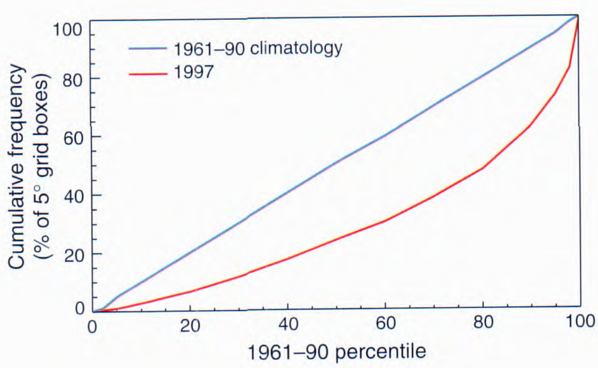


Figure 67b. Percentages of 5° x 5° pixel surface temperature anomalies which fell below the specified anomaly at each percentile during 1997, compared with that for all years 1961–90.

was 0.38 °C warmer than average. A major contributor to the warmth of 1997 was the very strong El Niño event in the eastern tropical Pacific visible in Fig. 67a. This El Niño was appreciably warmer than that of 1982/83, which had been the strongest event this century, see Fig. 68. SST anomalies exceeded 3 °C over a large area of the eastern tropical Pacific by December 1997, with anomalies exceeding 5 °C locally.

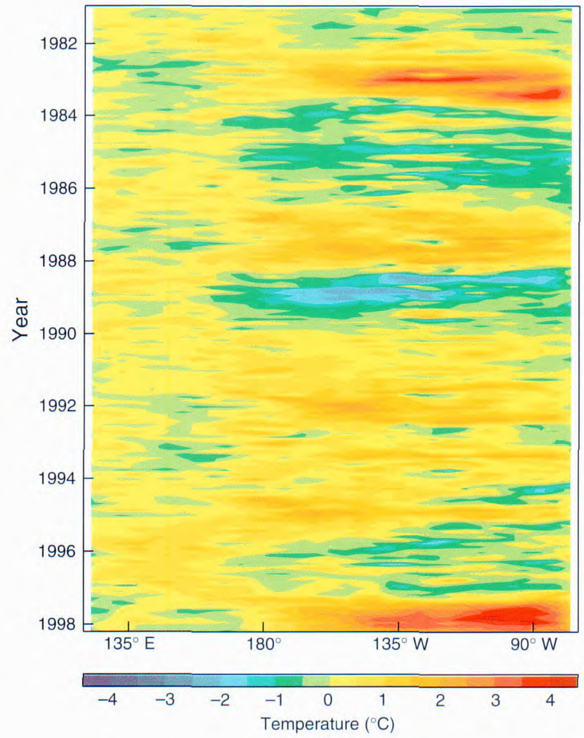
Over the UK, 1997 was the third warmest year, after 1990 and 1949, in the Central England Temperature record which began in 1659. August was the second warmest recorded: only August 1995 was warmer. Following rainfall shortages in much of 1995 and 1996, the period May 1995 to April 1997 had 71% of normal precipitation. This was the driest 24 months in the England and Wales precipitation series which began in 1766. The 30-month precipitation total up to September 1997 was also the lowest in this series.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was set up in 1988 to provide periodic assessments of current scientific consensus concerning climate change, its potential impacts and the range of possible response strategies. IPCC's Working Group I (WGI), co-ordinated by a Technical Support Unit based at the Hadley Centre, focuses on the physical climate system. WGI produced two major assessments, in 1990 and 1995, plus two interim reports in 1992 and 1994. These reports, written by international teams of the world's leading scientists, have played a major role in the negotiation and implementation of the UN Framework Convention on Climate Change (FCCC).

During 1997, WGI published three technical papers, *An Introduction to Simple Climate Models used in the IPCC Second Assessment Report*, *Stabilisation of Atmospheric Greenhouse Gases: Physical, Biological and Socio-economic Implications* and *Implications of Proposed CO_2 Emissions Limitations* and one report, *Revised 1996 IPCC Guidelines for National*

Figure 68. Monthly SST anomalies, relative to a 1961–90 climatology, across the equatorial Pacific (5° N to 5° S) from January 1981 to January 1998.



Greenhouse Gas Inventories. In partnership with WGII, a Task Group on Climate scenarios for Impact Assessment (TGCIA) was established to provide a common set of climate scenarios to the climate impacts community and work began on the *Special Report on Aviation and the Global Atmosphere* in conjunction with the Science Assessment Panel of the Montreal Protocol. Planning also began for the third major assessment scheduled for completion in late 2000 or early 2001.

Seasonal prediction

Several seasonal climate prediction activities are in progress. In one approach, for a range of a few months, skilful predictions can be made for many regions by using statistical models and dynamical atmospheric models. Such predictions rely mainly on the tendency of SST anomalies to change slowly on this timescale, and to exert a systematic bias on the atmosphere over the forecast period. At longer range, dynamical ocean models that interact with the atmosphere are used to predict SST changes, particularly in the important tropical Pacific region. By coupling ocean and atmosphere models, predictions over a range of many months can be made.

A very large El Niño event developed in 1997, and continued into 1998. By using the various forecast models, advice on the likely evolution and impact of this event was provided in response to many enquiries from a wide range of sources.

Atmospheric model

Seasonal climate simulations and predictions are being made with the climate-resolution version of the

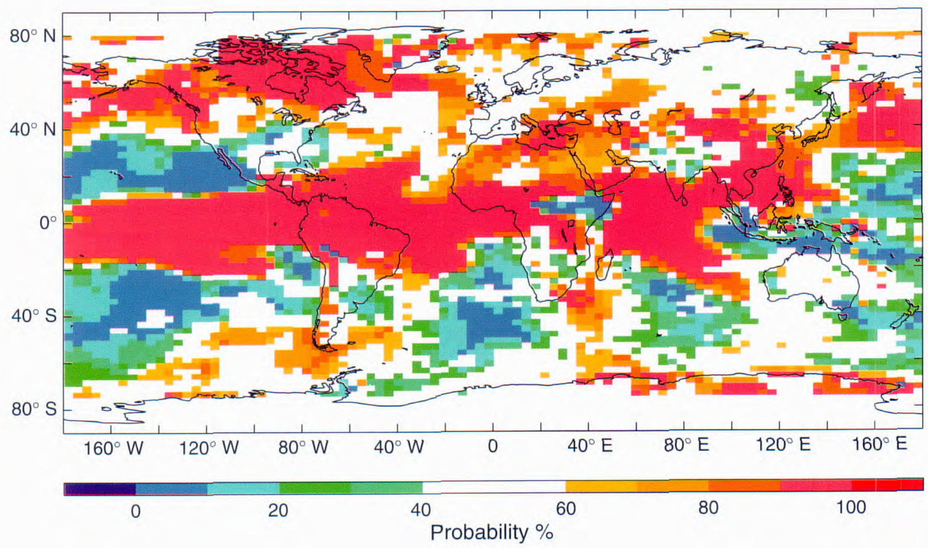


Figure 69. A global real-time probability forecast for December, January and February 1997/98 for 850 hPa temperature (a proxy for surface temperature). Increasing redness indicates higher probability of above-normal temperature; increasing blueness indicates higher probability of below-normal temperature.

