



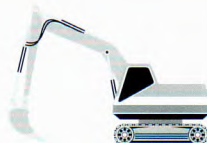
The Met.Office

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# SCIENTIFIC

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# TECHNICAL

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# REVIEW

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1994/95

## The Met. Office Charter Standard for the Public 1995/96

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

### Up-to-date weather information and forecasts

**We will provide weather information and forecasts through** radio and television, newspapers, telephone and facsimile services.

Our performance standards for forecast accuracy and customer satisfaction in 1995/96 are

to attain an accuracy of 84% for the 24-hour national forecasts broadcast at 1755 by BBC Radio 4 and to attain a satisfaction score of at least 80% for the general public forecasts on BBC Television and Radio 4.

Our achievements in 1994/95 were  
a forecast accuracy of 85%,  
a satisfaction score of 81%.

### Weather warnings

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

**We will also provide warnings of adverse road conditions** to the police, to local and national radio.

Our performance standard for these warning services is based on the satisfaction expressed by members of emergency organizations. This is measured in a survey conducted each year. In 1995/96 the standard is to attain a satisfaction score of at least 80%. Our achievement in 1994 was 79%.

**We will provide gale warnings and marine forecasts for radio.** Our performance standards for these marine services are based on targets set for the accuracy of gale warnings. In 1995/96 these are to attain a success rate of at least 81% with no more than 18% of false alarms for gale warnings issued 6-12 hours ahead for shipping.

Our achievements in 1994/95 were  
a success rate of 85%,  
a false alarm rate of 13%.

### Advice in emergencies

**We will provide** warnings of coastal flooding to the National Rivers Authority and the police.

Our performance standards are agreed with the Ministry of Agriculture, Fisheries and Food, the government department responsible for coastal flood protection and warning. Our targets are related to timeliness of issue, identification of major surges and the minimization of false alarms. All four targets were achieved in the eight months ending 30 April 1994 (few significant surges occur during the summer months). The most important target is to issue warnings to the National Rivers Authority and police forces concerned a minimum of 12 hours in advance of a major surge. There were two in the eight-month period, those of 14 November 1993 and 28 January 1994, and the target was achieved.

**We will provide** weather advice for the statutory authorities in environmental pollution emergencies.

These emergencies may arise, for example, from the accidental release of toxic chemicals into the atmosphere, and our response to them is given the highest priority. A performance target has been introduced for 1995/96 and is to provide specialised weather information within 30 minutes on at least 85% of occasions.

### Weather and climate information

**We will maintain** the National Meteorological Library and Archive at Bracknell which you may visit free of charge, and develop low-cost publications containing basic weather and climate information for schools and the general public.

We measure our performance by the high demand for our educational services. During 1994 over 7,000 enquiries were answered by our education section.

### Measuring how we are doing

#### Monitoring our forecasts

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

#### Public surveys

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

#### Performance targets

We have a number of performance targets in addition to those set out here. We review our targets each year and set standards for quality of service, accuracy and increases in efficiency. Further information on these targets, and our performance against them, may be found in our *Annual Report and Accounts*.

### Finding out more

**You can contact** your nearest weather centre, or the Enquiries Office at Bracknell.

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

#### Should you have a complaint

Please telephone the Enquiries Office or, better still, write in. We aim to respond to a complaint within five working days of its receipt, or at least provide you with an acknowledgement and an estimate of when a full reply may be expected.

RAISING THE STANDARD



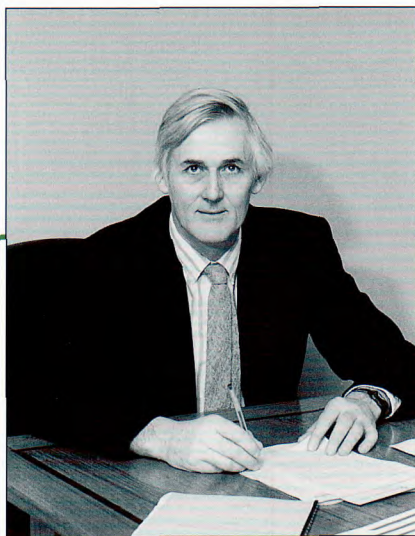




**The Met.Office**

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J.C.R. Hunt Chief Executive

## Chief Executive's Foreword

This year, our fourth as an Executive Agency, saw the organisation under review, as part of the Defence Costs Study. Its recommendations were accepted by the Ministry of Defence and HM Treasury. The first of the study's main conclusions was that The Met. Office should remain a world-class science-based organisation within the public sector. The second, that The Met. Office should change its administrative and financial framework to become a Trading Fund, is being implemented, with shadow Trading to start in mid-1995 in anticipation of full Trading Fund status from 1 April 1996. The first two stages in the implementation of these plans have been a change in the structure of our organisation — in order to improve the focus on our wide range of customers, as set out in our Framework Document — and the adoption of the commercial accounting system used by our sister agency, the Defence Evaluation and Research Agency.

Against this background of change, The Met. Office has achieved some outstanding results during 1994/95. The most notable of these is the significant improvement we have made in the accuracy of UK and worldwide forecasts from our numerical prediction model, resulting particularly from the close collaboration between our research and Central Forecasting teams. This, combined with recent progress in climate research, also produced marked improvements in climate simulation and prediction. While improvements in our day-to-day forecasting accuracy underpin much of our operational work, those associated with climate research further enhanced the scientific basis for the UK Government's presentation at the First Conference of the Parties of the UN Framework Convention on Climate Change held in Berlin in April 1995. We are also proud and pleased that Dr Paul Mason, our Chief Scientist, was elected to become a Fellow of the Royal Society.

Under its Director, Bernard Herdan, who has now left us to become Chief Executive of his own Agency, our Commercial Services (CS) Division had another



excellent year, achieving 8% revenue growth and making a highly valued £3.1m contribution to our core costs and general overheads. This result was achieved in the face of vigorous competition from the private sector. However, it is significant that some 44% of our CS revenue came through joint ventures with the private sector. The result confirms that the activities of our CS Division are definitely not subsidised by the Defence vote. The services provided to the UK and UN Defence forces have been further developed, with specialised numerical forecasts and tactical forecasting advice provided by our staff working alongside the Servicemen on location around the world.

We have met four of the six key Business Plan targets, narrowly missing the other two. We met the essential cash limit key target by delivering our agreed programme of activities within budget. This was achieved partly through the introduction of efficiency measures in most Departments and partly through the successful introduction of a programme of voluntary early retirement. This latter initiative has allowed us to reduce overall staff numbers by 151 over the year, yielding considerable cost-savings, equivalent to some £4m in a full year.

Work has continued to develop a new pay scheme based on the value of individual jobs and a reduction in the number of staff grades. While progress has been slower than originally planned, the new scheme is expected to be in operation from 1 November 1995. There have also been productive negotiations about increases in pay, and about certain reductions in the number and value of pay-related allowances. After some hard bargaining, and goodwill from all parties, agreement was reached. We expect the same robust but realistic relations to continue as we progress to Trading Fund.

From its inception in 1854, The Met. Office has made a vital contribution to the safety of the nation — the theme of the World Meteorological Day on 23 March 1995. In more recent years, the economic

benefits of meteorological services have also become increasingly valued here and throughout the whole world. These economic benefits were highlighted at a World Meteorological Organization (WMO) conference held in Geneva in September 1994 — just one of the many WMO programmes to which our staff made significant contributions. Other contributions have included the work on new methods and protocols for international warnings of meteorological and other natural disasters, and on a new co-ordination framework for the Inter-Agency World Climate Programme.

Our international focus is not just confined to WMO. Every year, more of our operational and research projects depend on collaboration with international partners. In the last year, collaboration with other European National Meteorological Services culminated in the approval in principle by the European Commission of the ECOMET scheme for a concerted approach to the provision of service, data and products in Europe. We also made progress in forming EUMETNET, a co-ordination framework for optional programmes designed to improve and to economise on the European-wide meteorological infrastructure. In the forum of the International Civil Aviation Organization (ICAO), Met. Office staff were heavily involved with the organisation and implementation of the SADIS (Satellite Distribution System) programme, particularly in Africa.

The speed and number of the changes we have faced during 1994/95 have made this a difficult year for all of us. Further changes and challenges are inevitable as we make the transition to Trading Fund. I am delighted at the progress we have already made and I am grateful to my staff for their loyalty and commitment; I am confident that they will rise to the challenges of new technical and financial responsibilities. I also feel sure that they will participate fully in developing the new organisation and will press on with the exciting advances we are making in all aspects of meteorology.



## Observing

### The objectives of observing

The objectives of observing the weather are to provide an adequate description of the present state of the atmosphere and its interfaces to the land and sea for three purposes:

- to provide input to numerical weather prediction (NWP), other automated methods of forecasting (e.g. FRONTIERS) and to manual forecast systems (the last being largely confined to the forecasting of local weather and the first having a global dimension);
- to monitor the weather specially to advise customers of hazardous conditions or major local changes in weather pertinent to their business, and for the purposes of examining the accuracy and adequacy of forecasts;
- to determine the variability of climate in space and time for a variety of commercial applications, to determine 'climate change', its impact and associated response strategies, and as a backcloth to decision making on sustainable development.

### UK data requirements

Relatively dense networks of local observations provide inputs for local, short-period forecasting and monitoring (for example as applied to aircraft take off and landing) and for determining variations in local climate. The data sources include *in situ* measurements of a wide range of variables such as cloud base, visibility, wind, temperature and pressure. There is also surface-based remote sensing (for example of rainfall by weather radar), atmospheric soundings, and products such as high-resolution visible, infrared, and water vapour imagery from polar-orbiting and geostationary satellites. By and large the data from these systems are complementary.

In order to predict the United Kingdom's weather in the medium term, i.e. 2–3 days ahead, it is also essential to secure an adequate supply of data from Europe and the North Atlantic, the latter being an area with very sparse data. For the North Atlantic, collaborative arrangements exist with our European and North American partners, and through the WMO and ICAO, to secure information from merchant shipping, a weather ship, drifting and fixed ocean buoys, oil rigs and platforms, satellites and aircraft.

The Office requires information from subsets of stations and observing platforms from all over the World for NWP, in return it provides a subset of the United Kingdom data through the Global Telecommunication System (GTS) of WMO and satellite communications systems. Technical Commissions of WMO keep under routine review, and regulate, the data requirements, including the spatial density of observations, the desired variables and frequency of measurement, data resolution and accuracy. The total set of data needed for NWP is the major element of WMO's World Weather Watch (WWW).

Much recent effort has been aimed at defining the characteristics of the observing networks and systems needed to monitor global climate (the Global Climate Observing System — GCOS) and documentation defining the space, terrestrial, atmospheric, oceanographic, hydrological and ecological components will soon be presented to the WMO and other UN Agencies.

### The approach to meeting the requirements

The 'customers' for observations are at present mostly internal (e.g. the NWP models, the outfield forecasters, researchers on climate change) and other National Meteorological Services; we are, however, engaged in a much wider review of the external customer base for all kinds of observational data and the organization necessary to supply them and provide value for money.



The activities needed to meet the customer requirements can be subdivided into those which sustain the Office's ability to act as intelligent specifier and/or purchaser of networks, systems, sensors, or data, and those related to the internal supply of a robust, high-quality data stream. The former include the accurate specification of user needs, including objective assessment of impacts of data of different characteristics on model forecasts, the translation of these into functional and technical specifications, and the trial and testing of industry-supplied products against those specifications. A very limited amount of prototype development and investigation of hardware and software is undertaken in order to advance our knowledge and to influence industrial capability in the light of ever more-demanding customer requirements.

The supply activities include the making of observations, calibration, installation and maintenance of equipment (much of it 'state-of-the-art'), inspections, quality monitoring and quality control of data, archiving of data for climatological use, and various remedial actions based in the quality evaluation. There are now only 13 manned stations which are dedicated, or mostly so, to the supply of information for core NWP (proposes).

The calibration or characterization of space-based systems demands not only a thorough conceptual and scientific knowledge of the instruments but also of their response to atmospheric constituents, thermodynamic and radiative properties. Other supply activities are becoming increasingly subject to open competition with outside industry through the Government's Market Testing initiative. Indeed much of the data from the UK land area, and nearly all from the oceanic environment, are supplied from private or company sources.

## Recent developments

### Land-based observations

#### Automation

On its own territory, the United Kingdom operates 30 key land stations manned by professional observers

reporting throughout the 24-hour period every day, and these data are contributed to the WWW in accordance with our international agreements. For regional forecasting within the UK and surrounding waters, the Office maintains a secondary network of 213 additional land stations and 39 offshore sites. Many of these are operated by auxiliary observers such as coastguards, oil-rig staff, power station personnel and private individuals; many are automated and about a quarter of the observations are provided by office personnel engaged primarily on other work.

It is not necessary, or cost-effective, to man secondary sites throughout the 24-hour period and an ongoing programme of automation has been introduced. The first generation of Semi-Automatic Meteorological Observing System (SAMOS 1) provides automatic measurements of all parameters except cloud, visibility, and present weather, so staff need not be present if these are not needed. A further 17 sites have received SAMOS 1 this year, bringing the total in the field to 61. Inevitably there are remote areas where it is impossible to obtain manual observations for even part of the day. The network of synoptic automatic weather stations (SAWS) was introduced to meet the requirement for data from such areas and was completed this year. Forty-three sites are now operational providing a range of parameters including radiation and soil temperatures.

A programme to equip SAWS with visimeters to provide automatic measurements of visibility has begun; 14 sites have been fitted so far. Trials have also been conducted of a Laser Cloud-Base Recorder (LCBR) connected to both SAMOS and SAWS. An exponential decay algorithm has been developed to provide observations of both cloud amount and height. A major milestone was achieved with the installation of LCBRs on three SAWS in Northern Ireland and local forecasters are very pleased with the data received. The algorithm still requires some development, and further trials will be conducted to establish clearly the behaviour of the instrumentation under a full range of weather conditions. There are 35 LCBRs and visimeters currently installed as stand-alone aids to observers.



These will be integrated with SAMOS equipment where this is available, and most of the fully automated sites will receive LCBRs and visimeters in the next two years. The final result will be an adequate network of automatic and semi-automatic sites providing a much better geographical coverage of observations between the key sites than we have ever had before. Trials of CCTV systems capable of showing present weather at remote locations are about to start, and following a comprehensive trial of candidate wind sensors, we have started to replace ageing and expensive operational systems with new technology capable of the low-speed measurements required for fog forecasting.

A new generation of semi-automated equipment has been developed (SAMOS 2) which is configured as a series of independent ('intelligent') sensor modules connected together. The design allows expansion to accommodate new sensors, it is easy to install and maintain, and it is readily upgraded to take advantage of new technology. The Irish Meteorological Service has ordered six CAMOS (Computer Aided Meteorological Observing Systems), the commercial variant of SAMOS, from the manufacturer, AGI Ltd.

When automated systems become important, it is essential to monitor their performance and rectify errors quickly. Forecasters react quickly to straightforward failures of equipment, but a slow drift of calibration can easily go unnoticed. A comprehensive suite of software is used to perform a routine quality evaluation exercise carried out 24 hours in arrears. If this identifies problems they are passed to the maintenance organization for rectification. Monthly summary statistics are also produced to allow efficient long-term management of the networks.

#### **Upper-air measurements**

In addition to the surface observing network, there are eight upper-air sites making soundings four times a day. The introduction of LORAN windfinding and more-flexible working practices has allowed most of these sites to be single-manned for much of the time; the last two sites changed to this system at the end of 1994. It is essential that costs are kept as low as possible, so the work at the upper-air sites has been diversified.

Seven of the eight sites are also key stations in the surface observing network. Amongst their other duties are trials of surface and upper-air equipment, and the provision of services to general and military aviation; they also make a range of measurements for other programmes, such as ozone, ultraviolet radiation, precipitation chemistry, pollution and seismic activity (for NERC).

A joint experiment with the Forecasting Research Division was set up to investigate whether extra radiosonde ascents would improve forecasts on occasions of 'trough extension'. When a likely case was identified, radiosonde sites made three-hourly ascents. However, it was established that the extra data did not make an identifiable impact. The next phase of the experiment involves use of dropsondes from the MRF C-130 aircraft. Because a new type of dropsonde is being used, the radiosonde site at Stornoway is assisting with initial trials by making extra ascents during overflights by the C-130.

Upper-air information on winds and temperatures is also obtained from civil airlines along with reports of turbulence, and automated reporting and distribution procedures will increase the volume of data available over the next few years; this will be especially useful for regional and local forecasting. For several years now the Office, with international partners, has supported the Aircraft to Satellite Data Relay (ASDAR) programme. In this, the processes of on-board data acquisition, processing and relay via meteorological satellites are done automatically. The system is installed on 15 aircraft flying over areas from which data is otherwise very sparse; contracts have been agreed for four further installations in 1995. (See also ref B page 25.)

Dobson spectrophotometers are used to make routine measurements of total ozone at Camborne and Lerwick, together with ozone sondes at the latter. During the Arctic ozone depletion period from January to March, the data have been used in the origination of weekly ozone bulletins on behalf of the Department of the Environment. In September 1994 the Camborne site hosted a group of 23 scientists from 7 European countries taking part in an international intercomparison of UV visible spectrometers, sponsored



by the CEC and lasting for 2 weeks. Both the organizers, Aberystwyth University College of Wales, and the participants expressed their satisfaction with the facilities and co-operation from local staff. The normal radiosonde programme was maintained throughout and a series of ozone sondes was also flown. At the end of the year, with the addition of one post funded by a consortium of interested departments outside The Met. Office, Hillsborough radiosonde station took over all inspection and maintenance of the climate and rainfall networks in Northern Ireland.