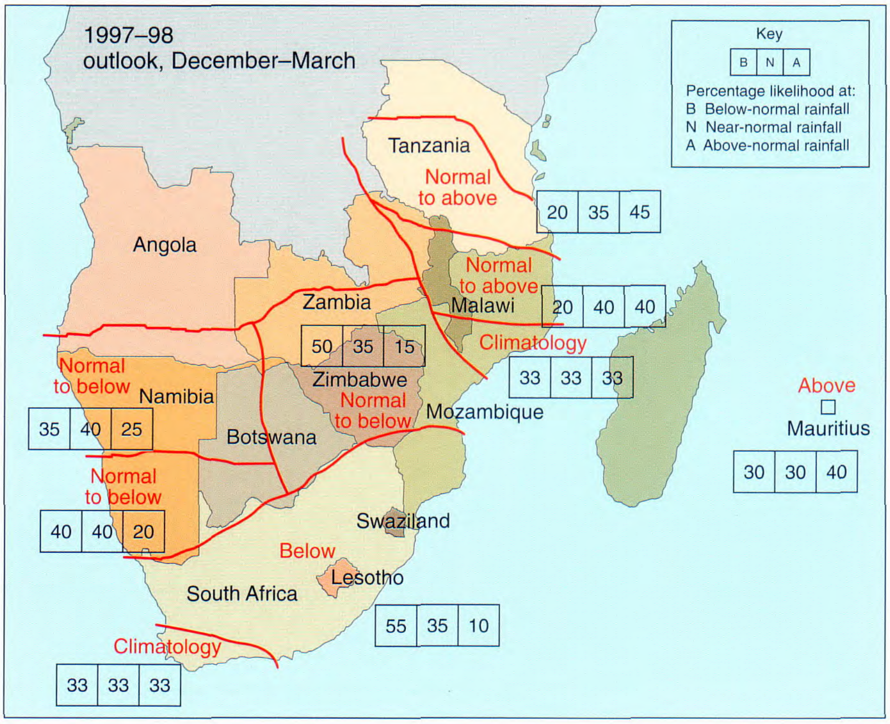
atmospheric UM, out to a range of four months. SST conditions over this range are either prescribed from observations (for simulations) or based on persistence of monthly anomalies. Several separate forecasts from nearby starting points are used to generate ensemble predictions. As part of a collaborative European seasonal prediction programme, called PROVOST, a database of nine-member ensembles for each of four seasons over 15 years has been created for four different models. Levels of predictability over Europe on seasonal timescales exceed prior expectations, and useful prediction may be possible in at least some seasons and years. Results indicate that predictability is enhanced by combining outputs from different models (Fig. 69).

Practical aspects of seasonal prediction have also been examined. In one approach, real-time predictions are made and assessed on a regular basis. These predictions are being used to examine benefits to applications both in the UK and in southern Africa. The latter is a useful test region where predictability is higher than in Europe. Here The Met. Office is taking a lead role in a major international programme to produce and assess seasonal forecasts, called ENSARCOF, see Fig. 70.

Coupled models

As part of the collaborative PROVOST project, sets of hindcasts (predictions of past events using only information prior to the hindcast period) are being made by several modelling groups, including The Met. Office. Analysis of the results will provide information about predictability with coupled models on a global scale. In the ocean–atmosphere system, the largest year-to-year changes occur in the tropical Pacific. In particular, El Niño events can have widespread effects on global atmospheric circulation, affecting temperature and

Figure 70. Forecast produced in the ENSARCOF project, as a consensus of 10 different forecast models. The oceans and atmosphere constantly interact with each other. To represent this interaction, and eventually provide improved seasonal forecasts, dynamical coupled ocean–atmosphere models have been developed.



rainfall patterns. There is evidence that even European climate may sometimes be influenced by the El Niño Southern Oscillation cycle. With coupled models the evolution of El Niño and its impacts over several months can be forecast. The evolution of a coupled model depends strongly on the initial upper-ocean conditions. Estimations of the ocean state can be made by using various sources of observations, such as *in situ* instruments and satellite remote sensors.

In collaboration with the Forecasting Ocean–Atmosphere Model team, a data assimilation scheme has been developed, and this is being used to improve the initial conditions for coupled model predictions. As a contribution to the European DUACS (Developing Use of Altimetry for Climate Studies) project, the effect of assimilation of sea level as measured by satellite altimeters is being studied.

Statistical methods

Empirical methods can also be used for seasonal prediction. Relatively long-lasting SST anomaly patterns influence seasonal land conditions in many areas and, by using historical data, statistical models can be developed to make forecasts based on such links. Such models have been used to make and issue forecasts for several tropical regions. The recently discovered connection between winter North Atlantic SST and summer European conditions has also allowed long-range European seasonal forecasts to be made. Figure 71 shows a measure of European forecast skill; it is modest, but sufficiently high (correlations around 0.5 in areas) to have potential practical application.

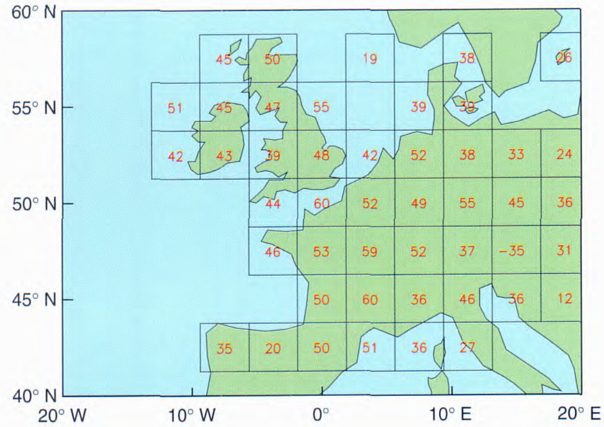


Figure 71. Correlation between forecast and observed July–August surface temperature for 1951–97. The statistical forecast model used January–February SST in the North Atlantic as the predictor.

Ocean Applications

Ocean Applications Branch develops and implements ocean modelling systems required to meet Met. Office customer needs. The Met. Office has long had a commitment to operational oceanography. Operational storm surge models and global and European wave models have been run for many years. The Met. Office also has a commitment to analysis and forecasting of global oceans for the Royal Navy. The Forecasting Ocean–Atmosphere Model (FOAM) has been brought into operational use and shelf-seas models are now being developed. Ocean Applications also supports climate research and seasonal forecasting, specifically providing the ocean component of coupled ocean–atmosphere models.

Ocean modelling for climate studies

Ocean general circulation modelling

The Met. Office's ocean general circulation model has been developed from a widely used code originating from the Geophysical Fluid Dynamics Laboratory in the USA. It runs within the Unified Model (UM) and is used for global coupled climate modelling, seasonal prediction studies and for FOAM. The model must be optimised to run efficiently on The Met. Office's computers and with successful transfer of the model code to the new Cray T3E supercomputer, more recent work has focused on code optimisation. This aims to improve efficiency in both present and future applications, in particular the anticipated need to run much higher-resolution ocean models than at present.

Hadley Centre ocean modelling groups keep the model's representation of physical oceanic processes up to date with new developments. This work contributes to the development of the ocean model for all applications, but is particularly aimed at the new versions of The Met. Office's coupled models (see *Coupled models* in the *Climate Research* section). Two configurations of the ocean model are used for climate studies, one at 2.5° x 3.75° and the other at 1.25° x 1.25° horizontal resolution. Both have 20 levels in the vertical, though trials with higher vertical resolutions have been carried out during the year.