### The future

Considerable effort is being put into identifying future upper-air sounding systems to meet our needs. It is expected that the Omega navigation system will be unavailable for wind finding in two or three years time, so a replacement system will be needed for the three overseas sites operated by the Office. We also need alternative sources of LORAN-based radiosondes. GPS and LORAN sondes from several manufacturers have been tested as a joint exercise and a radiotheodolite evaluated. PC-based software is available to intercompare the performance of sondes flown on multi-rigs within 30 minutes of the end of the flight. It was developed by S. Kurnosenko of the Central Aerological Observatory, Russia, while working in the Observations Division under the auspices of the visiting scientist programme. This same software has been used extensively during the WMO-sponsored international radiosonde intercomparisons. Met. Office staff have made a major contribution to these intercomparisons and will be involved in the next phase of intercomparison of humidity sensors. The skill of the trials staff in analysing and evaluating upper-air data was recognized in a request to carry out the analysis of trial data from the new army battlefield radiosonde system BMETS.

Much work has been devoted to collaborative work involving wind profiler radars to help to develop observing strategy over the next 10–15 years. Part of this effort has been the making of collocated radiosonde and wind profiler measurements up to a height of 20 km with the Aberystwyth MST radar (which

operates on a frequency of 46.5 MHz). This work included a period of intense activity in which 53 radiosondes were launched in 5 days; a preliminary analysis indicated systematic differences in wind speed of order  $1 \text{ m s}^{-1}$ . The data are routinely made available to forecasters in the Central Forecasting Office in real time and are considered to be useful. In a collaborative project with the manufacturer, a UHF Wind Profiler (915 MHz) was installed at the Aberystwyth site and operated in February and March to evaluate errors in wind measurement in general, and particularly in rain. A typical cross-section through a cold front is shown in Fig. 1. This cross-section shows good data up to altitudes of between 4 and 6 km although there are some spurious values due to weak echoes, and clutter gives some problems below 300 to 400 metres. The latter is site specific and was reduced by a revision of the anti-clutter software. However, it is clear that these instruments do have to be carefully sited.

Further work on the development of the weather radar network has been coordinated through a joint Working Group of The Met. Office and the National Rivers Authority. A new statement of requirement has been generated looking 10–15 years ahead which disaggregates the 'core' needs of each organization, the additional needs of the Water PLCs, of commercial interests and of research users. Technical options and costings for meeting the requirements are now being determined, covering the net-work structure, improved temporal and spatial resolution, and new products such as hail and snow indicators and wind fields within precipitation areas. The present radar sites continued to produce output which meet various availability targets, and considerable work was undertaken to improve accuracy, e.g. through intercomparisons with the DRAL Chilbolton radar. Good progress has been made towards the full automation of the thunderstorm detection system which is based on the Arrival Time Difference between the electromagnetic signatures of a storm at different receiving stations. (See also ref C, page 25.)

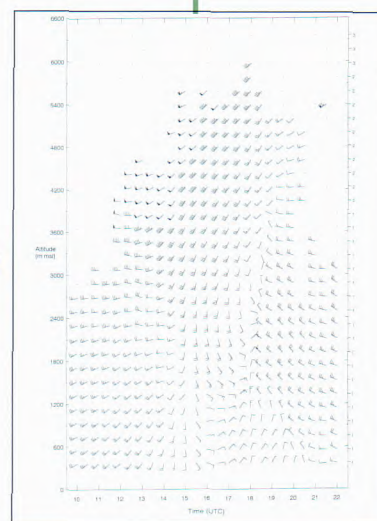


Fig. 1. Cross-section through a cold front from a UHF profiler.



The United Kingdom climatological network has been maintained at 509 sites with 19 automatic climate data loggers and the rainfall network has been reduced by 21 sites to a total of 4022. Work has continued on development and implementation of a new climate data bank and associated quality control programs.

### Marine observing

In addition to the offshore sites referred to earlier, the Office operates (in some cases in partnership with other NMSs) marine networks comprising one Ocean Weather Ship, eight instrumented fixed ocean buoys, twenty drifting buoys, and supports a large fleet of merchant ships which volunteer to make observations *en route*. An agreement was concluded with the French Meteorological Service to jointly establish another fixed buoy in the Bay of Biscay. The buoy is at Devonport waiting for a suitable vessel to deploy it.

Voluntary observers on merchant ships transmitted essential weather data from the vastness of the oceans which cover over 70% of the Earth's surface. 550 ships are enrolled in the UK Voluntary Observing Fleet; the overall WMO fleet comprises 7300 observing ships. Over 30 ships are now fitted with MOSS (Met. Office Observing System for Ships) which helps the observer to enter the readings into a database and subsequently transmits of the coded groups automatically. Logbooks from the fleet are kept by the Office for climatological purposes. The Office has become one of two Global Collecting Centres for marine climate data, undertaking to collect and quality control data from all ships worldwide before storage in computer archives.

Ocean Weather Ship *Cumulus* maintained her schedule of deployments for North Atlantic observing. Initially this was at station 'Lima' in position 57° N, 20° W, 500 miles west of Scotland, but later in the year she was deployed farther south, to a position west of southern Ireland in the same longitude, whence she was expected to provide meteorological data of more use. The weather ship continued to make hourly surface and six-hourly upper-air observations, which were transmitted to Bracknell from the ship via

Meteosat. *Cumulus* also maintained many additional regular scientific activities for various institutions. These included plankton sampling, the measurement of sea temperatures and salinity at various depths, and observations of natural life in the sea and in the air. The ship made special visits to Reykjavik, Iceland, on two occasions to deliver drifting weather buoys for later deployment by the Iceland Met. Service as part of an international programme.

An unusual variation to the new position of deployment took place in April 1994, when *Cumulus* operated at 47° N, 20° W to take part in a ten-day exercise with the US NASA Shuttle Planet Earth Mission, making intercomparisons between shuttle- and ship-measured sea wave data.

Observations from the Royal Sovereign Light Tower, formerly used in the station reports included in BBC Radio 4 shipping bulletins, were suspended on the demanning of the station by the Corporation of Trinity House. They were replaced by a new Automatic Weather Station on the Greenwich Light Vessel, situated in the English Channel shipping lanes south of Newhaven.

### Space-based observing

Observations from space are an important ingredient in the mix of observations assimilated into numerical weather prediction models; cloud and water vapour imagery also assists forecasters in the analysis of synoptic and smaller-scale features, especially over large regions of the world where there are few other data.

The Office's activities include the conceptual design of space instrumentation, representation on international bodies dealing with space technology, characterization and calibration of space instruments (increasingly on a fully commercial basis), and the development of methods for the conversion of basic satellite measurements (radiances) into meteorological information. On behalf of the UK Government the Office also handles the subscriptions to the European Meteorological Satellite organization (EUMETSAT) to



support the European operational missions. Bipartite arrangements exist between the UK and NOAA in which some instrumentation has been provided for US polar orbiters in return for a real-time access to a wide range of their instrumental data and products. This last year has also seen a strong involvement of the Office in the generation of the plans for securing space data for climatological monitoring.

#### European satellites

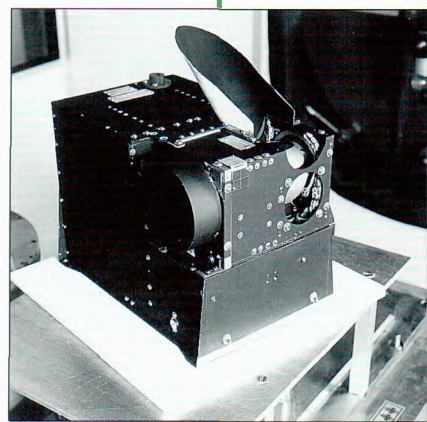
EUMETSAT operates Meteosat, a geostationary satellite with a field of view that contains most of Europe, all of Africa, the Middle East, part of South America and surrounding seas and oceans. The programme of Meteosat launches is planned to continue as far as 2012. The last three, from 2001, will be Meteosat Second Generation (MSG) carrying advanced instruments. Throughout the year EUMETSAT, in co-operation with ESA, has been developing its plans for a European Polar System (EPS) Programme due to be approved in 1995. The EPS Programme is expected to provide and operate polar-orbiting systems to take over the morning orbit from NOAA for about 15 years from a first launch in 2001, but proposals are presently being revised due to the decision of the US Government to rationalise its civil and military programmes. The satellite system will be developed by ESA under the METOP Programme, subject to approval. METOP satellites will have the capability to provide high-resolution imagery and vertical soundings of temperature and humidity using visible, infrared and microwave instruments and, eventually, improved soundings using higher spectral resolution interferometric instruments. The Meteorological Office continued to make significant technical user inputs to both the Meteosat and EPS programmes through membership of expert groups and directly through studies of instrumental performance trade-offs. Data-compression concepts were clarified for the MSG, leading to a decision to distribute compressed data for all channels on the high-resolution imagery. Two significant operational changes will be introduced by EUMETSAT in 1995. Firstly, the Meteosat satellites, of which three may be operational at any time, will be controlled and operated by EUMETSAT from new facilities in

Darmstadt, beginning in December. Secondly, high-resolution images from Meteosat will be encrypted, with the exception of a basic set; a licensing system for decryption equipment will be applied to track use of the data, and will allow charges to be introduced for some users.

#### Satellite sounders

The Development Model Stratospheric Sounding Unit (SSU), refurbished by the Remote Sensing Instrumentation (RSI) Branch of The Met. Office, was launched into orbit on NOAA-J (14) on 30 December 1994. It has continued to operate satisfactorily since switch-on on New Year's eve. Studies were performed to evaluate its performance and detailed comparisons with the SSU on NOAA-11 were begun and are continuing to support the maintenance of the climatologically significant record of stratospheric radiances started with the first SSU on TIROS N in 1978.

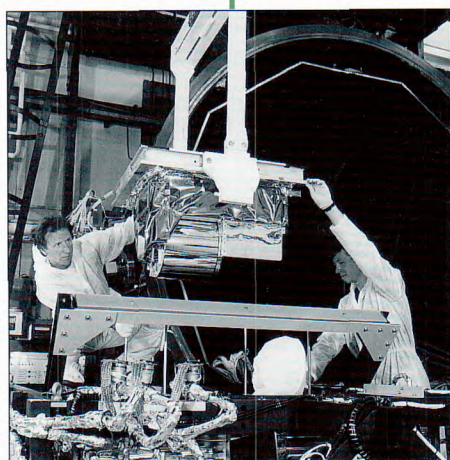
The Advanced Microwave Sounding Unit (AMSU-B) is a five-channel passive microwave sounder which will provide improved humidity profiles in the troposphere and also assist in the quality control of the temperature sounder (AMSU-A) data. The UK Met. Office has procured the AMSU-B flight models as its contribution to the new series of NOAA polar-orbiting satellites. The AMSU-B Proto-Flight Model F1 was integrated on the spacecraft NOAA-K during the last week of April 1994. Performance tests have been concluded and spacecraft level environmental tests will shortly begin. The satellite is due for launch in January 1996. Photographs of the SSU and AMSU-B are in Figs 2 and 3. A programme of comprehensive tests in a vacuum chamber, to simulate the space environment, was completed on all three AMSU-B flight models by December 1994. These tests were designed to fully characterize the behaviour of the instruments once they are in orbit. As an example, one simple measurement made was of the noise level in each of the five channels for the three instruments. The results show



*Fig. 2. The development model stratospheric sounding unit.*



that all the instruments had noise levels within the required limit. AMSU-B Flight Models F2 and F3 are now subject to long-term trend testing before launch call-up by NASA in July 1996 and November 1997.



*Fig. 3. Installation of AMSU-B into test rig prior to space simulation testing in vacuum chamber.*

The expertise and facilities developed for these vital calibration activities was utilised in additional collaborative and commercial work. NASA and The Met. Office collaborated using the Farnborough facilities to characterise the Microwave Imaging Radiometer, MIR, which is operated on the NASA ER-2 high-altitude research aircraft. A contract to calibrate the on-board target for the Microwave Humidity Sounder was completed for Matra Marconi and one was begun to characterise hardware developed for the Multispectral Imaging Microwave Radiometer (MIMR).

#### **Instrumental and modelling studies (Ref A)**

Fast radiative transfer models have been developed to improve the exploitation of data in NWP models from the current and future satellite sounders. The NWP fields are used to compute sounder radiances and these are compared with the corresponding measured radiances and the differences are used to update the NWP model's initial state. This work has allowed the results from the current 'state-of-the-art' atmospheric absorption models, such as new theoretical treatments and improved knowledge of the relevant spectroscopy, to be taken into account. This approach has allowed the parallel development of simulations for the new AMSU microwave channels and a microwave sea-surface emissivity model. The former is in preparation for ATOVS and the latter for use operationally with the fast model to improve the simulations for the microwave sounder channels.

The airborne microwave radiometer was used to measure emission from stratocumulus cloud

modified by pollution from ships. (See also ref E page 31.) The opportunity was also taken to underfly an American military satellite (DMSP) which has advanced microwave, visible and infrared instruments to compare in situ measured cloud parameters with the corresponding satellite retrieved values. To enable the utilisation of microwave sounder data over land and sea-ice, preparations are under way for a programme of surface emissivity measurements. This will be carried out using two airborne microwave radiometers on the C-130 aircraft which cover the frequency range from 24–157 GHz. It is hoped these measurements will be made during 1995/6, with the sea-ice/snow measurements being collected as part of an ESA-sponsored campaign called MACSI over northern Finland and the Gulf of Bothnia.

Instrumental and modelling studies for the proposed new generations of very high spectral resolution infrared temperature/humidity sounders (e.g. IASI) are under way. The Airborne Research Interferometer Evaluation System (ARIES) was received in March 1995 for testing. When the instrument is accepted it will be mounted in a pod on the wing of the C-130 to view both up and down at many different levels in the atmosphere. This will allow measurements at high spectral resolution throughout the troposphere to validate the models under development, and demonstrate with real data the capability for improved vertical resolution in the soundings. Recommendations have been made on the design of IASI following a study to determine what the optimal spectral resolution is for NWP temperature/humidity sounding. Some of the modelling work is being carried out in collaboration with Imperial College.

The final report of the UK Cloud Radar Feasibility study has been completed. This highlights the feasibility of a spaceborne Doppler radar capable of deriving winds from cloud echoes, with the potential for significant benefit to Numerical Weather Prediction. A brochure on cloud radar has now been produced by ESA/ESTEC. (See also ref F page 33)



## Computing and telecommunications

### Information systems

The principal business of The Met. Office is to gather information, mainly observational data, add value by generating weather forecasts and other weather-related products, and then deliver services to customers. Speed is of the essence to ensure that perishable weather forecasts are delivered in a timely fashion. Information Technology has a mission-critical role to play in the transmission of observational data, in numerical weather prediction, in the organization and presentation of information, and in the delivery of customer services.

This production system uses more than 90% of The Met. Office's resources devoted to information systems. The balance is applied to support the running of the business in areas such as finance, accounting, personnel management, management information and administrative systems.

Information Technology is also an important tool used to improve the efficiency and effectiveness of business processes, whether previously automated or not. Industry continues to offer rapid improvement in the price/performance of IT Systems. These improvements continually offer new opportunities to expand and improve customer services while reducing overall costs.

### The Information Technology (IT) infrastructure

The IT Infrastructure has been composed of two main, and separate, components for over 30 years, namely central computing and telecommunications. During the year the operations sections of both areas have been brought together into a single working unit. A significant improvement in efficiency has been achieved because the rationalisation allowed overlapping functions to be eliminated, so saving staff without any loss of service. Two other areas

which made intensive use of staff effort have also been re-examined. These areas were concerned with data monitoring and manual handling of various messages; revised manning levels have made a further significant improvement to efficiency. In combination, the reduction in input costs stemming from the above measures has met the target of improving efficiency by 2.78%.

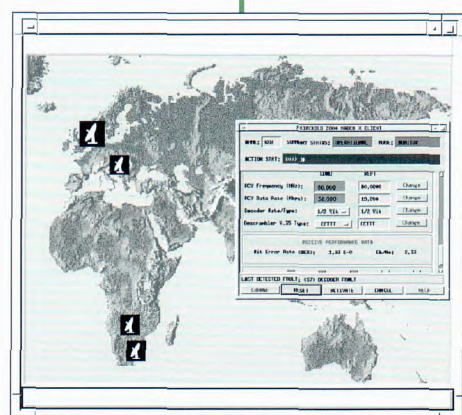
Following on from the successful merger of the operations sections, the supporting areas were reorganised into branches providing systems support and user services. Some savings arose from this process and the posts freed were used to form a small Information Systems Strategy and Consultancy Group. This group is critical to the development of coherent strategy and policy (underpinned by appropriate internal standards) for matching information systems and technology to business aims affecting The Met. Office as a whole.

### Satellite distribution of aviation products (SADIS)

SADIS is a communications system designed to meet the needs of ICAO high-integrity WAFS meteorological data. The service provides WAFS London products over an area which extends from the eastern Atlantic to central Australia. At the end of the year the system had been set up and was in final testing. (See also ref G page 13.)



*Fig. 4. The Cray Y-MP C90/16256 is used for numerical weather prediction, the climate prediction programme (under contract to the Department of the Environment) and research.*



*Fig. 5. Satellite distribution of aviation products – the network manager being tested.*



## Weather Information Network (WIN)

The WIN will replace a number of analogue and digital networks with a single, resilient, high-speed digital network. This network will provide facilities for the collection of observations, transfer of data between the Met. Office HQ, Weather Centres and forecast offices, and also play a role in delivery to customers. Early in 1995 a short list of three potential bidders was agreed and discussions and demonstrations are now taking place. The new network, which will use the Defence Packet Switched Network as main bearer wherever possible, is to be completed in 1996. Substantial savings are expected to result from network rationalisation and the replacement of obsolete equipment which is expensive to support and uses costly consumables.

## Administrative systems

The systems set up to support financial and accounting operations for The Met. Office as an Agency were not sufficient to meet the requirements of a Trading Fund. Arrangements have been made with DRA to use their accounting system as the heart of The Met. Office's system. The system is to operate from the 'shadow' trading year, starting in April 1995.

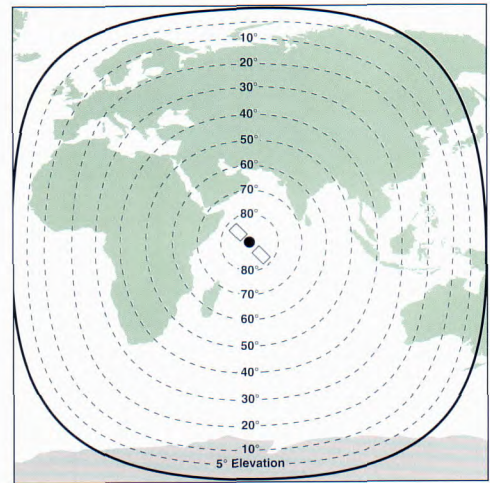


Fig. 6. SADIS coverage area, showing receiver aerial elevation.