Small-scale processes: mixing in the ocean

Sea-surface temperature (SST) is a key parameter in coupled models because of its importance in air–sea exchanges. Its simulation depends, for example, on how well the upper boundary layer (the mixed layer) is modelled, and how exchanges of heat momentum and freshwater between the ocean surface and the atmosphere are represented, some of which themselves depend interactively on SST.

Modelling of the mixed layer is also a priority for FOAM. Forecasting its variations in depth and the strength of the thermocline (the region of rapid temperature change between the mixed layer and the colder ocean beneath) are essential if the acoustic properties of the ocean are to be determined for naval operations. A new 'non-local K-theory' upper-ocean boundary layer scheme, developed in the USA, has been incorporated and tested in the ocean and coupled models. It improves the representation of the near-surface thermal, density and current structure. A revised scheme for mixing below the surface layer has also been implemented, derived from observations taken in the equatorial eastern Pacific Ocean. Figure 72 shows a comparison of global distribution of mixed-layer depths from observations and from a coupled model simulation with these new schemes.

Another essential process which must be represented is ocean mixing along and across density surfaces. One mechanism by which this can occur is through the effects of oceanic mesoscale eddies which have scales of a few tens of

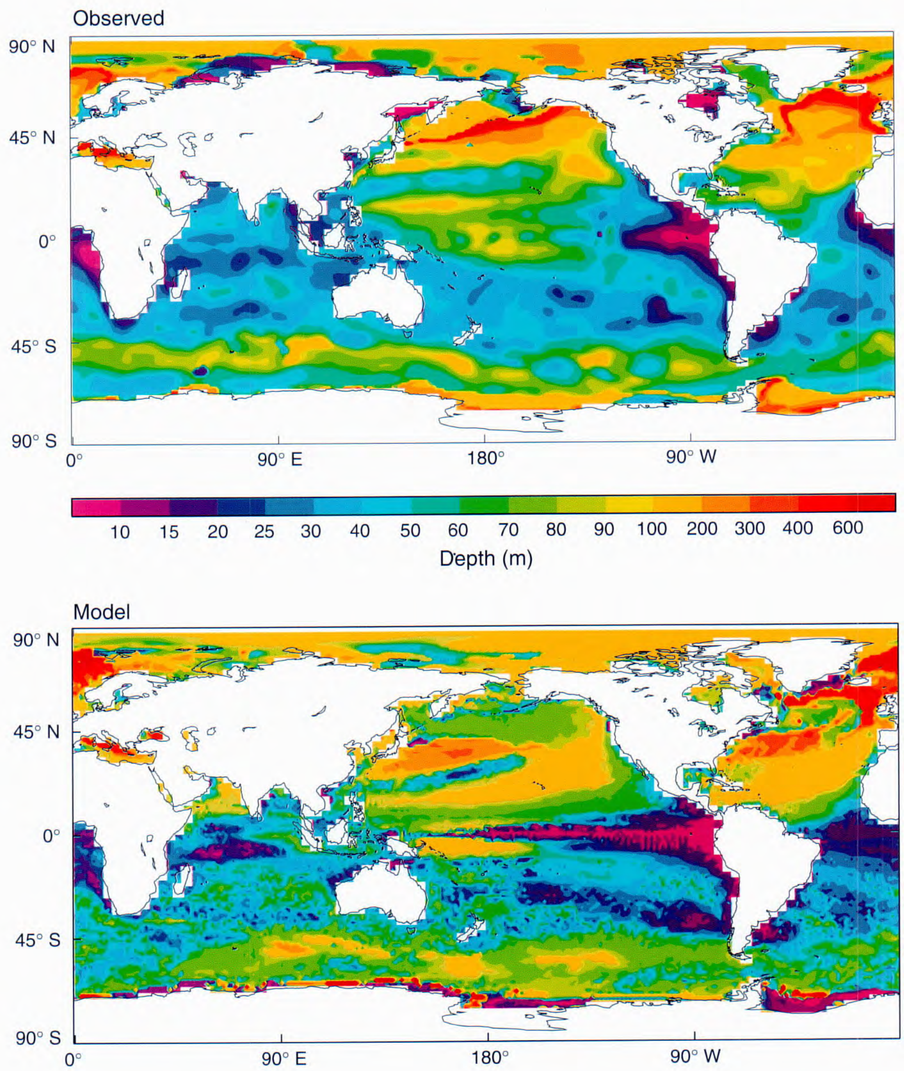


Figure 72. March 1994 monthly mean mixed-layer depths from: (top) observed climatology and (bottom) the new upper-ocean boundary layer scheme.

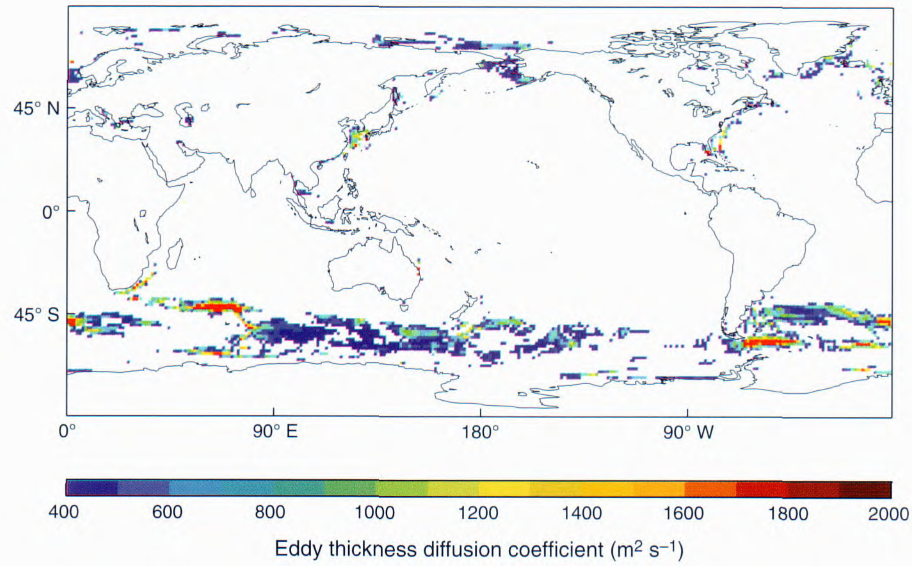
kilometres. Such eddies cannot be represented on the much larger scale (100–150 km) grids of the FOAM and climate models. Studies have been carried out using high-resolution versions of the ocean model (13–25 km resolution) to understand the role of eddies in determining ocean circulation. The aim is to develop techniques for representing eddy effects in the larger-scale global ocean models. Because of their high computational cost, these fine-scale models are run for an idealised (rectangular) domain. These studies have revealed the importance of using schemes to diffuse heat which can preserve water mass properties. This helps retain the sharpness of the model's thermocline. A new scheme which is suited to high-resolution models has been developed and tested. It may also be used in the standard climate model, making mixing in the model's ocean interior more realistic.

A new representation for the diffusion of layer thicknesses between surfaces of constant density has been incorporated into the model. Thickness diffusion coefficients are locally determined from the implied intensity of the activity of oceanic eddies (Fig. 73). The regions of large values also indicate regions of strong implied model eddy activity. The locations of these compare well with observations. Revisions have also been made to improve the numerical representation of diffusion of temperature and salinity along density surfaces. With this new scheme the 'background' diffusion can be chosen from physical rather than numerical considerations.