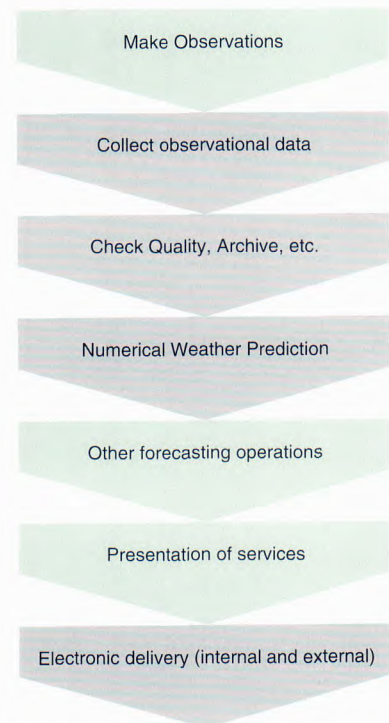


Fig. 7. From observation to customer service. Information Technology is critical to success in the highlighted areas.



## Central Forecasting

### Improvements to the operational Numerical Weather Prediction (NWP) system

Several changes have been made to the operational NWP system, extending both the range and quality of its products. The UK Mesoscale model configuration was expanded into a continuous cycle of data assimilation with four forecast runs per day. A new configuration of the global model, to produce analyses (and forecasts) for the stratosphere was implemented in November. In October, a new tropical cyclone bogusing scheme was introduced operationally, the results of which have been extremely well received by all users — it reduces the errors of predicted track movement of such features by around 25% at all forecast times. In January, the European Wave Model predictions were extended to run out to five days ahead of analysis time.

The scientific formulation of the Unified Model has been improved yielding very significant gains in the quality of operational forecasts. The most significant changes were to the representations of gravity-wave drag and orographic roughness which were introduced operationally in January into both the global model and the limited area model (LAM). (See also ref L page 26.)

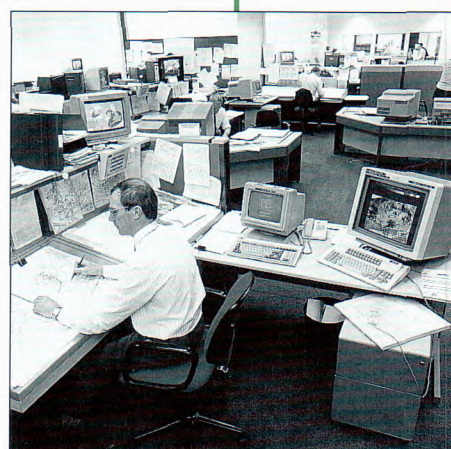
These changes in formulation of the model have led to very satisfying improvements in the operational performance of the NWP system. The target for the twelve-month period had been set as a 2% reduction in the average root-mean-square errors for the 48-hour forecasts over the North Atlantic and north-west Europe — to no more than 3.5 hPa (hectopascal) for surface pressure, and 3.2 dam (decametre) for 500 hPa height fields. These targets were surpassed. The 12-month running mean values at the end of the year were 3.32 hPa and 3.06 dam respectively.

### Progress with the Satellite Distribution System (SADIS) and Meteorological Data Distribution (MDD) (Ref G)

SADIS is a satellite-based system for the dissemination of aeronautical data on a global beam of an INTELSAT (International Telecommunications Satellite system) satellite. Good progress has been made towards getting it operational. Satellite uplink equipment was installed at Whitehill (near Oxford) in February, ready for space segment testing with the INTELSAT, and two VSATs (Very Small Aperture Terminals) were erected on the site to receive signals passed back from the satellite to test the full system. Two high-speed lines connect Whitehill to The Met. Office in Bracknell; these are used for the transmission of products to and from the uplink connecting the customers directly to WAFC London. The VSAT equipment for a trial of the operational system was dispatched to the four States involved following the successful commissioning of the uplink hub. It is expected that SADIS will be operational early summer 1995.

Over 100 new WAFS charts have been introduced into the operational NWP suite in anticipation of the operational introduction of SADIS; these are for three extra areas covering the Pacific, eastern Asia and the north and south Indian Ocean.

The MDD system is a more established form of satellite-based dissemination, aimed at the meteorological, rather than the aviation community. This system was also enhanced with a new uplink installed by Météo-France in Toulouse. This led to the routine additional dissemination of some 156 charts, about 100 are added by the Office.



*Fig. 8. The Central Forecasting Office.*



## Production of semi-automated Significant Weather (SIGWX) charts

This project aims to produce civil aviation Significant Weather charts for the whole globe using a semi-automated, work-station-based technique. Graphical editing is performed by a forecaster using the workstation, allowing maximum use to be made of 'first guess' fields produced objectively by the operational NWP system.

During January the Regional Area Forecast Centre (RAFC) Frankfurt reported their satisfaction with the SIGWX data produced by the World Area Forecast Centre (WAFc) London for the map areas Europe/Asia (MID) and European Domestic region (EUR). Unfortunately a technical problem with the digital facsimile transmissions delayed the transfer of operational production from Frankfurt to Bracknell until the end of March 1995.

## HORACE

The aim of this project (the name of which is based on a somewhat convoluted acronym) is to develop a workstation-based system to support the Principal Forecast Offices (PFOs) at HQSTC, CFO and now also at the Royal Navy's Fleet Weather Oceanographic Centre (FWOC). The project will develop and enhance tools to semi-automate many of the routine functions of the PFO, and maximize the use of screen displays. (HORACE will eventually incorporate the work associated with the SIGWX Project.)

At HQSTC outdated earlier-generation equipment was successfully replaced by HORACE equipment in July; the system was installed operationally at FWOC in December. A limited form of HORACE has been used since the turn of the year in CFO to support the management of a new chart/mapping package. The new package provides a more efficient means of paper chart production for CFO; and all the different observation types can now be plotted using the HORACE database. The next phase will see an implementation of the system throughout CFO later in 1995.

HORACE is the natural platform for delivering many new advanced operational applications, with a migration away from paper to on-screen production of forecasts, and we are trying to find the best way of doing this quickly. Technical and user evaluations of externally written software have been completed and are encouraging. They show that it is possible to produce such vital documents as the main forecast charts on-screen more quickly than on paper.

## Information Technology advances in the Central Forecasting Division

There have been major investments in new technology, in various forms, to support the forecast production process in CFO. A major upgrading of the CFO electrical power system, costing of the order of £100k, started in earnest in February; its completion is necessary before the commissioning of the many new HORACE workstations in CFO.

The Intervention and International Forecasting Unit Benches are now connected to the Internet, primarily for satellite picture reception. Other possible applications of Internet are being considered.

All the Central Forecasting Systems staff who need them (approximately 60) now have access to workstations. There has been an appreciable improvement in productivity of such staff partly because of the transfer from mainframe to workstation working, which permits a faster turn-round of development work, but also because the latter provide new facilities for display and output.

## Imagery displays

A system has been developed which allows the two-way exchange of satellite image products between any two centres. The first application has been a two-way link between Bracknell and Dorval (Montreal) for the exchange of Meteosat and GOES imagery.



Considerable progress has been made, with European cooperation, in the production of composite radar rainfall displays based on an enlarged European network. These European radar composites can also now be merged operationally with infrared satellite data; the merged image is produced half-hourly.

The Australian Bureau of Meteorology is now routinely generating full-disk GMS satellite images at the same resolution as Meteosat ones. A dedicated line was installed between Bracknell and the Bureau in Melbourne to allow the GMS images to be transferred 3-hourly.

Work is in progress to develop a successor to the existing AUTOSAT II satellite data reception system. A feasibility study for AUTOSAT III has suggested substantially cheaper ways of receiving satellite data at Bracknell than those used now; this will be investigated further during 1995.

## NIMROD

At present forecasts of precipitation for up to six hours ahead are produced by an interactive system, based on radar and satellite data and a choice of options, by a forecaster. An automated system, part of the NIMROD project, has been developed to replace this system. The first test of this new system was suspended in March when it became clear that it was failing to meet the specified acceptance criteria. The NIMROD Project Board decided to make further enhancements to the system before resuming the trial in August. (See also ref H page 24.)

## Automation of forecasts

There is now considerable attention being turned to ways of automating the forecast process wherever it can be demonstrated to be cost effective to do so. A necessary step towards this goal is to have a verification system which will permit assessment of agreed forecast parameters and guidance, at successive stages of the forecasting process, from numerical model output to

outstation forecaster. Such a system is now being developed, and already a sub-system has been defined in which an agreed set of forecast parameters, at agreed sites and for agreed forecast periods, will be verified.

## Publications

A quarterly newsletter, the *nwp GAZETTE* is now being published to keep all users of the Office's NWP products informed on all aspects of the operational NWP system and the many different dissemination facilities.

## New products and services

As part of the National Severe Weather Warning Service, flash warnings of severe weather are now offered to private weather companies which provide public forecasts through radio and television. This will contribute towards effective dissemination of the warnings, and help ensure that consistent and authoritative advice reaches the public in severe weather events.

As part of the Office's obligations as a Regional Specialized Meteorological Centre (with Environmental Emergency Response specialization) the Office has played a full part in international exercises in conjunction with three other designated RSMCs (Toulouse, Washington and Montreal). In such exercises, model products were exchanged between all four centres and compared, and joint statements were prepared by Bracknell and Toulouse for the WMO Region VI area of responsibility (Europe).

MOS (Model Output Statistics) are a valuable means of enhancing NWP output. The Global Model maximum/minimum products for the UK have been completely overhauled, expanding from 100 stations to over 200 UK and Eire stations.

Two new MOS products were introduced — probability of precipitation forecasts in 12-hour steps for 200 UK stations are produced out to six days from



each Global Model run. A separate run provides the same information for 150 European stations. A working group of forecasters is looking at the use of ensemble forecasts for the medium range. To date the emphasis has been on the use of the Ensemble Prediction System (EPS) developed at ECMWF. Three probability forecasts are carried out for day 6, the first based on climate, the second based on all currently available products except the EPS products, the third includes the EPS forecasts. Following initial feedback on these a more substantial range of assessment products is under development. (See also ref I page 27.)



## Defence Services

### Introduction

The Defence Services (DS) Division is responsible for the provision of operational meteorological services on RAF and Army airfields and various (Army, DGTE and CBDE) training and testing ranges. (The Royal Navy has its own uniformed meteorological staff, although The Met. Office provides basic data and numerical forecasts.) Staff are based at military airfields and ranges in the UK, Germany, Mediterranean and South Atlantic. However, meteorological advice is not just required for fixed locations but also for crisis situations (e.g. peace-keeping), to the Allied Command Europe Rapid Reaction Corps and for major exercises. This support is provided through the Mobile Meteorological Unit (MMU), which forms part of the RAF Tactical Communications Wing. The MMU is currently providing meteorological support for operations in Bosnia and northern Iraq with meteorologists deployed in-theatre. In addition, DS manages the Office's response in the event of civil or military nuclear and chemical accidents (see page 21 of last year's report), develops specialized techniques and products for DS meteorologists and new IT (Information Technology) facilities to improve the delivery of services.

### Service delivery

The delivery of meteorological information to the defence customer is largely through personal or telephone contact with outstation meteorologists based on the airfield or range. The outstations receive guidance on broad-scale development from the Principal Forecast Office at Headquarters Strike Command and centrally generated products from Bracknell via the Outstation Display System (ODS). The outstation meteorologist adds detail to this broad-scale guidance and provides advice to the customer for specific operations. Whilst IT has been used for some years to deliver meteorological data and forecasts to the outstation meteorologist, the benefits are

increasingly being extended to deliver both centrally and locally produced data and forecasts to the military customer.

The RAF's Automated Low Flying and Enquiry Notification System (ALFENS) is expected to be installed at all military flying stations in the UK (including Naval Air Stations and Army Air Corps airfields) and at sites overseas. Although ALFENS will be primarily a flight-planning system, it will also provide meteorological data directly to the pilot. Phase I of ALFENS, which should become operational by Spring 1996, will provide basic alphanumeric information generated at Bracknell. Phase II will involve linking local ALFENS networks to the Outstation Communications Processor which will be installed at each outstation as part of the Weather Information System. This will allow the outstation meteorologists to input more detailed and specialized local products (textual and graphical) into the system for display to its military users.

As there are no plans to install ALFENS in Northern Ireland, a MIST (Meteorological Information SysTem), developed by Matra Marconi (formerly British Aerospace) has been provided instead. This system is driven by a host processor linked to COSMOS at Bracknell and provides meteorological data directly to Army and RAF bases in the Province. Another version of MIST has been installed at a few airfields in the UK and Germany prior to ALFENS, although ALFENS will eventually provide similar meteorological capabilities. DS has also developed the means to exploit the MIST host at Bracknell further, by providing telephone dial-in facilities to allow remote PCs to receive data from the host; this will allow access to specific data that is not yet available on ODS. Plans are also being developed to provide PCs in the outstations with access to the ODS database.

A high-priority project is the development of a Mobile Outstation Display System (MODS) for use by the MMU in theatre or on exercise. A rugged prototype system has been put together, using off-the-shelf



components and tested with the RAF — these trials clearly demonstrated the benefit of such a system to the military. Contracts have been let for the delivery of five further systems which will be able to receive data via land-line or satellite (commercial or military). However, for small-scale detachments it may not be necessary to deploy MODS and for these it is planned to use the Defence MIST and dial-in facilities.

## Defence application models

The availability of powerful PCs at the outstations and with the MMU has made it possible to provide sophisticated application models for use by forecasters. These include, for example, models to predict runway icing conditions, low-level wind flow over undulating terrain, and soil-moisture deficit/content. DS outstation trials of an Air Mass Transformation (AMT) model for predicting fog and low cloud (developed by the Atmospheric Process Research (APR) Division) have identified a number of aspects of the model which need refinement (e.g. the entrainment of dry air from above the boundary layer), and APR are working on these.

The new Acoustic Prediction Package (APP), developed with the Department of Applied Acoustics, Salford University, was introduced during spring 1994, and a paper describing its formulation and assessment against trials data has been completed. The results confirm that the new model is able to give more-reliable predictions than the semi-empirical Larkhill Mk. II model used previously. During the year further work has been done on looking at sound propagation over water, and the influences of terrain and turbulence, with the intention of incorporating these effects into the APP.

## Tactical meteorology

Tactical Decision Aids (TDAs) are tools that enable the forecaster to predict the impact that weather has on military systems and equipment. Meteorological conditions affect the performance of electro-optic

systems such as Night Vision Goggles (NVGs) and Forward Looking InfraRed (FLIR). During the year an improved night illumination TDA was issued to all DS (and RN Air) stations for use in supporting NVGs and other image intensifiers. This TDA has also been provided to a number of other military customers and the 'core' calculation module made available for inclusion on the RAF AMPA (Advanced Mission Planning Aid) for the Harrier GR7. FLIR systems see the thermal contrast, consequently predicting the background temperature contrast is important in forecasting the effectiveness of FLIR as a navigational aid and for feature identification. A surface temperature prediction model, based upon energy balance calculations for a variety of vegetated and unvegetated backgrounds, has been delivered to DS by APR. An assessment of the model predictions against various trials and published data shows that it gives surface temperature predictions with an r.m.s. error of less than 1 °C. Work is now needed to exploit this model in a FLIR TDA.

Atmospheric refraction is well known to be a factor that can affect the performance of radar, giving extended ranges in ducting conditions and reduced ranges in sub-refracting conditions. Although Parabolic Equation (PE) models can give accurate predictions of radar performance, the reliability of the predictions is usually limited by the quality of the available meteorological data, i.e. the vertical structure (temperature and humidity) of the atmosphere. In DS, work has concentrated on assessing the ability of the Mesoscale Unified Model (MUM) and the AMT model to predict these parameters and so diagnose ducting conditions. Recent results (page 20 of last year's Report) showed that the performance of the new MUM for predicting ducting conditions was considerably improved over the old mesoscale model. In particular the results indicated that the forecasts were most reliable for ducts below 500 m (1640 ft). Such low-level ducts are of prime interest to RN applications and it was considered that the MUM may now be able to provide them with useful advice on predicting ducting conditions. A joint trial with the RN FWOC (Fleet Weather and Oceanographic Centre) was conducted during June/July 1994 to



assess the operational potential of MUM forecasts for making radar performance predictions. MUM data for a region in the Adriatic were extracted and downloaded via a dial-in link directly into a PC at FWOOC. Software was provided to allow FWOOC forecasters to read, display, edit and output the data (in a format suitable for use with the PE model). Radiosonde ascents were made in the Adriatic from an RN ship and these were compared against the nearest MUM profile. Radar-range predictions were made with the PE model using both the radiosonde and MUM data and examples are shown in Fig. 9. The results suggested that the use of MUM meteorological profiles in the PE model has potential as a planning tool for the RN and further studies are being made. In the long term, the use of mesoscale, or even smaller-scale models with a higher resolution, is likely to be the best way of determining the complex and range-dependent refractivity structure needed to support RN operations in coastal areas.

One of the tasks of the range stations is the provision of ballistic meteorological messages to support gun firing at various Army training ranges around the UK. The Standard Ballistic Met. Message (SBMM) contains ballistic (i.e. weighted) winds and temperatures, and the Standard Computer Met. Message (SCMM) contains winds and temperatures, for specified 'zones' up to a height of 20 km. Many of the training ranges are distant from Met. Office sites making upper-air measurements so there is usually little representative data available. A joint study was completed, with HQ DRA (Director Royal Artillery), to investigate the potential of using forecasts from the MUM for producing ballistic data. Site-specific MUM profiles for Larkhill ( $51.2^{\circ}$  N,  $1.8^{\circ}$  W) were extracted and compared to on-site radiosonde data. Fig. 10 shows a comparison of the errors in the calculated ballistic winds made using MUM data against those made with on-site radiosonde data for the period July 1994 to February 1995. The r.m.s. ballistic wind error is typically  $1.75\text{--}3\text{ m s}^{-1}$  for 6- (and 7-) hour forecasts and  $2.5\text{--}4.25\text{ m s}^{-1}$  for 10- (and 11-) hour forecasts. The results show that MUM data can be used to produce ballistic met. messages which are in good agreement with those

prepared using radiosonde measurements. To exploit this capability DS has developed a dial-in facility, using the MIST host, to enable selected outstations to obtain site-specific MUM profiles and to produce SBMM and SCMM automatically.

DS is also supporting an international cooperative programme, under the auspices of NATO AC/225 Independent Special Working Group No. 3 on Meteorology, to identify a recommended suite of TDAs to support Army activities. With the increasing emphasis on multi-national operations and forces, the harmonisation and consistency of tactical meteorological advice is becoming more important.

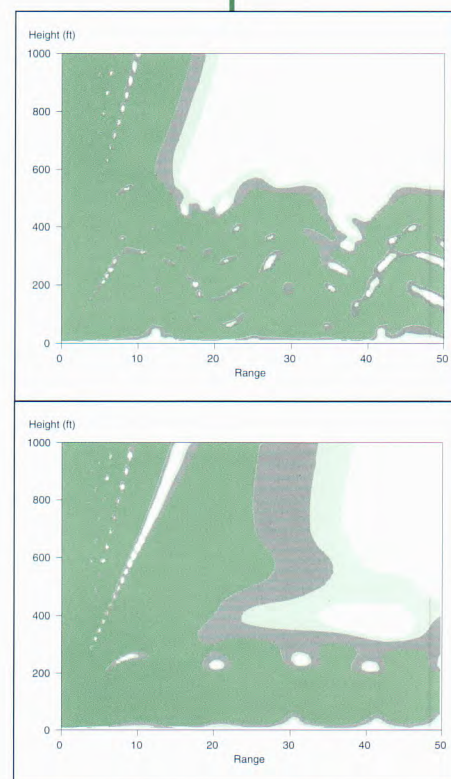


Fig. 9. PC PEM (Parabolic Equation Model) coverage predictions for midday 3 June 1994 based on (top) measured radiosonde data and (bottom) MUM forecast.

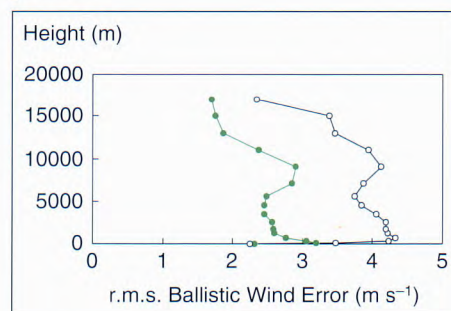


Fig. 10. Mesoscale Model r.m.s. ballistic wind errors ( $\text{m s}^{-1}$ ) against height. The green line shows the predictions for  $T+6/7$ , the black line for  $T+10/11$ .



## Commercial Services

### Introduction

Commercial Services (CS) Division provides a wide variety of services on repayment terms. These services vary from the consultancy type which can be very labour-intensive and are usually customer specific, to those aimed at the high-volume low-cost end of the market where the same product or service is made available to a large number of customers. The first part of this short article describes some of the consultancy work undertaken during the past year. The second section is more concerned with the way developments in technology and systems have been used to provide the customer with the other types of service they need. The third briefly looks at how technology is helping the CS Production units increase their efficiency.

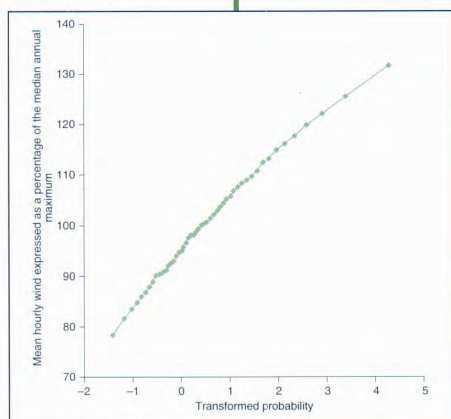


Fig. 11. Extreme winds normalized against median annual maximum.

### Consultancy services

CS provides a very wide range of consultancy services and this section gives a brief overview of some of the work that has been undertaken in the past year.

#### Air quality

Concern about air quality has been a major source of consultancy work over the past year. Two main tools, both including dispersion models, are used to support these studies. The first is the UK-ADMS model, a practical PC-based short-range dispersion model that has been developed jointly with Cambridge Environmental Research Consultants and National Power; the second is a multi-point source Gaussian model, with topography adjustment, that has been procured commercially. These models have been used to predict the ground-level concentrations of gases and

particulates generated by biomass power stations (2–30 MW power stations fuelled by straw and wood coppice). Other uses have been to produce design values of odour emissions from sewage treatment plants and intensive livestock rearing units. (See also Ref J p. 35)

#### Building

A study, sponsored by a consortium headed by Nuclear Electric, was to develop a method that would enable 1 in 10 000-year winds to be estimated for any location in the UK. The annual maximum wind speeds were extracted for 20 stations, each of which had a 50-year record. These data were normalized using the median annual maximum for each station and the normalized data plotted (Fig. 11). Fitting a generalized extreme-value distribution to this pooled and normalized data gives an estimate of the 1 in 10 000-year wind as being about 1.6 times the median. This compares with the linear Gumbel technique which yields a value of 1.85 times the median. The study also investigated the spatial and directional variability of the extreme winds and gusts thus enabling comprehensive estimates to be made for any location in the UK.

#### Marine

Consultancy services were provided to an international consortium designing a natural gas processing plant on the coast of Oman. The prime concern was that tropical storms in the northern Arabian Sea could generate large swells that would affect the operations of tankers offloading at the site. For European waters there was further development of the Offshore Downtime Analysis, which uses European Wave Model archived information, to generate a concise summary of time which might be expected to be lost due to adverse weather at any specified offshore location. This material finds use both as a planning tool and to help confirm or refute claims for lost time after the event.



By using a Met. Office archive of wind and wave forecasts, matched with actual reports, it is possible to quantify the uncertainty inherent in a forecast. This uncertainty can then be used as one of the risk factors in planning offshore operations. Extension of this work was commissioned by the Offshore Safety Division of the Health and Safety Executive.

## Hydrology

METSTAR, a Business Unit of The Met. Office, continues to undertake the more scientifically based consultancy work bringing to the market some of the research undertaken in The Met. Office and elsewhere. Two major areas of work include PMP (Probable Maximum Precipitation) and GANDOLF (General Advanced Nowcasts for Deployment in Operational Land surface Flood forecasting).

The PMP studies seek to update the results of the FSR (*Flood Studies Report*). The FSR gives design engineers a method for estimating maximum rainfalls, both point and areal, for various durations. The PMP technique is based on a simple and totally objective storm model of convective systems. Results based on this technique are similar to those obtained from the FSR for storm durations of less than 11 hours. For longer periods, however, the PMP based on storm models exceeds that derived from the FSR and probably reflects the existence of mesoscale convective systems. These results have an obvious importance in the design of structures that have to handle water flows.

The FSR also notes the importance of snowmelt and gives methods for estimating it. For example the FSR recommends that 42 mm is the value for 24-hour snowmelt likely to occur anywhere in the UK on average once in 100 years. The Department of the Environment contracted the Scientific Support Group, a small unit attached to CS, to improve on the FSR methods for estimating snowmelt. Using observational data from both hourly reporting stations and daily stations, estimates of the once in 5-, 20- and 50-year snowmelts for 3, 6, 9, 12, 18, 24, 48, 72, 120 and 168 hours were obtained. This, coupled with further analysis, enables maps of the type given in Fig. 12 to be produced.

The exact location and timing of the occurrence of deep convection and thunderstorms are of primary importance for flood forecasting. GANDOLF is a system that attempts to identify those meteorologically significant features and weather types present at a particular time and to determine which approach to forecasting is likely to work best on any one occasion. Various data sources (radar, satellite, mesoscale model and FRONTIERS) and analysis techniques (cross-correlation methods applied to radar data and an object-oriented approach to the identification of convective cell maturity) have been integrated into a single intelligent system to give best advice to flood hydrologists.

## Retail

The Weather Initiative, a Business Unit set up to handle the requirements of the retail industry, has undertaken a number of weather sensitivity analyses (WSAs) on behalf of its customers. A WSA looks for, and attempts to quantify, relationships between a customer's data (sales or demand, production figures, breakdowns, etc.) and weather. Once proven on the basis of historical data the same relationships can be used to forecast those parameters that are of particular interest to the customer. This can give the customer an opportunity to anticipate the demand and provide him with a competitive edge. WSAs have been undertaken by The Weather Initiative for a few years now, but the last year has seen an increase in this type of business.

## Routine Services

A multitude of routine type services, as opposed to one-off consultancies, are provided in response to customer demand. Many of these are generated at the Production Units and their mode of production will be discussed in the next section. Only those services which make use of modern or novel technologies will be discussed here.



Fig. 12. An example of an estimated snowmelt map.



## Telephone and fax services

Access to the Weathercall service via premium-rated telephone numbers is slightly down on the previous 1993/94 figure of 3.9 million. This is indicative of a market reaching saturation. However, the market for premium rate dial-up fax services continues to grow. This year should see over 1 million calls to the service.

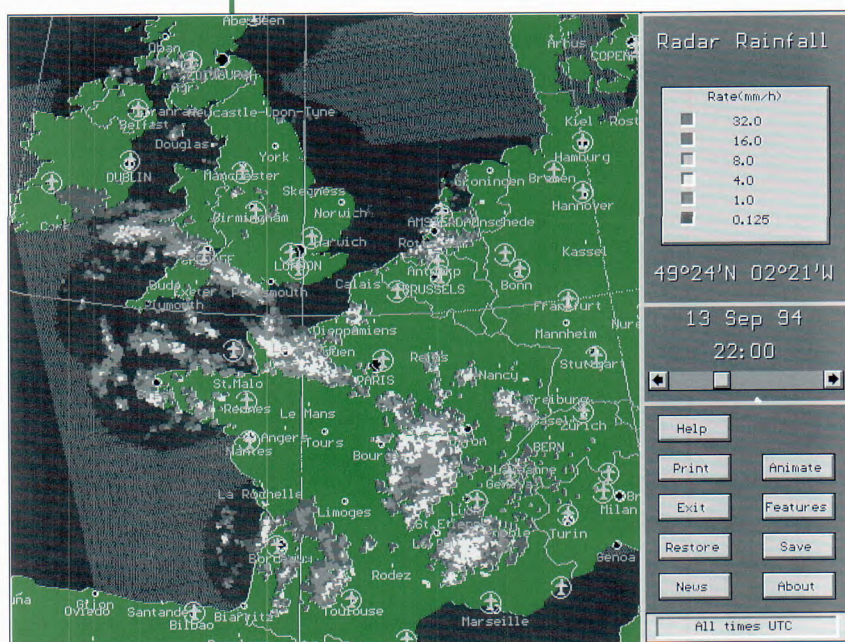


Fig. 13. An example of a radar-derived rainfall field available on MIST.

This year has seen the start of a collaboration with Delrina (UK) Corporation who produce the popular WinFAX PC fax software. A range of fax products will be promoted by Delrina in the WinFAX package.

## PC-PC Services

Use of the CS MIST system continues to grow. This gives registered users interactive access to a database of products and data via their PC. There are currently about 60 commercial MIST customers of whom some have more than one system and

others network the information once it has been received. Approximately 75 000 products annually are being downloaded via dial-up MIST.

The application and display software run on the user's PC has undergone development and enhancement over the past year as has the variety of products and data available. In particular the latest release of the software produced by Matra Marconi Space, collaborators with The Met. Office in this project, allows users to customize most of the displays to meet their particular requirement. Figs 13 and 14 give examples of radar-derived rainfall fields and forecast wind from the mesoscale model, in these the area and content of the map background have been defined by the customer.

## Other methods for electronic delivery

Some customers, who have in the past received services and data on paper or via fax, are now wanting the same products delivered electronically and in a form that they can redistribute on their networks. A typical example is the monthly summary used by insurance companies. These can now be sent by X.400 either direct to customers or to a mail-box from where it can be picked up by the customer.

A more innovative service, involving the automated production of sea-area type forecasts downloaded onto British Telecom's SatMail system, is currently being tested. Ships at sea can interrogate the service via satellite links and download the information they select.

## CS Production Units

Except for the fully automated services that are produced centrally, most of the products and services are generated by the various CS Production Units. The technology used by the production units to generate and distribute the outputs is evolving. This section identifies the major changes that have taken place over the last year.



## OPUS

This last year has seen OPUS (Outstations Production Unified System) introduced into most of the Weather Centres, the distributed production units. OPUS has been designed to tidy up and enhance the production facilities and to improve communications. The design objectives are:

- more-efficient transfer of information between the Production Units and Bracknell;
- more-efficient transfer of information between the Production Units;
- to give Production Units enhanced fax distribution facilities;
- to tidy up all asynchronous (PC-PC) links to customers;
- to allow connectivity to customers' networks and electronic mail systems using X.400;
- to present a standard interface to Production Unit personnel by integrating present facilities and automating them wherever possible, and
- to provide a unified method of external data communications.

The system is still new, and a job for the future is to learn how to make best use of the versatile infrastructure and freedom given to staff at the production Unit, while still preserving a corporate style.

## IWP

IWP (International Weather Productions), a business unit of The Met. Office, is the specialist TV production unit providing services to independent TV stations in the UK and overseas. In late 1994 IWP again won the contract to supply the ITV National Weather for a further two years. The bid was based on new and revolutionary graphics which aimed at

providing the viewer with a progressive view of the weather as it develops, not just snapshots.

The requirement was for the various weather symbols and patterns to move, grow and change shape as the weather itself was predicted to change. The specialist equipment procured to generate the video graphics comprises two Silicon Graphics INDIGO 2 work stations running Parallax 'morphing' software coupled with the latest Abekas DISKUS digital storage devices. Once stored on the DISKUS the information can be played out live at the request of the presenter. The use of this type of leading-edge and specialized technology is likely to increase.



Fig. 14. An example of forecast winds available on MIST.



## Forecasting Research

### Introduction

The Forecasting Research Division has the task of developing and extending automatic systems for forecasting the weather on time-scales from a few minutes up to a month ahead. Much of the forecasting is based on assimilation of all available data into a large computer model, the Unified Model, which is then used to make predictions. For very-short-period predictions it is necessary to use extrapolation techniques based more directly on observations. For longer-period forecasts it is necessary to predict a probability distribution of possible weather patterns, and use statistical post-processing to give the probability of particular types of weather. In addition to this primary task, the Division is responsible for developing systems to forecast the sea state and the ocean circulation, and for carrying out specific investigations in support of meteorological advice to aviation.

### Very-short-range forecasting (ref H)

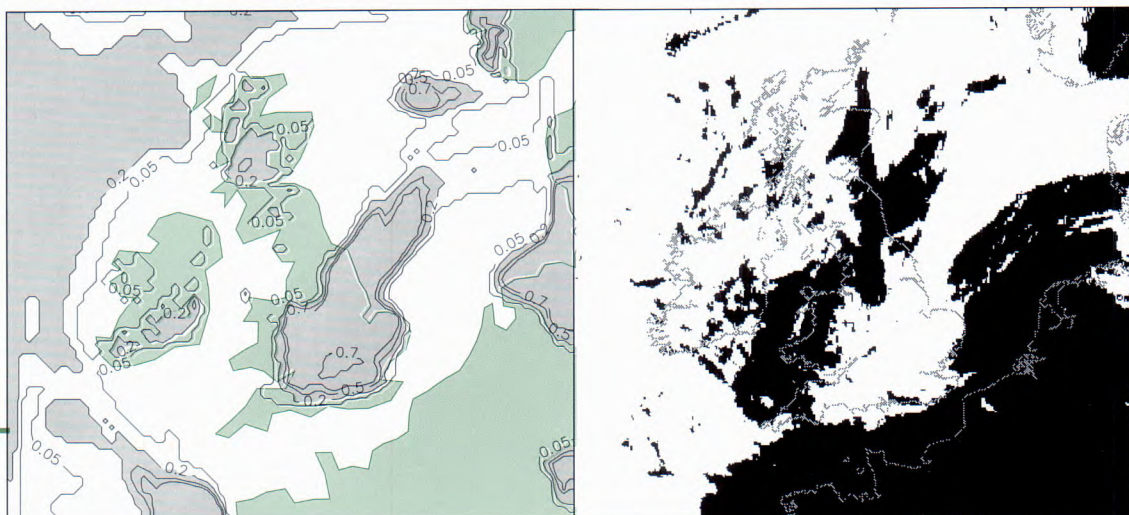
At present, forecasts of precipitation for up to six hours ahead are produced by a forecaster on an interactive system (FRONTIERS) based on radar and satellite data with a choice of options. An automatic

replacement for this system has now been developed and is currently undergoing its operational acceptance trial. The new system processes radar and satellite data automatically to produce a precipitation analysis, followed by an advection forecast. During the last year suitable hardware was obtained to run the system, database software was implemented, and the algorithms converted to run in an operational environment.

The trial is showing that rainfall accumulations can be forecast more accurately by the automatic system early in the forecast. However, subjective assessment suggests that the system does not always match FRONTIERS in analysing and predicting precipitation distribution. This is partly because of the difficulty of interpreting satellite data in terms of precipitation.

Forecasts of all weather parameters up to 30 hours ahead for the UK are produced by a mesoscale configuration of the Unified Model. This has a grid length of 17 km and covers an area about 1500 km square. Since September 1994 this model has been run four times a day with a continuous data assimilation cycle. At the same time, a number of improvements were made with the particular aim of improving the fog forecasts. Relative humidity

*Fig. 15. Left. Contours of fog probability valid at 08 UTC, 14 October 1994, from a forecast starting at 18 UTC on 13 October. The shaded area shows where widespread, thick fog is expected, while the surrounding contour shows areas where patchy or thin fog might develop. Right. Meteosat image for same time processed to show significant cloud and fog as white.*





observations from screens are now incorporated and assimilation parameters, particularly in the boundary layer, have been refined using long-term statistics. This enables more-accurate mesoscale detail to be introduced into the analysis. Refinements to the model have also had considerable impact. An increase in vertical resolution near the surface has improved radiation fog prediction, while use of a scheme to represent orographic roughness has improved both the general forecasts of relative humidity and forecasts of hill fog (see next section).