Sea ice

Sea ice forms on the ocean when its surface temperature falls below the freezing point of sea water (−1.8 °C). As sea ice forms, it releases the salt within the sea water back into the ocean, causing convective mixing. Ice melt puts relatively fresh water onto the upper surface of the ocean, suppressing mixing. Melting can take place a long way from the regions of ice formation due to movement of the ice by wind and ocean currents. It also markedly changes the albedo of the ocean surface. Sea ice must be explicitly modelled because of these processes.

Figure 73. The eddy thickness diffusion coefficient as calculated in the ocean component of the coupled model. High values indicate regions of implied strong eddy activity.



The sea-ice distribution in the latest coupled model has been improved by revisions to the model's thermodynamic scheme and to the representation of ocean surface currents. Figure 74 shows ice concentrations for March, the time of maximum ice extent in the northern hemisphere, from satellite observations and from the latest coupled model.

Ocean climate model validation

Validation of the coupled climate model's ocean simulation against observations is necessary to quantify how much confidence we can have in the model, and to identify future model development needs. Recent validation has focused on heat transport by the ocean, which is a fundamentally important process for the climate system. This, in turn, has led to validation of both the water mass properties and the large-scale circulation.

Two approaches have been taken. The first is to validate against observed values of the heat transport in a way as consistent as possible with the methods by which they were derived. Figure 75 shows modelled heat transport across selected ocean sections, and the corresponding observational estimates. There are notable discrepancies in the South Pacific and Indian Oceans. These are associated with difficulties in representation of the Indonesian throughflow, which is believed to be too strong in the model.

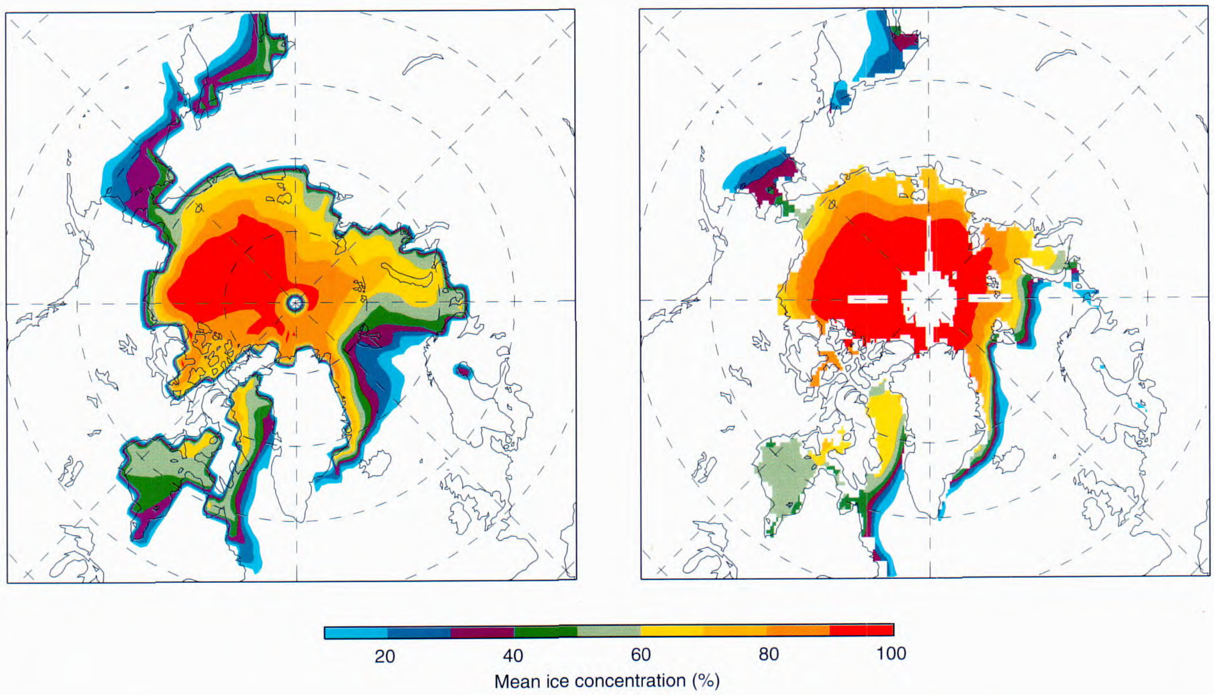


Figure 74. (left) The distribution of mean ice concentration for March from the latest coupled model simulation without flux adjustment. (right) The same distribution from satellite observations.

The second approach is to compare the model with the observational analyses of particular ocean sections. This approach was used for the World Ocean Circulation Experiment (WOCE) 'A11' section in the South Atlantic Ocean (see Fig. 75). Many important features of the circulation can be diagnosed, giving insight into model performance. Figure 76 shows an example. This work is being extended to other WOCE sections in the Southern Oceans, in collaboration with scientists at Southampton Oceanography Centre.

Comparing different models provides another profitable way of understanding model behaviour. In another long-term collaborative project with Southampton Oceanography Centre, The Met. Office's ocean circulation model has been compared with the Miami Isopycnic Co-ordinate Model. Recent work has focused on the tropical Pacific and has demonstrated the importance of sub-gridscale mixing in controlling the equatorial current systems. Modifications to the way in which this mixing is dealt with have resulted in reduced errors in the

Figure 75. The ocean heat transport (in petawatts, PW) across key latitudes (24° N and 30° S) and across the WOCE A11 section from the coupled model (green) and from observational estimates (purple).

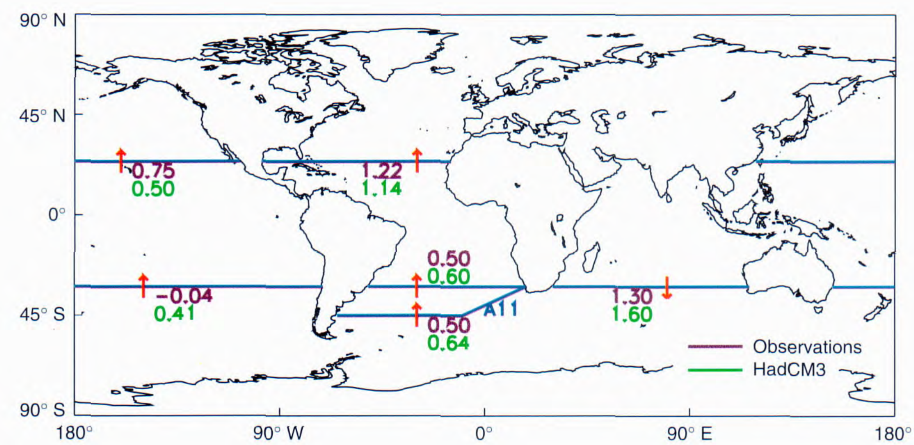
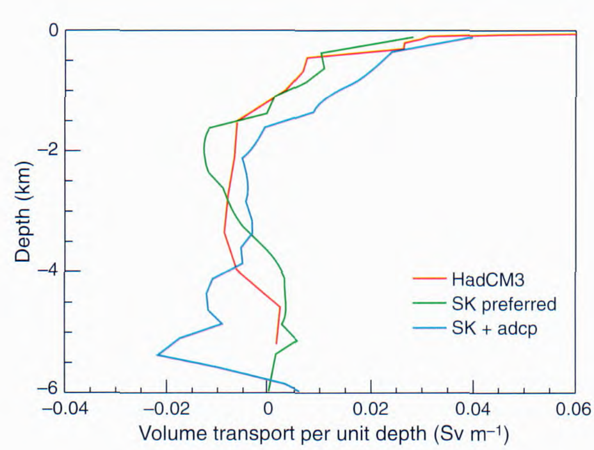


Figure 76. Profiles indicating the average circulation across the WOCE A11 section implied by the coupled model (red) and from two observational estimates by Saunders and King (SK). Northwards flow is positive (1 Sverdrup, Sv, is 10^6 m^3 s^{-1}).



simulation of thermocline temperature in the central and eastern Pacific Ocean (Fig. 77).