The example in Fig. 15 shows that the general distribution of fog can be forecast well, but there is a tendency to erode the fog around its edges (e.g. the Vale of York) because of inadequate horizontal resolution and limitations of the current advection scheme.

## Global and regional short-range forecasting

Forecasts of the general weather pattern over the UK area up to 36 hours ahead are provided by a regional version of the Unified Model covering the North Atlantic and Europe. A global version of the Unified Model provides forecasts of the weather patterns, and detailed information required for civil aviation, defence and commercial customers up to 72 hours ahead.

## Observation processing (ref B)

In order to make these forecasts, maximum use has to be made of available observations. Remotely sensed data are particularly difficult to use, as they are not directly related to variables predicted by the model. The way observations benefit numerical weather predictions, and the best use of the available resources, are being investigated. For example, cases are selected by identifying unusually large differences between 72-hour and 60-hour forecasts from the global model valid at the same time. Large differences indicate a significant impact from the additional 12 hours of observational

data assimilated prior to the 60-hour forecast. Results so far confirm the importance of radiosonde data over North America and winds reported by aircraft there and over the Pacific and Atlantic Oceans. The impact on the regional model of additional information immediately upwind of the UK is also being assessed. Experiments have shown that forecasts of precipitation over the UK have improved when upper-air wind and humidity data, based on information from infrared and water vapour satellite images, have been inserted into the model. Experiments to assess the impact of additional wind, temperature and humidity profiles from sondes ejected from the Met. Research Flight's C-130 have begun. These are being done during weather situations in which numerical forecasts are most likely to be improved.

## Radar data (ref C)

Ways of further improving estimates of surface precipitation rate from radar are being developed. Attention is focused on the differences between the precipitation at the surface, and as sampled by the radar when the beam is a few kilometres above the ground. The problem is acute at longer ranges where the radar beam is sampling mainly above the freezing level, because the rate of decrease in the signal with height is highly variable within snow. This variability is not properly represented in the present correction methods and this can lead to large errors in calculated surface precipitation rate in extreme conditions. To try and reduce these errors, we plan to use radar data from a number of beam elevations, not just one as at present. The extra radar data will be used to diagnose the rate of decrease in the signal and thus improve the estimates of surface precipitation rate at long range.

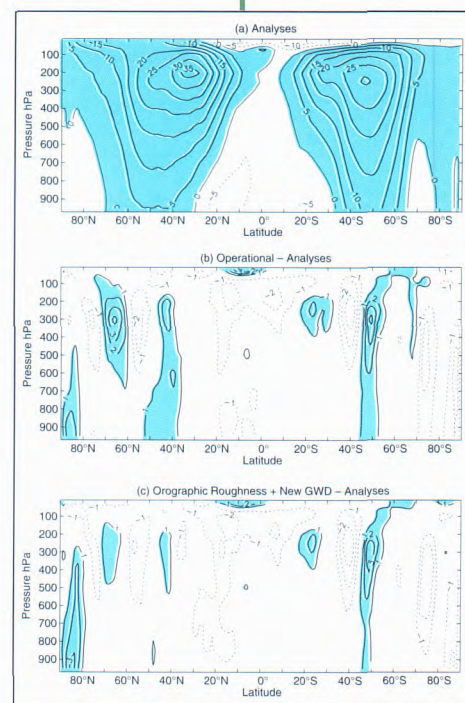


Fig. 16. Zonally averaged latitude–height cross sections averaged over five case-study forecasts with the global model from December 1993 showing: (a) the zonal wind analyses; (b) zonal wind mean error in operational forecasts at T+120; (c) as (b) but in forecasts with the new parametrizations of gravity wave drag and orographic roughness.



Initial tests suggest the extra radar data may be of value in avoiding large errors in some cases of vigorous convection or where snow is evaporating beneath the radar beam.

## Data assimilation

Observations have to be assimilated into the model and, in common with other institutes (notably ECMWF and the National Meteorological Center in the USA), the Office is moving towards using variational methods of data assimilation. In this, a model state is constructed that is the best statistical fit to the observed data.

A system like this requires a method of blending the

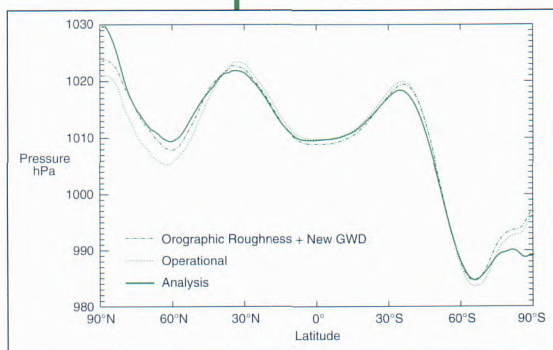


Fig. 17. Zonally averaged mean sea level pressure averaged over five case-study forecasts with the global model from December 1993 showing profiles for the analyses, operational forecasts, and forecasts with the new parametrizations of gravity wave drag and orographic roughness.

observations with the background field of a simple model which is integrated forward and backward in time to fit the observations to an evolving model state. By the end of the research year, the observation blending system was within a few months of full-scale trials with real data.

During the last year a number of improvements were made to the existing data assimilation system; humidity data is now incorporated in a way

which results in analyses much more consistent with the model formulation. This removes the deficiency in total precipitation in the first few hours of the regional model forecast and reduces the cold and moist bias in middle latitudes in the global forecasts.

## Model development (ref L)

Diagnostics of the momentum balance, and systematic errors in the global Unified Model, suggested that too little parametrized drag was applied

to the model atmosphere (see page 33 of the 1993/94 *Scientific and Technical Review*). Improving the physical realism of flow over orography alleviates this problem. Accordingly, two new parametrizations of sub-grid-scale orographic forcing in stable and turbulent flows were introduced into the operational regional and global model from 10 January 1995. The first is a revised gravity wave drag scheme which includes additional drag due to trapped lee waves and 'high drag states'; it gives more drag in the lower troposphere. Anisotropy in the orography is also included in the expression because wind blowing parallel to a ridge does not generate much in the way of gravity waves. The second parametrization deals with form drag generated in turbulent flow by pressure forces across sub-grid-scale orography. Observations and modelling studies show that the wind speed exhibits a logarithmic profile above the orography. This allows form drag to be parametrized using an effective roughness length which includes the effect of orographic and vegetative roughness elements within the grid box. Both of these parametrizations increase the drag in the Unified Model leading to improved momentum balance, reductions in the westerly bias in mid-latitudes (Fig. 16), improved mean-sea-level pressure fields (Fig. 17), and improved objective verification scores. The form drag parametrization also gives major benefit in very-short-range forecasts.

## Oceanographic forecasting

FOAM, the Forecasting Ocean Atmosphere Model, is being developed to produce analyses and forecasts of the ocean temperature and salinity structure. It is based on the ocean component of the Unified Model, and is driven by surface fluxes of heat, fresh water, and momentum that are calculated by the weather forecast models. It uses observations of the ocean to adjust the model fields in the same way that the atmosphere models do for weather forecasting.

In August 1994, regular runs of a prototype for FOAM were started, using a global grid with 1° horizontal resolution. This system produces daily



ocean analyses. Results are illustrated in Figs 18 and 19. Fig. 18 shows how the oceans have been divided up to help interpret the statistics. Fig. 19 summarises the statistics from FOAM for December 1994. FOAM analyses represent a slight improvement on the climatology. There are few ocean observations; this makes the statistics very sensitive to the distribution of observations, and the statistics for January 1995 were less uniformly favourable.

Synoptically the results of FOAM are very encouraging. Evolution of the depth of the mixed layer is of particular interest to the Royal Navy. In early September FOAM responded realistically to the passage of deep Atlantic depressions by deepening the mixed layer.

## Extended-range forecasting (ref I)

The UK Met. Office (UKMO) is collaborating with ECMWF in developing methods of ensemble forecasting. In this approach a large number of forecasts are run from slightly different initial conditions, reflecting the uncertainty in the initial analysed state of the atmosphere. The use of the UKMO Unified Model alongside the ECMWF model has allowed a more complete estimate of the uncertainty in the forecast. This is because an individual model tends to have specifically favoured behaviour patterns which may not correspond to those of the real atmosphere.

Twice a week from autumn 1994, initial perturbations generated at ECMWF have been applied to UKMO analyses, producing 33-member ensemble forecasts from the UKMO Unified Model for up to ten days ahead. Initial analysis has concentrated on the 500 hPa field over the North Atlantic and Europe. Results from the first ten cases demonstrate that combining the ECMWF and UKMO ensemble sets can produce a greater range of solutions than either ensemble alone and substantially reduces the number of occasions when the verifying analysis lies outside the range covered by the ensemble (Fig. 20). Cluster and eigenvector analysis of the joint distributions show that the two models often explore different regions of phase space, and that the initial perturbations may not cover the differences between the

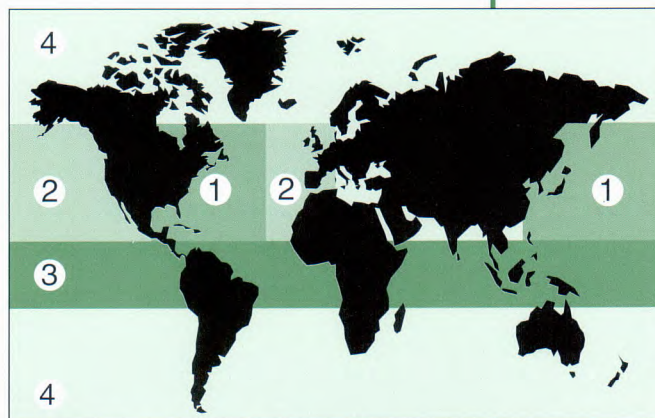


Fig. 18. Areas used to define statistics for assessing the FOAM analysis system. Area 1 (circle shading) corresponds to the western part of basins and area 2 (brick shading) to the eastern parts. Area 3 (dark solid shading) represents the tropics equatorwards of 15°, and area 4 (light solid shading) is the 'rest of the world'.

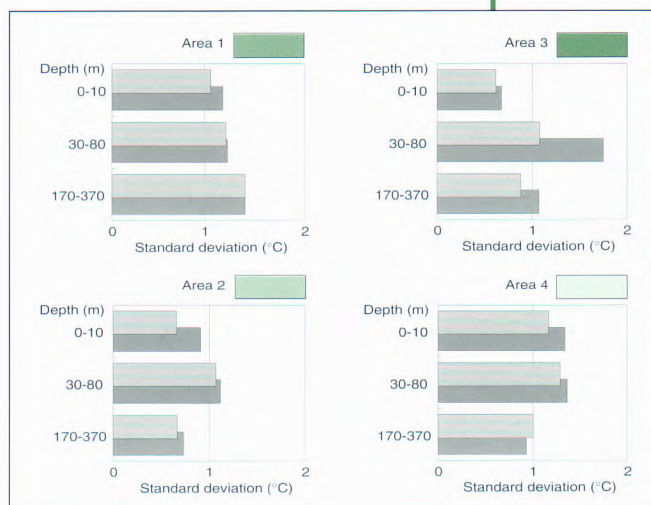


Fig. 19. Standard deviations of errors from the FOAM analyses for December 1994 for the areas shown in Fig. 18. Depths are grouped into three bands. Light shading represents the FOAM analyses, and dark shading climatology.



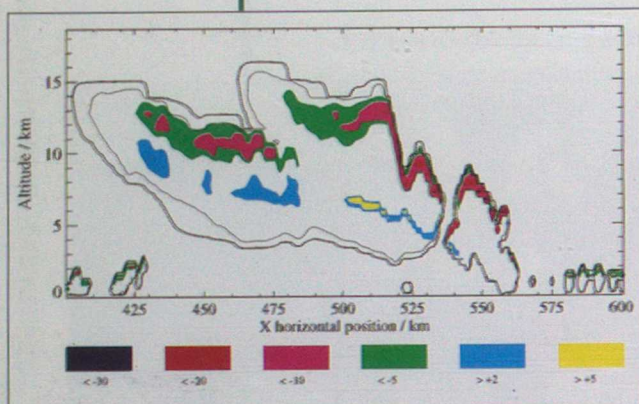


Fig 26. Long-wave radiative heating rates calculated by the cloud-resolving model. The bold (thin) solid line encloses a region with the sum of cloud water, cloud ice, graupel and snow greater than 0.001 (0.01)  $\text{g kg}^{-1}$ .

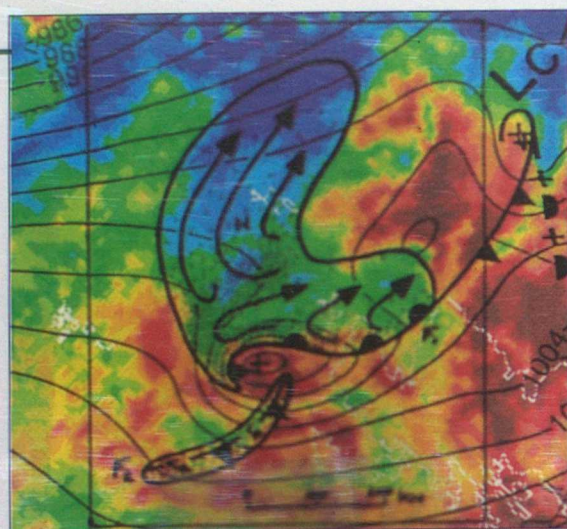


Fig. 29. Infrared Meteosat image for 1200 UTC, 14 March 1992 (blue=cold (high) cloud, red=warm (low) cloud, with isobars (thin contours, 2 hPa interval) and fronts (F1, F2) relating to an intense polar low (centre marked X). Thick lines bound areas of significant cloud associated with the low. Stippling represents precipitation (mainly snow, more dots = heavier precipitation) and arrows indicate approximate system-relative trajectories of ascending air parcels. 'H' is the 'cloud head'.



Fig. 31. The Cardington tethered kite-balloon at low level in the Llanthony valley during an experiment to measure nocturnal airflow over hills. The balloon, which is held by a mooring cable to the winch on the left, can be operated up to 2 km with turbulence probes attached at suitable intervals to the tether wire.

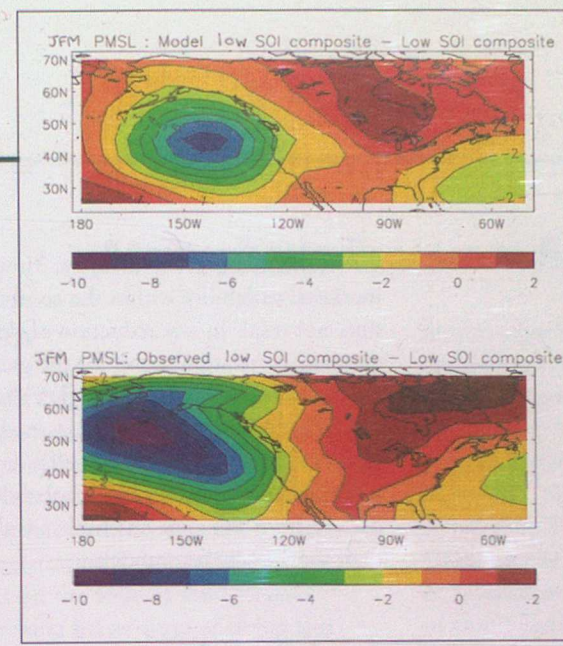


Fig. 39. Warm minus cold ENSO composite mean-sea-level pressure anomalies (hPa) for a January to March average from the model, and as observed.

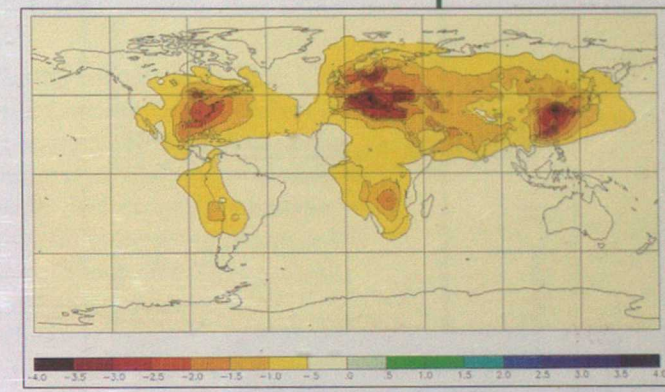


Fig. 41. Annual mean of the direct forcing in  $\text{W m}^{-2}$  due to anthropogenic sulphate aerosol.

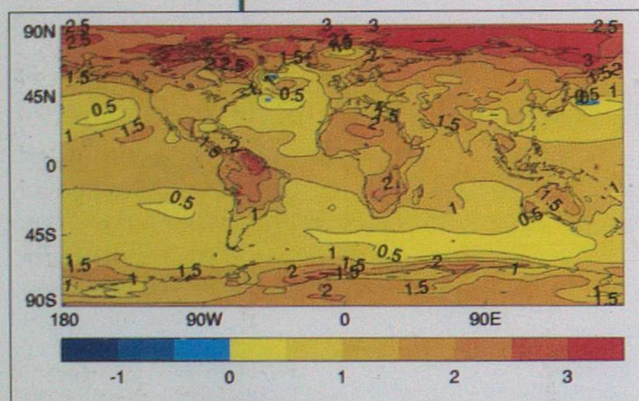


Fig. 44. Change in surface air temperature ( $^{\circ}\text{C}$ ) for 2030-2050 relative to 1970-1990 simulated in an experiment including greenhouse gases and sulphate aerosol.