Ocean model spin-up

Before beginning a model experiment to study a climate change scenario, the model must be brought close to equilibrium. This is because the model must not drift so fast as to swamp the expected climate change signal. This can be computationally costly because of the enormous heat capacity and slow response time of the ocean; runs covering several centuries are needed for the ocean component to approach a steady state. A quicker way of reaching equilibrium is needed, rather than simply running the coupled model for this length of time.

A saving may be made by running only the ocean component of the coupled model for these very long spin-up periods, using atmospheric forcing prescribed from a short coupled run. A major problem here is in prescribing the atmospheric forcing for the sea-ice model. One solution is to remove the ice model completely and treat ice in the same way as the atmosphere, i.e. as a forcing of the sea-ice surface of the ocean, derived from the coupled run. This approach has been tested in very long spin-ups of the low-resolution coupled model, also used for carbon cycle modelling (see *Ocean carbon cycle modelling*, and is being adapted and refined for the high-resolution (1.25°) ocean version of the climate model.

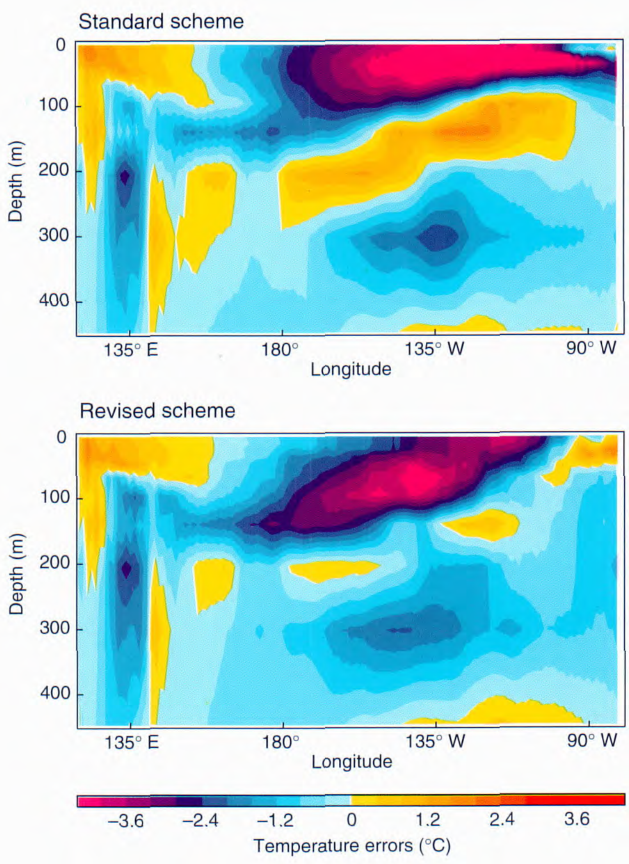


Figure 77. Cross-section along the equator in the Pacific Ocean, showing model temperature errors relative to climatology from an ocean model with (top) the standard mixing scheme used in previous coupled model experiments, (bottom) a revised subsurface mixing scheme.

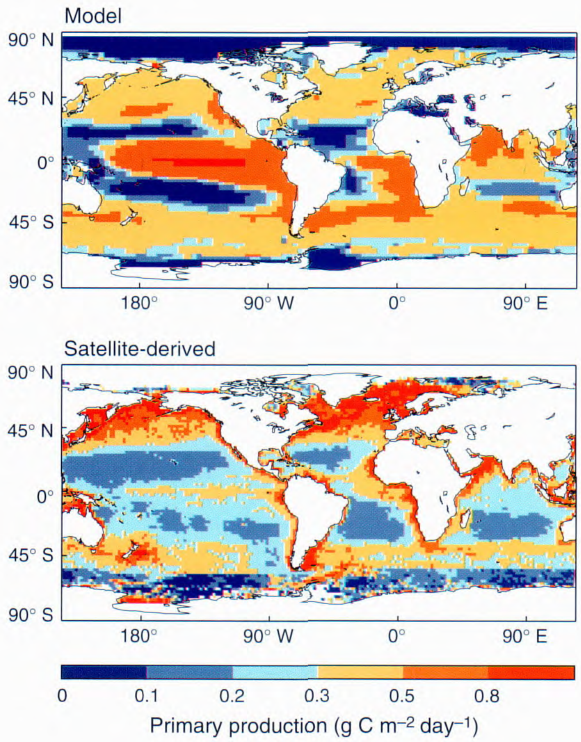
Ocean carbon cycle modelling

An ocean carbon cycle model has been developed as part of a wider project to model the overall global carbon cycle, which also includes the land surface (see *Carbon cycle* in the *Climate Research* section). The ocean model component has two parts, a representation of the inorganic chemistry, including transfer of carbon dioxide across the air–sea interface, and a model of the important biological processes. Primary and export production are key diagnostics of the ocean biology model, again developed in collaboration with Southampton Oceanography Centre. These represent total phytoplankton growth and the amount of carbon exported by sinking particles below the zone of light penetration.

Other components modelled are the nutrients needed for phytoplankton growth and effects of zooplankton.

Global primary production in the model is about 48 Gt C yr^{-1}, comparing well with recent estimates based on *in situ* and satellite measurements. The geographical distribution of production is compared in Fig. 78 with the distribution from satellite measurements of sea-surface chlorophyll. The differences between observed and modelled primary production have been studied. The excessive equatorial production in the model is probably because of too much upwelling of nutrient-rich deeper waters.

Figure 78. Primary production of carbon from: (top) the ocean carbon cycle model and (bottom) derived from satellite observations.



The model will be used to study the possible effects of climate change on ocean ecosystems and the ocean carbon cycle. It has recently been included in short ocean–atmosphere coupled model runs, and is soon to be used in land–atmosphere–ocean coupled carbon cycle experiments. Techniques for spinning up the ocean and ocean carbon cycle models are important to ensure the carbon cycle model drift is minimal on coupling to the atmosphere.

Operational oceanography

Forecasting Ocean–Atmosphere Model (FOAM)

FOAM is a global ocean data assimilation and forecast system which has been developed for the Royal Navy. FOAM is based on the global ocean circulation model in the UM and runs on a 1° grid with 20 vertical levels. It incorporates a data assimilation code which is based on that used in The Met. Office's numerical weather prediction (NWP) models.

A major achievement this year has been bringing FOAM into operation within the NWP suite. FOAM now runs once a day, providing an analysis of the ocean for the past 24 hours, followed by a five-day forecast. All available temperature profiles are assimilated, as well as *in situ* and remotely sensed SST. The model is forced by six-hourly values of surface fluxes of heat, momentum and fresh water from the operational NWP model. FOAM output will be transmitted to the Navy's Fleet Weather and Oceanographic Centre at Northwood, for visualisation on the Horace workstation system (see *Horace* in the *Operational Services* section). This includes information on temperature, salinity and currents at all model levels, together with charts of mixed-layer depth and sea-ice concentration and thickness.

Assessments of FOAM and model development

Assessments of operational output have concentrated on parameters of interest to the Royal Navy. In particular the mixed-layer depth forecasts have been assessed to determine their strengths and weaknesses, and how they might be best used by Navy forecasters. Statistics of differences of FOAM fields from independent observations demonstrate that over much of the world's oceans, FOAM provides useful analyses (Fig. 79).

Other assessments have focused on understanding the growth of errors in the analyses and forecasts. Integrations have been performed assimilating no observations, observations only at the surface, observations at all depths and with different data sets of surface fluxes. Error growth is mainly due to inaccuracies or biases in the surface forcing fields and inadequacies in the model representation of the ocean. This is controlled in FOAM by the assimilation of observations.

Analysis has concentrated on model errors in the North Atlantic Ocean, where the flow across the continental slope is thought to have an important role in the steering of currents near the western boundary.

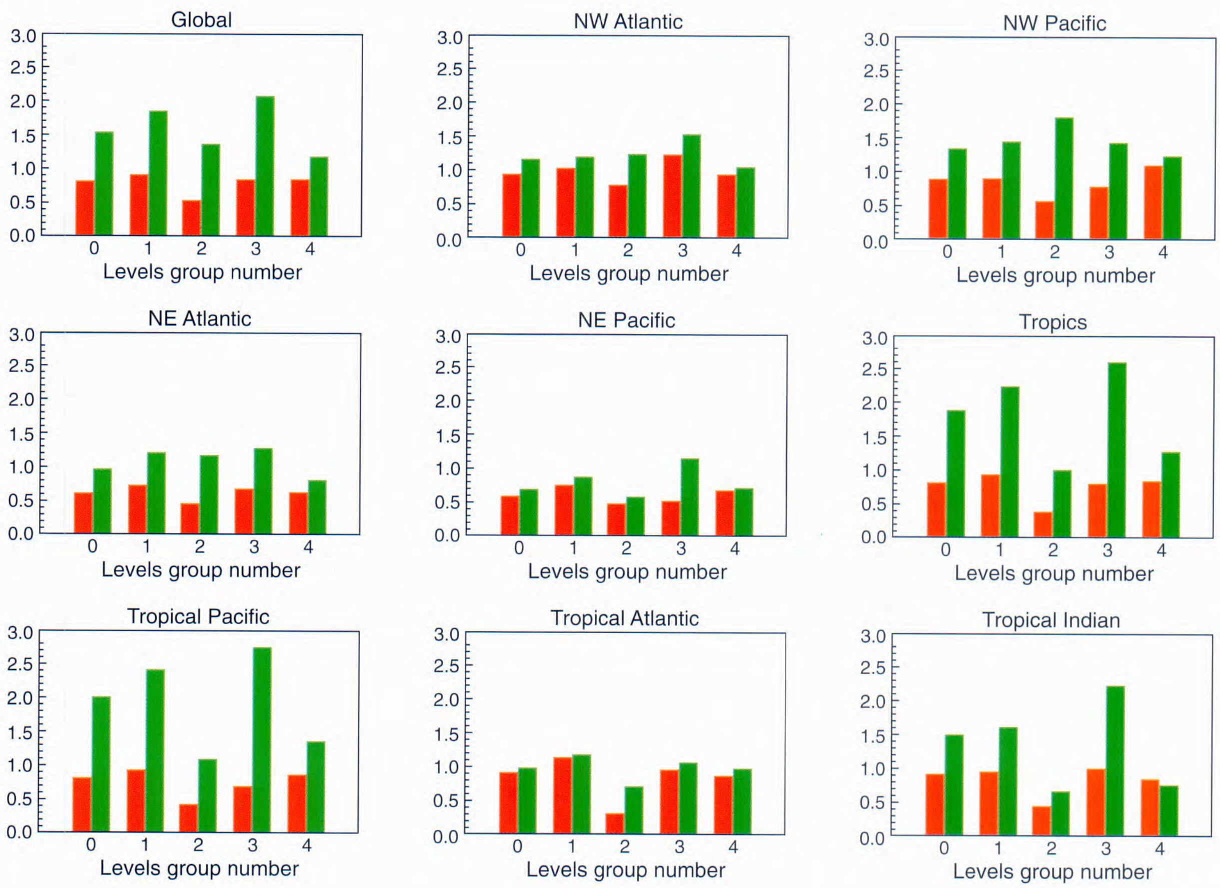


Figure 79. Comparison of observed temperature profiles with FOAM output (red) and climatology (green) for January 1998. The statistics of mean bias are grouped by oceanographic region, with data grouped by depth level for each area. Within each panel, Level zero shows statistics for the full depth range (0–4,000 m), Level 1 shows results for the 0–305 m depth, Level 2 shows the surface layer statistics, Levels 3 and 4 are for 34–68 m and 200–305 m depth.

The relationship between the flow over the stepped bathymetry of the model and the pressure torque on it has been investigated (Fig. 80). Some insight has been gained into the differences between the separation of the western boundary currents from the continental shelf in FOAM and simpler models, which appear to represent this better.

The velocity field used by the model is stored on a grid, staggered from the grid on which the tracers (temperature and salinity) are stored. The formulations for the velocities advecting the tracers and horizontal momentum then differ. These were found to be inconsistent near the bathymetric steps in the model and an improved formulation has been developed.

FOAM data assimilation system

The assimilation system has been extended to enable salinity observations as well as thermal observations to be used. The quality control and preparation for assimilation of ocean observations has been included in the new Observation Processing System for NWP. This will allow more-sophisticated quality control of observations to be introduced and reduce maintenance costs.

Future development

The Navy has a requirement for forecasts using models of about one tenth of a degree resolution capable of resolving the ocean's mesoscale phenomena. Accurate ocean surface height data from satellite altimeters which can resolve mesoscale eddies have recently become available within 2–3 days of real time. One third and one ninth of a degree models, for the Atlantic and part of the North Atlantic respectively, are therefore being developed for nesting within the global FOAM system. This will be the major area of development, together with coupling of shelf-seas models into high-resolution FOAM.