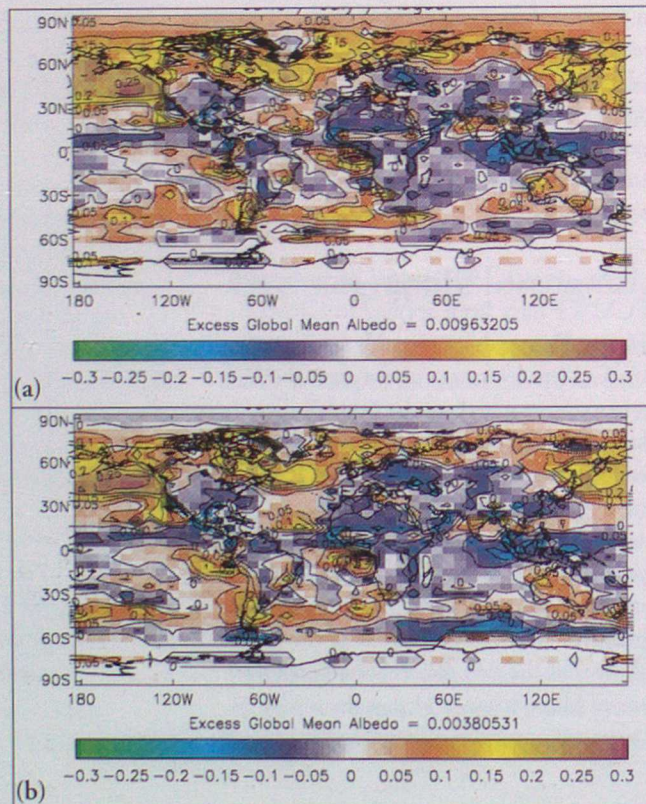


Fig. 47. Impact on albedo for northern hemisphere summer of changing the temperature range over which mixed phase cloud is assumed to exist (a) 0 to  $-15^{\circ}\text{C}$ , (b) 0 to  $-9^{\circ}\text{C}$ . The difference of the model from Earth Radiation Budget (ERBE) data is shown.

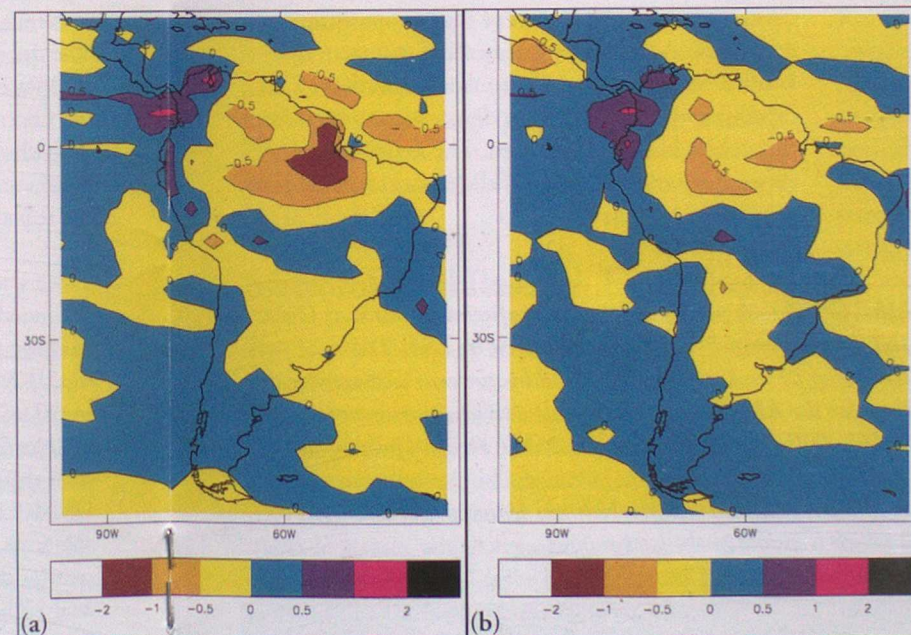


Fig. 50. Rainfall changes ( $\text{mm/day}$ ) for (a) full and (b) half deforestation experiments.

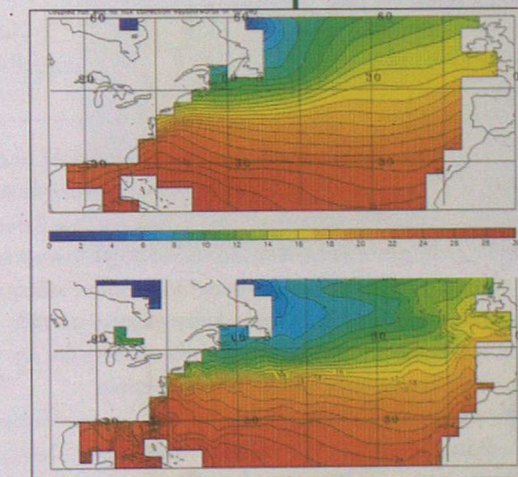


Fig. 51. North Atlantic sea surface temperatures ( $^{\circ}\text{C}$ ) from the  $2.5^{\circ} \times 3.75^{\circ}$  and  $1.25^{\circ}$  ocean models.

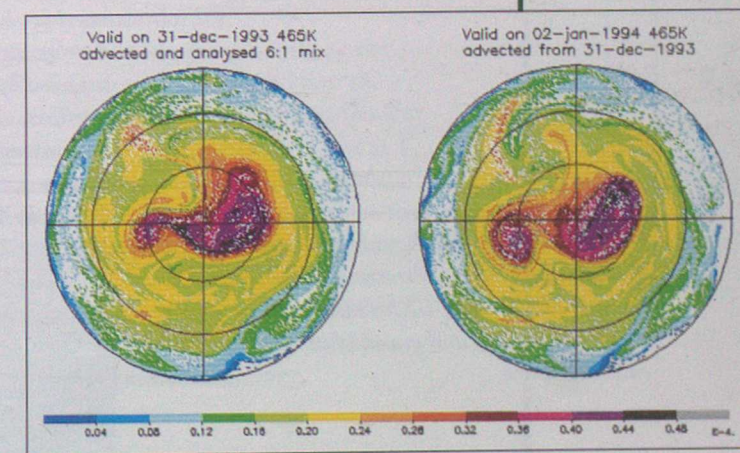


Fig. 55. Evolution of flow in the stratosphere during one of the episodes when the stratospheric vortex was split in the winter of 1993/4.



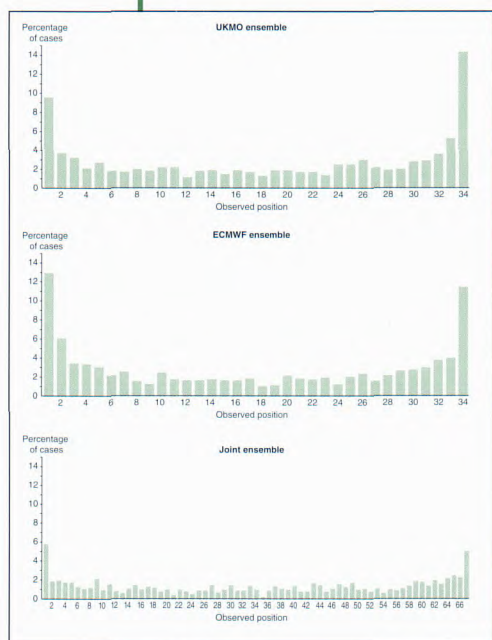


Fig. 20. Position of the observed height in the ensemble distribution for 500 hPa height over the North Atlantic and Europe at day 7 over ten cases. The extreme left-hand (right-hand) bar indicates the percentage of occasions where the observed height was below (above) all the ensemble members, i.e. the observation lay outside the ensemble distribution.

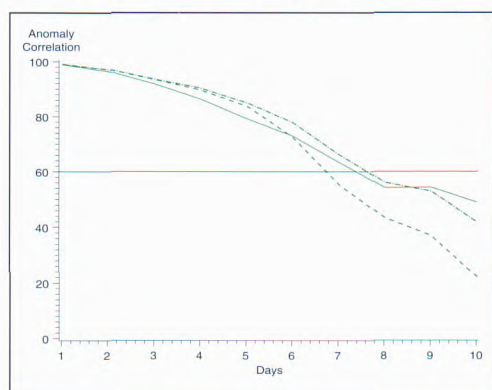


Fig. 21. Average 500 hPa ensemble mean anomaly correlations over ten cases for the North Atlantic and Europe; UKMO (solid line), ECMWF (dotted) and grand (dash-dot) ensemble mean.

UKMO and ECMWF analyses. However, the increased variability within the combined ensemble does not result in any reduction of skill; in fact anomaly correlation scores for the grand ensemble mean over both models are higher than for either individual ensemble (Fig. 21), demonstrating a gain in predictability of the order of half a day over the individual model ensembles. Probability forecasts derived from the joint ensemble are also more skilful than for the separate models.

## Advice to the aviation authorities

Interest in the subject of freezing rain in elevated layers has heightened considerably following the crash of the American Eagle ATR-72 near Chicago on 31 October 1994. This crash was provisionally blamed on icing, and the aircraft was forbidden by the FAA and European airworthiness authorities from flying in freezing rain or drizzle. This precipitated immense interest in the climatology of freezing rain as operators of the aircraft were understandably concerned about the impact of the ban on their operations. A climatology of freezing rain from the Unified Model is being accumulated, and the capability of generating extra diagnostic products from the archive has been enhanced. The availability of the climatology enabled many of the questions to be given provisional answers.

Fig. 22. The MRF C-130 took part in a two-week experiment based at Oulu, northern Finland, in March/April 1995 part sponsored by ESA. The microwave signatures of ice and snow were studied by airborne radiometers to develop algorithms for the AMSU-A and AMSU-B satellite instruments, supplied by The Met. Office, to be flown on the NOAA series of polar-orbiting satellites.

Also taking part in the experiment was the Helsinki University of Technology Skyvan aircraft which is visible in the background. (Photo by S. O'Donnell, RSI)





## Atmospheric Processes Research

### Introduction

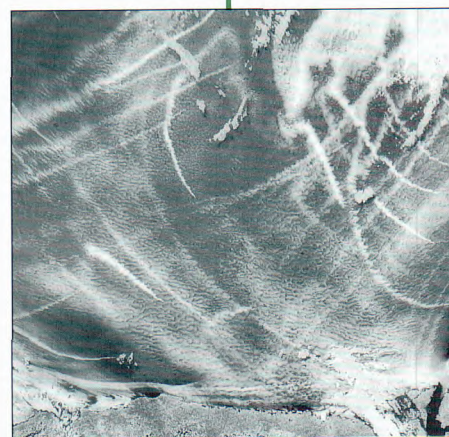
The Unified Model can only explicitly represent meteorological phenomena that have a sufficiently large scale to be resolved by the model's finite difference grid. Atmospheric processes smaller than this need to be represented through sub-models (known as parametrizations) that calculate their aggregated effects on the scale of the Unified Model's grid. Devising better ways of doing this involves research employing experimental facilities, such as the Meteorological Research Flight's C-130 aircraft and the Cardington Meteorological Research Unit's tethered balloon, as well as state-of-the-art very-high-resolution numerical models, such as the large eddy simulation (LES) model. Realistic physical models are also needed for the development of automated forecasting techniques and ancillary models, such as the long-range pollution transport model NAME. Collaboration with outside research groups and participation in international research programmes provide a valuable source of ideas and data that can be developed and adapted to meet Met. Office objectives; the Joint Centre for Mesoscale Meteorology (JCMM), sponsored jointly by The Met. Office and the University of Reading, provides one channel for such co-operative research.

### Meteorological Research Flight (Ref E)

This was the first year of operation of the C-130 aircraft from its new base at Boscombe Down, following the closure of Farnborough airfield to experimental flying. The aircraft had several detachments abroad, which included California (Fig. 22) to gather data on the formation of visible tracks in stratus which reveal the movement of ships below the cloud layer (Fig. 23), and Bahrain to assess the atmospheric microwave refractive index for radar ducting; both were undertaken as UK components of major field experiments sponsored by the US Navy. Other, less extended, detachments were made to Laarbruch (for research

into continental stratus) and the Azores (for atmospheric chemistry measurements), both as part of international co-operative research programmes. Flights were also made in co-operative research projects (sponsored by the Natural Environment Research Council (NERC)) involving groups at UK universities and research institutes. These were the University of Manchester Institute of Science and Technology studies of cloud condensation nuclei generation, the Institute of Terrestrial Ecology studies of methane and nitrous oxide budgets and the University of Reading frontal measurements during the hydrology and radar experiment (HYREX). The transfer of some responsibilities for atmospheric chemistry measurements to NERC has enabled the scaling down of in-house effort on the topic. (See also Ref O page 34.) New instruments installed on the aircraft included an improved radiometer for sea surface temperature measurements, an optical probe for sampling an extended size-range of precipitation particles, and a replacement inertial navigation system.

Future operation of the aircraft is likely to depend on external funding of a considerable portion of the operating costs. A working group set up by the European Commission (EC) reported that the C-130 was an important, and unique, component of airborne research facilities within Europe; as a consequence, there is an expectation that some funding of facility and operating costs may be made available from EC research funds. Also, a debate has been initiated by the Inter-Agency Committee on Global Environmental Change on appropriate funding mechanisms for UK national research facilities for experimental meteorology.



*Fig. 23. Tracks produced by ships steaming underneath a stratocumulus cloud deck off the coast of California can be seen clearly in this combination of two channels ( $3.7\ \mu\text{m}$  and  $10.8\ \mu\text{m}$ ) of the AVHRR instrument on the NOAA satellite. The C-130 aircraft flew through a number of similar tracks during an experiment in June.*

*(Satellite image courtesy Dr P. Durkee, Naval Postgraduate School, Monterey, California.)*



## Boundary layer experimental facilities (Ref D)

Measurements of fluxes of momentum, heat and humidity at a number of heights simultaneously throughout the depth of the atmospheric boundary layer are made using surface instrumentation and probes attached to the tethering cable of a large kite-balloon. The facility has the capability of operating on remote sites to study the effects on the boundary layer of different surface types. Operations will become considerably more efficient with the deployment of

the mast mooring system (Fig. 24) currently being constructed for the tethered balloon. This will replace the concreted balloon-bedding system hitherto used for tethering the balloon; setting up the present system for experiments away from Cardington is time consuming and expensive. The new equipment will make it possible to deploy the balloon at remote sites speedily, in stronger surface winds and with fewer operating staff. (See also Ref K page 34.)

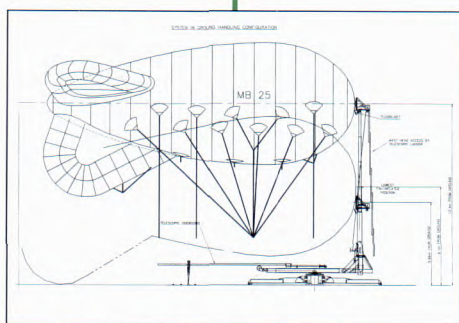


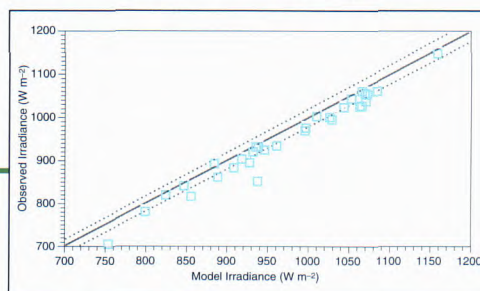
Fig. 24. Engineering drawing of the mast mooring system being constructed for the Cardington tethered balloon facility.

## Clouds and radiative transfer

### Radiative transfer in cloudy and cloud-free skies (Ref N)

Measurements of solar broad-band irradiance made by the C-130 have been used to help validate a new flexible radiation code developed for the Unified Model. Observations from flights carried out in cloudy and cloud-free conditions over the sea around the UK, over the tropical Atlantic and over the east Pacific, were compared directly with irradiances calculated by the model from profiles of temperature and

Fig. 25. Aircraft measured solar irradiance compared directly to model calculation. The full line indicates perfect agreement, the dashed lines show a 2% variation for comparison.



humidity measured by the aircraft. The comparison between cloud-free aircraft irradiances and model irradiances (see Fig. 25) indicated general agreement to the level of accuracy of the measurements (about 3%) so giving considerable confidence in the performance of the model under these conditions. Further comparisons on the performance of the model when dealing with boundary-layer clouds worked well but highlighted the need to improve the representation of the intrinsically inhomogeneous nature of clouds. (See also Ref N page 43 and Ref A page 10)

### Long-wave radiation in deep convection

A numerical cloud-resolving model (developed from the LES model) has been used to investigate the sensitivity of tropical squall lines to long-wave radiative effects. The model includes a Kessler type parametrization for liquid water and a three category ice-phase scheme (ice crystals, snow, graupel). The calculated long-wave radiative heating rates show a substantial horizontal variation related to the variability of ice crystal amounts within the anvil. Maximum long-wave cooling rates of up to 30 K/day are found at cloud tops, whilst maximum long-wave warming rates of 10 K/day occur at cloud base (Fig. 26 colour pages). Model simulations show that long-wave radiative effects increase the size of the anvil cloud and enhance the surface rainfall by 30%.

### Ice-phase physics (Ref M)

The effective radius ( $r_e$ ) of water droplets is an quantity important in model radiation transfer schemes; over the last few years significant progress has been made in our understanding of the important processes that govern  $r_e$  in layer clouds. However, our knowledge of the of ice particles in these clouds is still very limited and, in the absence of alternative advice, the Unified Model currently assumes that all the ice



particles are spheres with an  $r_e$  of 35 microns. During the European Cloud and Radiation Experiment (EUCREX), which was carried out in the autumn of 1993 over Scotland, the C-130 collected a large amount of cloud microphysical data in cirrus clouds associated with frontal systems. These data have been extensively analysed and the variation of the  $r_e$  of ice particles in these clouds examined. Fig. 27 shows how it varied with temperature during nine of these flights. If a relationship could be found between the  $r_e$  and the mean volume radius for all the particle spectra, then it would be possible to parametrize the  $r_e$  of the ice particles in terms of the ice water content. Fig. 28 illustrates the relationship between mean volume radius and  $r_e$  deduced from the aircraft data; a quadratic relationship can be seen that is a function of temperature. This would form the basis of a potentially useful parametrization if it could be shown to be representative of clouds in other regions of the world.