Assimilation of historical data

Apart from short-range ocean analysis and forecasting, FOAM can also be applied to seasonal forecasting and climate research. As a first step towards initialising coupled ocean–atmosphere

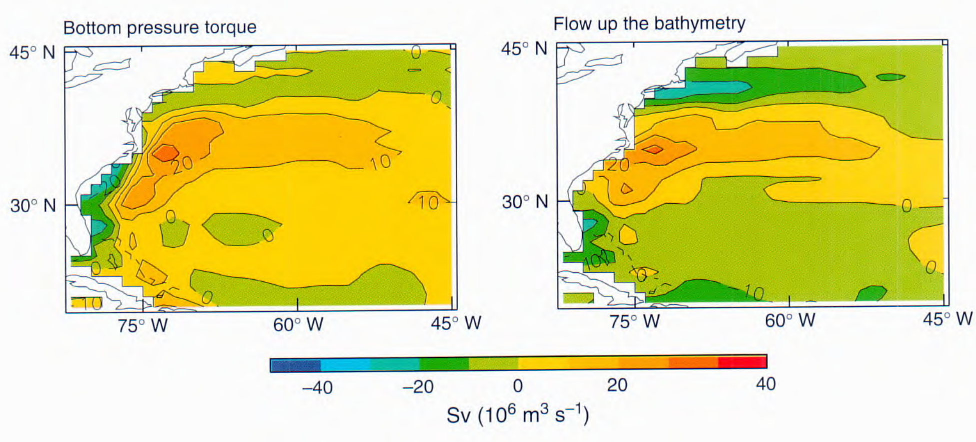


Figure 80. Contribution to the depth integrated flow driven by (left) the bottom pressure torque and (right) the flow up the bathymetry. In simpler diagnostic models the two contributions are identical.

models for experiments on decadal timescale predictability, a model run has been performed assimilating the full historical set of thermal profile observations. All observations taken on a particular day in the year were merged regardless of the year in which they were taken, consistent with the use of the historical data set in currently available ocean climatologies. The observations are found to provide strong constraints on the system's evolution. In the tropical region, however, the assimilation has been found to generate spurious overturning. This 'first ever' assimilation of the global data set of historical *in situ* observations into an ocean model is therefore also giving new insights into the working of the assimilation scheme. Strategies for other techniques of assimilation of data into ocean models are being studied with the University of Reading.

Shelf-seas modelling

Some numerical models are now available which allow simulations of the marginal shelf seas. One is the UK Operational Model (UKOPMOD) of the north-west European continental shelf which was developed by the Natural Environment Research Council's Proudman Oceanographic Laboratory (POL). The model is similar to that used by the Storm Tide Warning Service for storm surge forecasts, but allows prediction of the ocean current profile with depth as well as the sea-surface elevation. It was run daily in a real-time trial in which output was sent to potential customers who requested it between December 1996 and September 1997. This revealed the need for higher resolution, particularly near the coasts and for forecasts of current profile in deeper water, especially at the continental shelf break.

The feasibility of introducing near-coastal models is being investigated and, in a collaborative project with POL, a more complex numerical model is being introduced which includes the effects of density. As well as being able to predict the larger-scale variation in current speed and direction along the continental shelf slope, this model will also predict the temperature structure of the shelf seas, including the change in conditions from water masses which are well-mixed to those which are stratified.

Wave modelling

Operational wave models

Ocean Applications develops and maintains global and European area wave models, both of which run operationally as part of The Met. Office's NWP suite. The wave models have recently been implemented on the T3E supercomputer and they now run using wind data from the high-resolution global NWP model. However, these wave models are at a lower resolution than the high-resolution winds. A new high-resolution global wave model, which will include shallow water physics, is being developed at the same resolution as the NWP model.

Inshore wave modelling

The wave models predict the wave conditions at points offshore. To transform these into conditions at the beach, a further model needs to be applied, taking account of the influence of the shape of the sea bed. The SWAN (Simulating Waves Nearshore) spectral wave model is being set up to run using data from The Met. Office's operational regional wave model. The SWAN model, which was developed at TU Delft, and sponsored by the US Office of Naval Research, includes calculations of the relevant physical processes that affect waves as they approach the shoreline. During 1998 SWAN will be tested for several sites around the UK coast.

ERS-2 wave energy spectra

The synthetic aperture radar (SAR) on the ERS-2 satellite takes measurements of the sea-surface wave energy. To convert the measured values into a wave energy spectrum, a 'first-guess' spectrum from a wave model is needed, along with a complex set of algorithms. Programs developed by the Max Planck Institut für Meteorologie (Hamburg) have been adapted to retrieve spectra from the SAR observations using first-guess spectra from The Met. Office's operational global wave model.

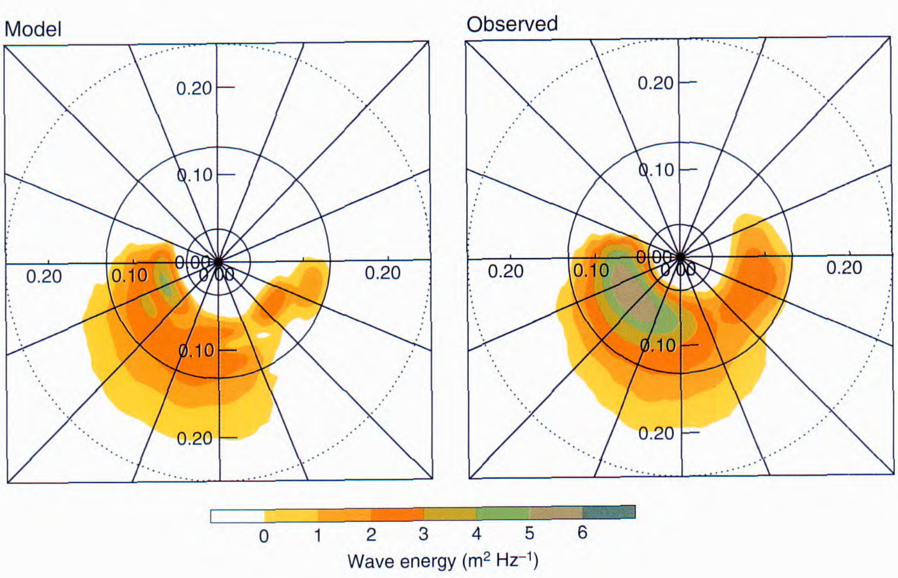


Figure 81. Modelled and observed wave energy spectra at 49° N, 9.25° W on 23 February 1998. Observed wave height is 2.15 m. The plots show contours of wave energy, with wave frequency increasing away from the centre. The waves are travelling in the direction of the ray from the central point.

SAR wave observations from ERS-2 are spaced approximately 200 km apart, along the track of the satellite. Figure 81 shows the model first-guess wave energy spectrum, and the retrieved SAR observed wave energy spectrum, for a point in the Irish Sea. The observations will be used both to assist in wave model development, and also, in real time, to assist with the forecasts of heave for the offshore operations west of Shetland.

Seasonal modelling and prediction

There is increasing evidence that for some regions and seasons, useful predictions of seasonal conditions can be made. This predictability is due mainly to SSTs, which change relatively slowly and can be predicted on a seasonal timescale. Predictions can made using dynamical physically based models using the observed SST at their lower boundary (see *Seasonal prediction* in the *Climate Research* section). Coupled models now allow the developments of the SST field, and in particular those associated with El Niño, to be interactively predicted.

El Niño

The most influential year-to-year SST changes occur in the tropical Pacific Ocean, and they can have an atmospheric effect that extends around the globe. There was a dramatic example in 1997/98, when east equatorial Pacific temperatures reached record levels in a major El Niño event, the impact of which had serious consequences for many nearby and distant regions.

A coupled model, consisting of a high-resolution tropical Pacific Ocean model and the climate version of The Met. Office's atmospheric model, is being used to make predictions of seasonal variability in the ocean and atmosphere up to two seasons ahead. Another version uses the tropical ocean model and a statistical relation between SST and surface winds to make predictions of Pacific Ocean conditions. Development of such models is a major part of international climate research programmes in which The Met. Office is participating. Examples are the European PROVOST (Prediction of Variability on Seasonal Timescales) project, and the World Climate Research Programme's Climate Variability (CLIVAR) project.

Tropical ocean model development

Improvements to the tropical ocean model are made and tested regularly, taking into account the developments to the global version. The equatorial upper-ocean structure is an important feature, as it relates to SST and to the internal equatorial waves that can travel long distances and influence seasonal ocean evolution. One recent modification was to increase the vertical resolution, using 36 instead of 16 levels. The rapid transition through the thermocline from warm near-surface water to cold deeper water was found to be represented more accurately by using more vertical points (Fig. 82). Errors in equatorial upper-ocean temperature are also reduced. However, this can also be achieved through a change in the representation of sub-gridscale mixing.

Ocean data assimilation

The accuracy of a coupled model seasonal prediction relies strongly on the initial ocean state. This can be estimated just by forcing the ocean model with observed atmospheric winds for several seasons up to the initial time required. A more accurate initial state can be obtained by using data assimilation to combine

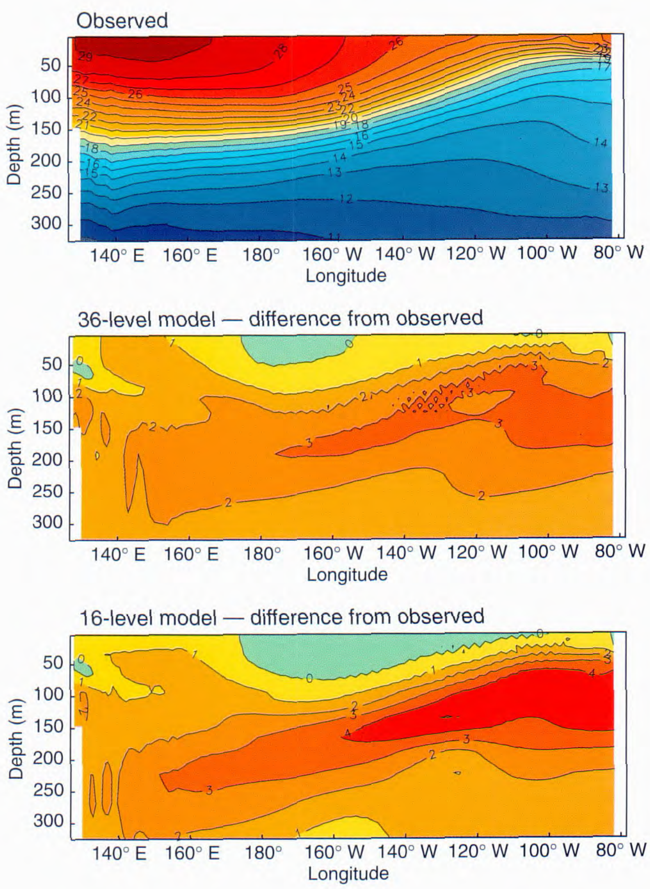


Figure 82. Average observed upper-ocean temperature in the equatorial Pacific Ocean (top), and difference from the 36-level (middle) and 16-level (bottom) ocean models.

the model with ocean observations. A version of FOAM is being used to assimilate ocean temperature and sea-level information into the Pacific Ocean coupled model.

Sea-level information is obtained by satellite altimeter measurements, which can provide high-resolution global information in near real time. The Met. Office is assessing the impact of such data on seasonal climate predictions as part of the European DUACS (Development of Use of Altimeter data for Climate Studies) project.

Statistical forecasts

Statistical methods have been used to make seasonal rainfall predictions in selected tropical regions for several years. The same methods were used previously to relate summer Central England Temperature to preceding winter SST anomalies in the North Atlantic. That relationship has been extended, and recent research has revealed a significant connection between winter SST and summer temperature and rainfall over much of western Europe.

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Acronyms

ACSOE	Atmospheric Chemistry in the Oceanic Environment
ADMS	Atmospheric Dispersion Modelling System
AMSU	Advanced Microwave Sounding Unit
APR	Atmospheric Processes Research
ARIES	Airborne Research Interferometer Evaluation System
ARIMA	Auto-regressive integrated moving average
ATD	Arrival time difference
AWS	Automatic weather station
BUFR	Binary Universal Form for Records
CAT	Clear air turbulence
CCTV	Closed-circuit television
CMETS	Computerised Meteorological System
CNES	Centre National d'Etudes Spatiales
COST	Co-operation in Science and Technology
CPU	Central Production Unit
CWINDE	COST Wind Initiative Network Demonstration
DARTH	Development of Advanced Radar Technology for application to Hydrometeorology
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DUACS	Development of Use of Altimeter data for Climate Studies
EEMS	Electromagnetic Environment Modelling System
EPS	EUMETSAT Polar System
ESA	European Space Agency
EUMETSAT	European organisation for the exploitation of meteorological satellites
EURICE	European research on aircraft ice certification
FASTEX	Fronts and Atlantic Storm Track Experiment
FOAM	Forecasting Ocean–Atmosphere Model
GALES	Global Agroclimate, Land-use, Elevation and Soils database
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-surface Flood forecasting
GIS	Geographic Information System
GISST	Global sea-Ice and Sea-Surface Temperature
GPS	Global Positioning System
GTS	Global Telecommunication System
HSB	Humidity Sounder for Brazil
IASI	Infrared Atmospheric Sounding Interferometer
IESSG	Institute of Engineering Surveying and Space Geodesy
INDOEX	Indian Ocean Experiment
IPCC	Intergovernmental Panel on Climate Change
ISDN	Integrated Services Digital Network
LAN	Local area network
METOP	Meteorological Operations Satellite

MHS	Microwave Humidity Sounder
MICOM	Miami Isopycnic Co-ordinate Model
MIDAS	Met. Office Integrated Data-Archiving System
MIST	Meteorological Information Self-briefing Terminal
MMS	Matra Marconi Space
MOLFAX	Met. Office Land-line Facsimile Network
MOMIDS	Met. Office Military Information Distribution System
MOSES	Met. Office Surface Exchanges Scheme
MSG	Meteosat Second Generation
MSU	Microwave Sounding Unit
MWR	Microwave Radiometer
NAME	Nuclear Accident Model
NAMIS	NATO Automated Meteorological Information System
NMC	National Meteorological Centre
NMS	National meteorological service
NOAA	National Oceanic and Atmospheric Administration (US)
NWP	Numerical weather prediction
PE	Processor element
POL	Proudman Oceanographic Laboratory (UK)
RDBMS	Relational database management system
RIEHW	Route-integrated equivalent headwinds
r.m.s.	Root-mean-square
SAM	Source Area Model
SAMOS	Semi-Automatic Meteorological Observing System
SAR	Synthetic aperture radar
SR	Synoptic Review
SSFM	*Site-Specific Forecast Model*
SSMI	Special Sensor Microwave Imager
SST	Sea-surface temperature
STOCHEM	A Lagrangian chemistry model
SWAN	Simulating Waves Nearshore
TACIA	Testing Atmospheric Chemistry in Anticyclones
TCP/IP	*Transmission Control Protocol/Internet Protocol*
TRIFFID	Top-down Representation of Interactive Foliage and Flora Including Dynamics
UM	Unified Model
VLF	Very low frequency
VMS	Voice mail service
WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe
WIN	Weather Information Network
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

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