### Cloud radar (Ref F)

The JCMM has made a preliminary study of the ability of a spaceborne cloud radar to detect 'radiatively-significant' ice clouds. Long-wave flux calculations for a variety of model clouds were used to define the threshold optical depth which would alter the outgoing or downwelling long-wave fluxes by more than 10 or 5  $\text{W m}^{-2}$ , respectively. Crystal size spectra derived from aircraft observations of cirrus in mid-latitudes (during EUCREX) and in tropical regions (during the Central Equatorial Pacific Experiment) were used to estimate the optical depth and radar reflectivity of 1 km-thick cirrus layers. The results suggest that over 90% of radiatively significant cirrus would be detected by a radar with a threshold of  $-30$  dBZ. This detection efficiency may be reduced for very cold tropical cirrus at temperatures of around  $-80^\circ\text{C}$ . Another potential application of such a radar is the derivation of wind profiles by measuring the Doppler shift of an off-nadir return signal; the height resolution would be about 500 m.

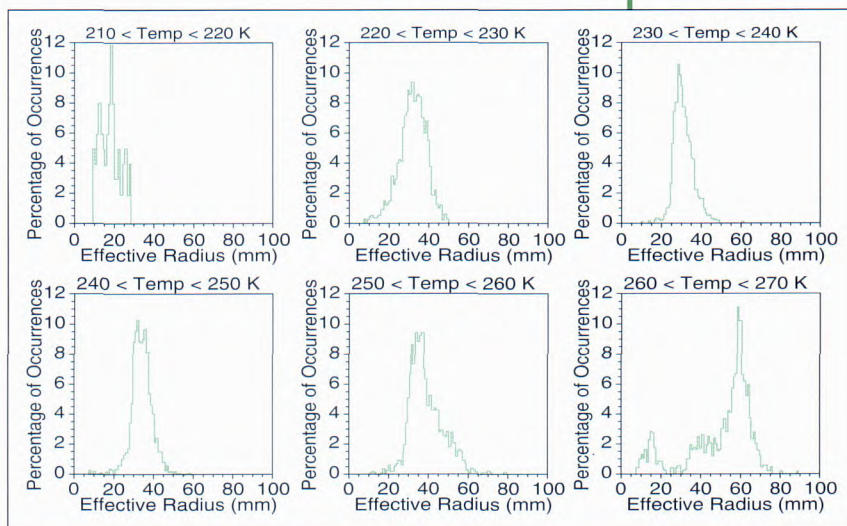


Fig. 27. Histograms of the effective radius of ice particles measured in nine of the C-130 aircraft flights during EUCREX for six different temperature ranges.

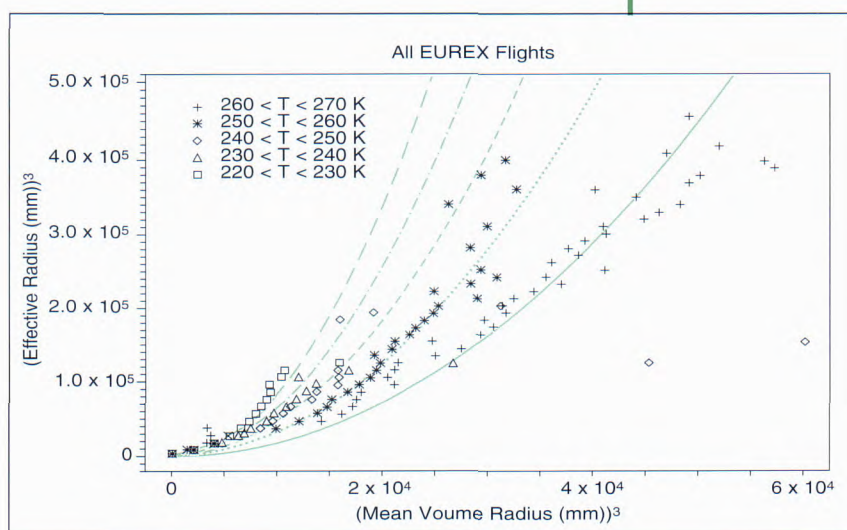


Fig. 28. Plots of the cube of the ice-particle mean volume radius against the cube of the effective radius averaged over equal intervals for specified temperature ranges for nine C-130 flights during EUCREX. Best fit exponential lines have been fitted to the data in these temperature ranges; the coefficient of the exponential is found to be a quadratic function of temperature.



## Mesoscale weather systems

### Polar lows

Polar lows are a significant weather forecasting problem over polar waters as they have small scales and can develop heavy snow and strong winds in short periods. Detailed mesoscale analyses of an intense, but poorly forecast, polar low benefited greatly from the weather radar installed in 1992 at Beacon Hill in north-west Scotland. These analyses (Fig. 29, colour section) showed well-defined surface fronts (F1, F2), a cloud head (H) and other features of conventional mid-latitude depressions, though with only 1/5 of the accustomed length scales.

None of the available observations suggested that upper-level forcing was present, but in this trial case new diagnostics based on the deformation in the large-scale low-level flow were found to provide a helpful forecasting indicator.

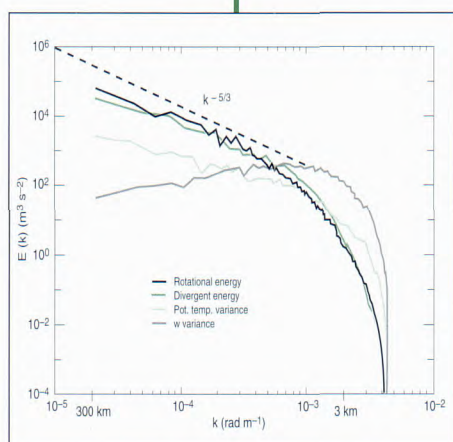


Fig. 30. Spectral energy densities of the horizontal kinetic energy (split into rotational and divergent components), vertical velocity variance and potential temperature variance in a LES model simulation of a deep convective cloud ensemble. The model domain is cyclic on a scale of 300 km.

the Unified Model's gravity wave drag parametrization scheme utilizing an idealized description of the orography. Representation of this aspect of gravity wave drag will cause parametrized wave-drag to be more uniformly distributed with height in certain synoptic situations. (See also ref L page 26)

### Mesoscale energy cascade

Aircraft observations of horizontal wind variations have established that the kinetic energy spectrum follows a  $k^{-5/3}$  power law (where  $k$  is the horizontal wave number) for scales between 5 and 700 km. For quasi-horizontal motion, this form of power law suggests an upscale energy-cascading inertial sub-range. The LES model has been used to investigate the potential for deep convection to force such an energy cascade. Convection in cold airstreams over warm seas was simulated by fixing the surface temperature and continually cooling the atmosphere. After one day of model integration, the energy spectrum of the rotational and divergent wind components follow the  $k^{-5/3}$  power law for scales greater than about 20 km (Fig. 30). In an identical run without the Earth's rotation (Coriolis parameter set to zero) the power law was absent and little energy escaped to large scales. The reason for the different efficiency of upscale energy transfer lies in the differing forms of vorticity anomaly forced in the with-rotation and without-rotation cases.

## Boundary layer

### Experimental studies (Ref K)

Two detachments were undertaken with the tethered balloon and other boundary layer instruments. During these, simultaneous measurements were made of surface conditions and of fluxes of momentum, heat and humidity at various heights within the boundary layer. During the first, in June, at a site in Sherwood Forest, the structure of the boundary layer flow over heterogeneous terrain was investigated. In the autumn, at Llanthony in Wales, the evolution of stable nocturnal boundary layers over complex terrain was studied (see Fig. 31, colour section). Both field experiments provided good data which will form the basis of future research.

The measurements obtained during an earlier field experiment near Wantage have been analysed.



The heterogeneous terrain in this location is unusual and the rougher of the two types of surface elements predominantly induced pressure drag rather than the skin friction (transverse stress) type of drag assumed by most numerical model parametrizations.

The observations of effective roughness length were compared with those deduced from a scheme which quantifies the form component of the total surface drag around isolated obstacles, and good agreement was obtained although only a limited variation of element densities was present.

### Boundary-layer modelling

Results from numerical investigations using the LES model to simulate the convective boundary layer are being applied to assess the performance of various parametrization schemes. Fig. 32 shows the variation of surface stress with stability predicted by the LES model, by a simple mixing-length model, and by the single column version of the Unified Model.

The serious underprediction by the Unified Model in convective conditions is consistent with its known tendency to underestimate near-surface winds over land in summer, a feature that has been shown to be related to the interaction of the boundary layer and convection schemes. The sensitivity of model results to the amount of mixing performed by these two parametrizations is being assessed.

The introduction of the 'orographic roughness length' for momentum into the Unified Model, has significantly improved the parametrization of surface momentum fluxes in the model. The numerical flow-over-hills model has been used to investigate an appropriate scheme for deriving orographic roughness lengths for temperature. Calculations were made of the roughness lengths consistent with modelled fluxes at each model level. Fig. 33 shows that such roughness length profiles are almost constant with height in the boundary layer (at values of about 0.23 m for temperature and 1.2 m for momentum), indicating that an orographic roughness length for temperature is a suitable quantity to characterize the influence of the underlying terrain on heat fluxes in the boundary

layer. It is therefore appropriate to use it in a parametrization scheme for the area-average surface heat flux within the Unified Model. (See also Ref L page 26.)

## Atmospheric dispersion and air quality

### Short-range dispersion (Ref J)

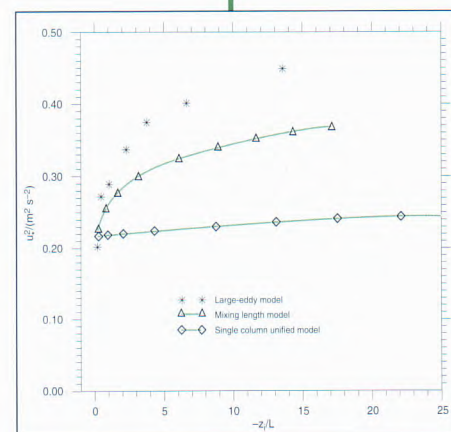
The turbulence in the atmospheric boundary layer is the dominant cause of dispersion over short ranges.

However, plumes are not spread by a smooth diffusive action but by advection by random turbulent eddies. This leads to large fluctuations in concentration within the plume which are of great importance when considering the consequences of releases of toxic, flammable or odorous material.

A range of simple analytical models has been developed which provides a fairly complete description of the fluctuations in the various phases of a plume's development. In stable conditions the rate of spread of the plume in the vertical is limited, and wind shear increases the rate of spread in the horizontal. These effects have been investigated using the LES model with a view to improving the treatment of dispersion in stable conditions in ADMS (the Atmospheric Dispersion Modelling System — a practical PC-based system developed in collaboration with Cambridge Environmental Research Consultants and National Power).

### Urban pollution

An improved city 'box model' to forecast urban air quality is under test with NETCEN, Culham Laboratory, and is scheduled to go operational in Spring 1995. One component, a street canyon model,



*Fig. 32. Variation of surface stress with stability, predicted by various models given a geostrophic wind of  $10 \text{ m s}^{-1}$ , a boundary layer depth of 1000 m and a surface roughness of 0.1 m.*



has been applied successfully to air-quality data from Cromwell Road, London. Evidence was supplied to the Royal Commission on Environmental Pollution for its report on Transport and the Environment. The report argues that the potential health impacts of heavily trafficked major roads in urban and suburban areas appears to have been underestimated, and that the present system of producing urban air-quality forecasts could be extended, at very little extra cost, to cover all major towns and cities in the United Kingdom.

### Long-range dispersion

At longer ranges dispersion is dominated by advective processes. Under contracts with the Department of the Environment and the Ministry of Agriculture Fisheries and Food, a mesoscale domain covering the British Isles at 17 km resolution has been nested into the NAME long-range transport model (originally developed for predictions following a nuclear accident) and sulphur chemistry added (Fig. 34). Validation of long-range models is difficult, but a major step was taken in the autumn when The Met. Office participated in the European Tracer Experiment (ETEX) organized by Joint Research Centre at Ispra in Italy for the EC, WMO and the International Atomic Energy Authority. On two occasions passive perfluorocarbon tracer (with background concentrations only 4.4 fl/l (or  $10^{-15}$ ) was released from Rennes in Brittany, and its dispersion

across Europe monitored by 170 ground stations. Numerical models from organizations worldwide, including NAME, were used to forecast the tracer spread. With the aid of the NAME model the C-130 intercepted the plume over northern France and measured concentrations in real time (Fig. 35). Analysis of the surface and aircraft data is now under way.

### Atmospheric chemistry (Ref O)

A global Lagrangian chemistry model has been assembled to study the behaviour of radiatively active trace gases in the troposphere. The model, which utilizes archived meteorology from the Unified Model, employs a detailed chemistry scheme involving 53 species and about 100 reactions. Photochemical processes are described using solar radiation (varying with solar zenith angle, cloud and aerosol scattering) and emissions of methane, CO, SO<sub>2</sub>, NO<sub>x</sub> and a range of organic compounds. The model is being used to calculate the distributions of the main radiatively active gases and aerosols — methane, ozone and sulphate aerosol — for the pre-industrial, present-day and future atmospheres (Fig. 36). The two-year EC-supported airborne atmospheric chemistry programme, OCTA, was completed in May; it involved a total of 16 flights of the C-130 aircraft across a wide region of the North Atlantic to collect data on photochemical pollutants and their precursors in the troposphere.

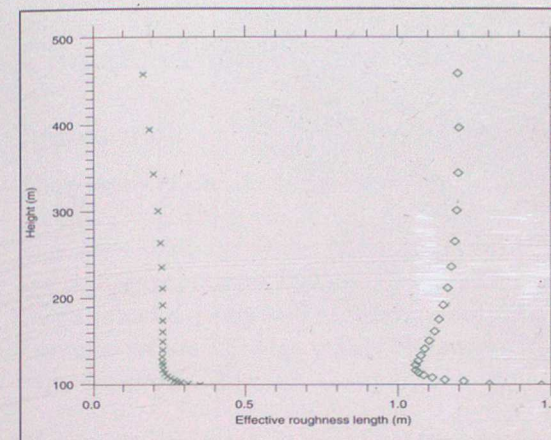


Fig. 33. Effective orographic roughness-length profiles for temperature (crosses) and momentum (diamonds) diagnosed for a 2-D numerical model for flow over a 100 m hill with a slope of 17°, assuming neutrally stable conditions and a surface roughness length of 0.1 m.

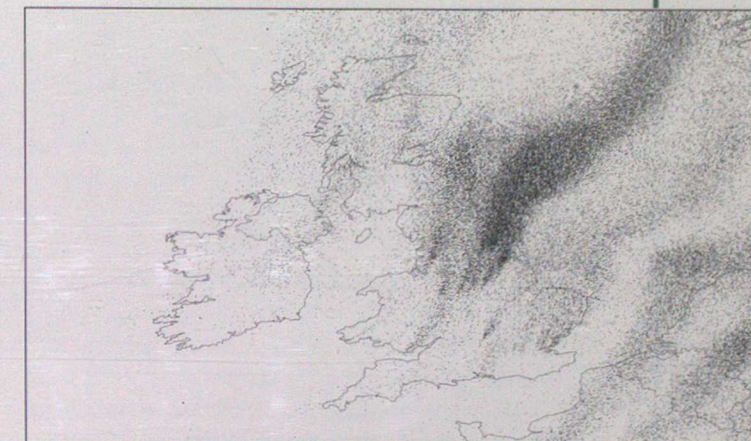


Fig. 34. An integration of the new NAME sulphur model starting 0000 UTC 15 January 1995. Particles representing the assumed emissions were released continuously from 90 major point sources such as power stations and oil refineries, and from sources 50 km square. The plot shows the end-points of particle trajectories after four days. Concentration and acid deposition can be calculated from these distributions.

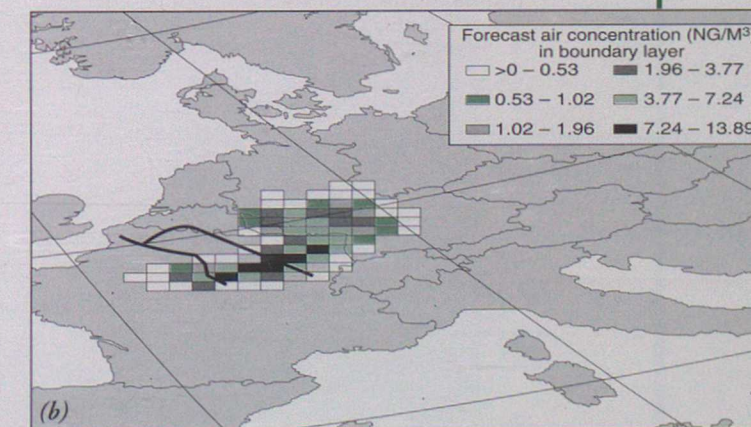
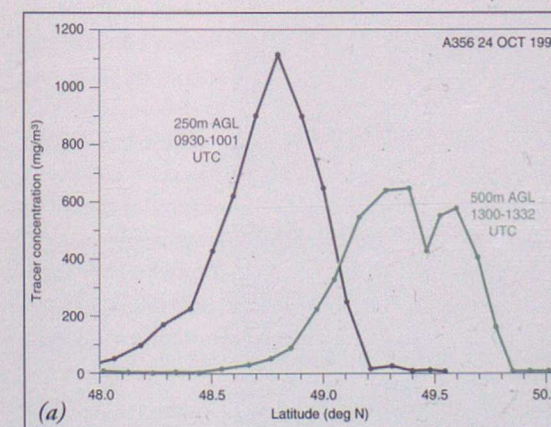


Fig. 35. (a) Concentrations of perfluorocarbon tracer measured at two heights and times over northern France by the C-130 during the first ETEx experiment, 24 October 1994. (b) A plot of the NAME forecast (based on the 1200 UTC analysis on 23 October) of 3-hourly mean boundary-layer concentrations at Auxerre, 47.5° N, 3.3° E, one of the closest points to the C-130 traverses at which a model diagnosis was made. The smoothed 3-hour means suggest (b) is intermediate between the curves in (a).



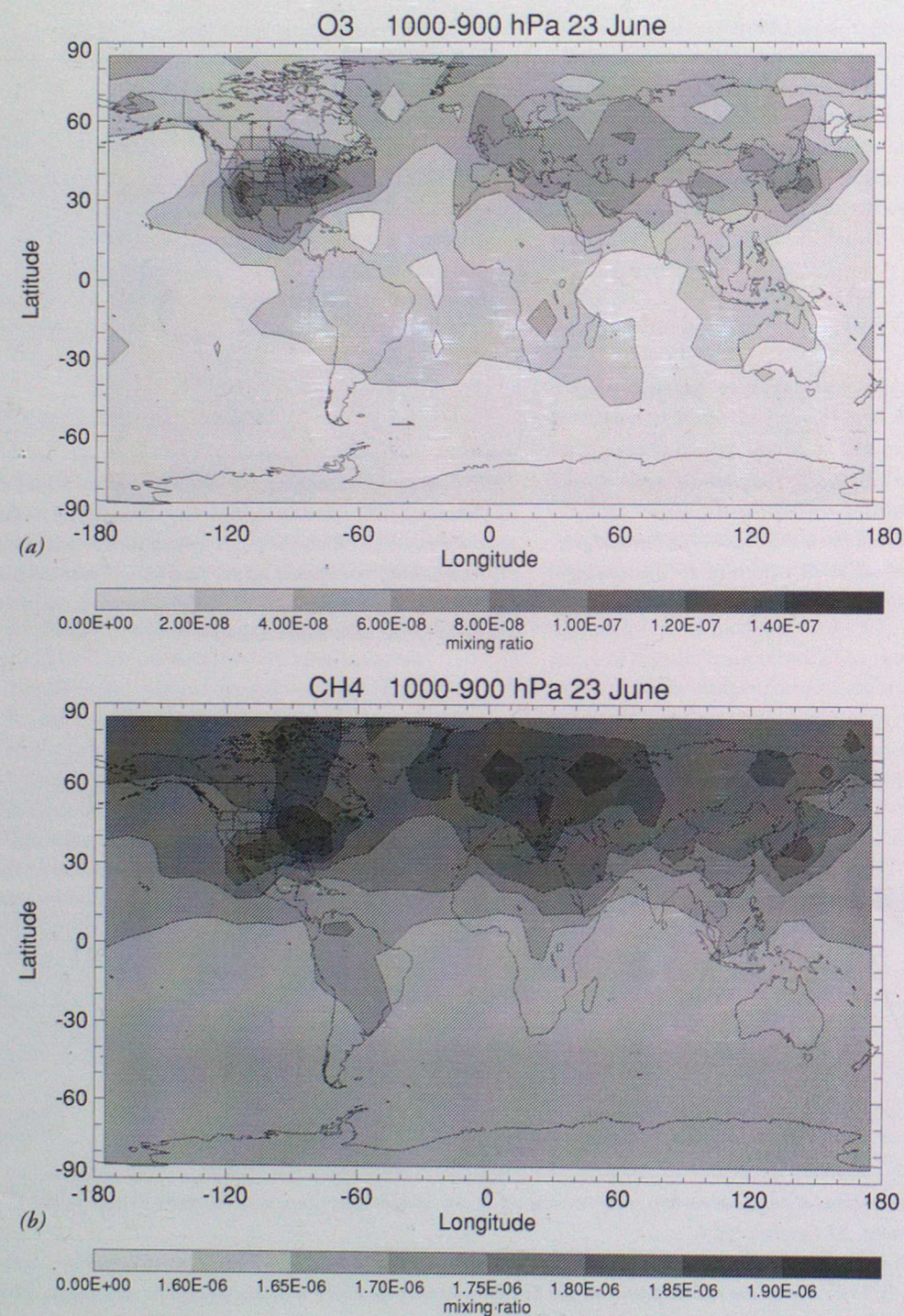


Fig. 36. Output from the Lagrangian tropospheric chemistry model showing the global, 24-hour mean near-surface distributions of (a) ozone and (b) methane following an integration from 2 May to 23 June, 1994.

## Climate Research

### Climate variability and change

#### Introduction

The prospect of climate change due to man's activities continues to be a high profile scientific and political issue. Monitoring and prediction of climate variability and change are principal aims of the Hadley Centre which is funded jointly by the Department of the Environment and The Met. Office. The major objectives of the Centre are

- to simulate present climate, understand its natural variability and seek the 'fingerprint' of anthropogenic climate change;
- to understand the factors controlling climate change and to predict regional and global climate change up to the end of the 21st century;
- to develop and use global climate models to support the above tasks.

It aims to provide a focus for other national research programmes relevant to these areas of work, in particular by incorporation of their results into predictive models of the atmosphere, ocean, land surface and sea ice which are continually being developed. Climate prediction requires these models to be run in 'coupled' mode, so that the interactions between them are represented. Most of this work is done on the Cray Y-MPC90/16256 supercomputer. Rapid and effective analysis of results is provided by a graphics workstation system.

#### Observed climate variability and change

The study and monitoring of worldwide climatic change and variability requires a range of databases which must be continually improved as new data become available and better techniques of analysis are developed. For example, archives holding at least 8 million undigitized marine meteorological

observations, which have great potential to improve our knowledge of climate then, have been discovered for the years around the two world wars. In addition, real-time sea-surface temperature and marine air temperature analyses now incorporate more efficient data capture with better quality control.

A major development has been the creation of a new version of the Hadley Centre's Global sea-Ice and Sea Surface Temperature (GISST) data set which runs from 1871 to the present. This gives much-improved representations of sea-surface temperature (SST) patterns in earlier, data-sparse years. Better sea-ice data have been provided by collaborators in the USA and the specification of SST in marginal ice zones has been improved. The validity of the complex corrections involved in the derivation of GISST for the south-west Pacific is confirmed by Fig. 37 which compares data sets of annual mean temperatures for New Zealand and the surrounding area for the period 1870 to 1993.

Expanded analyses of worldwide maximum (day) and minimum (night) land surface air temperatures confirm earlier calculations showing that recent warming has occurred largely at night. To fully understand these and other climatic changes, we need a comprehensive global data set of atmospheric circulation. The most complete data are for sea-level pressure, so a quality controlled data set is progressively being built with substantial help from scientists abroad.

Temperature data for the troposphere and lower stratosphere measured by radiosondes are especially important for detecting man's influence on climate. However, the data are of variable quality. Comparisons of radiosonde temperature data with collocated, and relatively accurate, Microwave Sounding Unit measurements provides a new approach to the

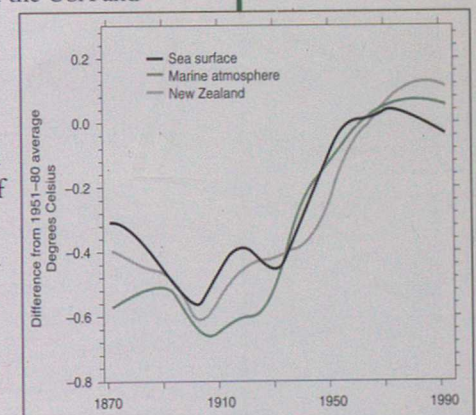


Fig. 37. Smoothed changes in annual air temperature (°C) over New Zealand, and in sea-surface and air temperature over the immediately surrounding ocean since 1871.



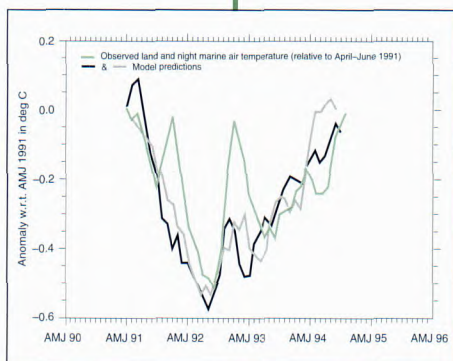


Fig. 38. Model simulations of the impact of Mount Pinatubo on global mean surface air temperatures ( $^{\circ}\text{C}$ ) versus observed values. AMJ=April, May, June.

homogenization of radiosonde data since 1979. Such comparisons reveal a likely artificial cooling in the radiosonde record for the lower stratosphere since 1979 which is thought to be due to instrumental bias.

The 1994 globally averaged near-surface temperature, based on measurements over land and at the sea surface, was the 3rd or 4th highest in the record (data voids continue to give significant uncertainties in ranking). A reason for the undoubted greater warmth in

1994 (by about  $0.12^{\circ}\text{C}$ ) compared with the previous two years is likely to be the waning of the cooling influence of the 1991 eruption of Mount Pinatubo in the Philippines (Fig. 38).

### Simulated climate variability

The links between climate variability and SST anomalies are being examined in ensemble experiments using the Unified Model (see FR section) run with the GISST data set. The first phase of these experiments is now complete. These consist of an ensemble of six model runs for the period 1949–93, and four runs for 1974–93, with fixed concentrations of  $\text{CO}_2$  in the model atmosphere. Each is forced with the same surface data but starts from different initial atmospheric conditions. A number of results are emerging from these studies. For example, the model has been found to simulate the observed reduction in sub-Saharan rainfall between the 1950s and the 1980s and, as demonstrated in Fig. 39 (colour section), the mean atmospheric response over North America in late winter to warm and cold events in the tropical Pacific. These studies have now entered their second phase. This consists of experiments for the period 1903–93, which include rising concentrations of greenhouse gases (expressed as equivalent  $\text{CO}_2$ ) and which will later be expanded to include effects of aerosols.

### Interaction between trace gases, aerosols, clouds, radiation and climate

There is increasing worldwide interest in the impact of anthropogenic sulphate aerosol particles on climate. Most attempts to quantify the effect of these particles have concentrated on the degree to which they reflect solar radiation back to space (the so-called direct effect). Aerosols also have an indirect effect, in that they increase the number of cloud condensation nuclei (CCN) in the atmosphere. If cloud water contents remain the same, then the mean size of cloud droplets formed on these nuclei can be expected to decrease. This leads to more reflective clouds which exert a negative (cooling) radiative forcing on the climate. Estimating this forcing has proved difficult due to the complex interactions of aerosols, clouds and radiation.

A scheme to predict cloud droplet effective radius, needed to assess the indirect effect of sulphate aerosols, has been developed for the Unified Model. Using data on sulphate aerosol distributions, the scheme gives volumes of effective radius for present-day conditions which compare favourably with observational data. The first published estimate of the indirect radiative forcing by anthropogenic sulphate aerosols has subsequently been produced (Fig. 40). Globally, this amounts to mean cooling rate of  $-1.3 \text{ W m}^{-2}$ , compared to a mean warming rate of  $+2.5 \text{ W m}^{-2}$  estimated by IPCC for the increases in greenhouse gases to date.

A new radiation code in the Unified Model (see below) has been used to estimate the direct radiative forcing from sulphate aerosol also (Fig. 41 colour section). The global mean value of the forcing was found to be approximately  $-0.4 \text{ W m}^{-2}$ , which is near the lower end of recent estimates in the literature.

Work has also begun on a scheme to simulate the distribution of sulphate aerosol to be used within the Unified Model. Processes taken into account include specified sources, modelled transport mechanisms (including boundary layer turbulence and convective mixing) as well as large-scale advection, and scavenging by precipitation.



The greatest uncertainty associated with the representation of clouds in climate models is the change in cloudiness as global temperature increases, the so-called cloud feedback. There have been various attempts to deduce this by considering how clouds vary with the observed seasonal cycle and also from year to year. The Unified Model has been used to compare this approach with methods of determining cloud feedbacks from climate change simulations. Results indicate that although there are qualitative similarities, the quantitative differences are significant. This suggests that cloud feedback cannot be derived from present-day observational studies alone.

Recent claims that clouds absorb much more solar radiation in the real atmosphere than previously supposed have been tested in the Unified Model. The results showed a warming of the model atmosphere which was strongest in the mid-latitudes and substantially reduced the model's cold bias. However, other aspects of the simulation were worse, including the simulation of precipitation, which was reduced by 20% globally; the investigations also suggested the changes would make little impact on the simulation of climate change.

A new radiation scheme which incorporates the minor greenhouse gases methane, nitrous oxide and CFC-11 and -12 has been developed. Experiments have been performed to compare the impact of implicitly allowing for these gases using CO<sub>2</sub> as a surrogate, and explicitly representing them in the model. Preliminary results suggest that, while the overall response is similar, there are significant quantitative differences (Fig. 42). In particular, the use of 'equivalent CO<sub>2</sub>' underestimates the mean warming by about 12%.

## Simulation and prediction of climate change

### The transient response to increased greenhouse gases and sulphate aerosol

A key objective of the Hadley Centre's programme is to make predictions of anthropogenic climate change through the next century. The coupled

ocean-atmosphere model has been used this year in two experiments to simulate and predict climate change from 1860–2050. In the first of these, CO<sub>2</sub> was increased to represent changes in greenhouse gases from 1860–1990, whilst from 1990–2050 an increase of 1% per year (compound) was assumed. In the second, the direct effect of anthropogenic sulphate aerosols was also included by increasing the surface albedo. The prescribed aerosol forcing was based on historical emission records (1860–1990) and on a scenario of future concentrations for 1990–2050. Unlike the greenhouse gas forcing, the direct aerosol forcing is spatially variable, being concentrated over the major industrial regions of the northern hemisphere (see, for example, Fig. 41 colour section).

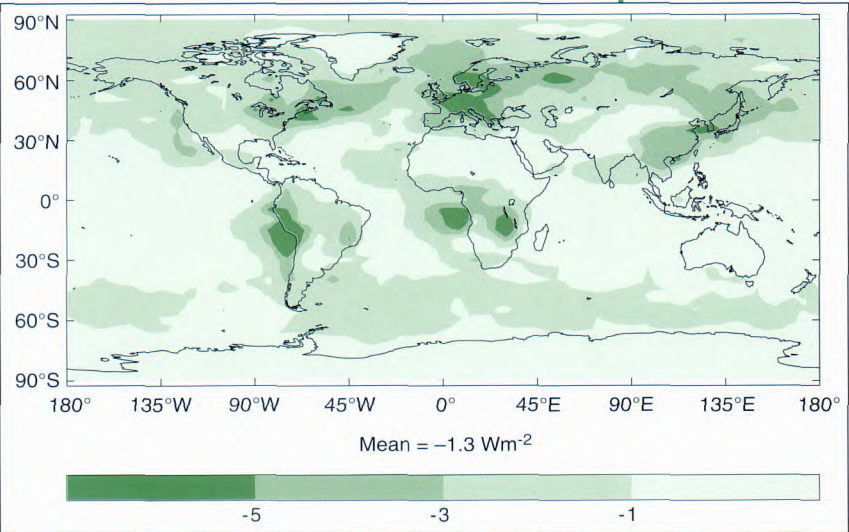


Fig. 40. Distribution of the annual mean indirect radiative forcing ( $W m^{-2}$ ) due to anthropogenic sulphate aerosols.

When driven by greenhouse gases only, the simulated global mean warming exceeds the observed value at 1990 by about 0.5 °C (Fig. 43). With the inclusion of the effects of aerosol, however, the difference between the model and observations is reduced to 0.1 °C, bringing it into much better accord with the 20th century record, and increasing confidence in the model's ability to predict future climate. The distribution of the observed change since the end of the



19th century shows patchy areas of cooling over the northern hemisphere continents. The aerosol run captures this feature qualitatively, although in the simulation the areas of cooling are larger. This reflects the uncertainty associated both with the effects of natural variability and of aerosols (see above).

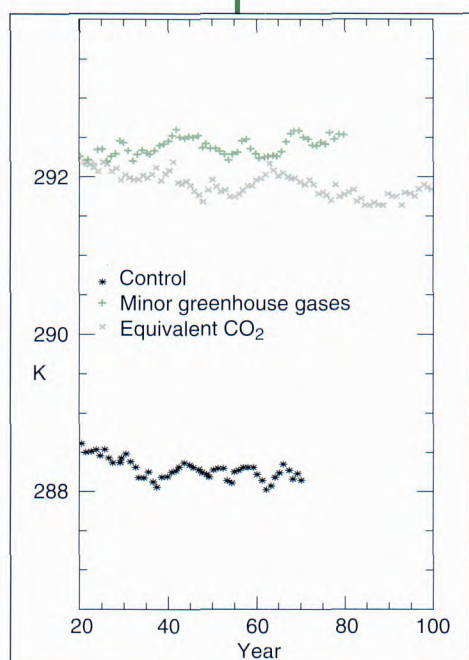


Fig. 42. Annual global mean surface temperatures after equilibrium in three climate model simulations: control (black), an experiment explicitly including the minor greenhouse gases (green), and with these represented by 'radiatively equivalent' CO<sub>2</sub>.

For the next century (see Fig. 43), both simulations predict an accelerated rate of warming. This amounts to 0.3 °C per decade in the greenhouse-gas-only run and 0.2 °C per decade in the run including aerosol. In the latter, almost all areas show a warming over the next 50 years relative to 1990 (Fig. 44, colour section). Predicted changes in sea level amount to around 3 cm per decade, even after allowing for the cooling effects of aerosols. The Secretary of State for the Environment, the Rt. Hon. John Gummer, was briefed on these new results prior to his participation at the first Conference of the Parties to the UN Framework Convention on Climate Change, held in Berlin from 27 March to 7 April 1995. A summary brochure and presentations by Hadley Centre scientists also attracted a great deal of attention at the Berlin meeting. Later, in answer to a question in the House of Commons,

Mr Gummer cited the Hadley Centre work as giving "every indication of the link between the emission of greenhouse gases and global warming".

#### Regional climate modelling

High-resolution regional simulations have been obtained for Europe by nesting a limited-area version of the climate model inside the global version. Fig. 46 compares the precipitation field simulated over the UK by the global and regional models against a high-resolution observed climatology developed at the

Climatic Research Unit, University of East Anglia. The results show that the enhanced fine-resolution detail available from the regional model compares well with the observed distribution. The model is being applied to obtain greater regional detail in enhanced greenhouse gas scenario experiments.

#### Changes in variability and extremes

Although climate change predictions are usually presented in terms of changes in time-averaged quantities, the most serious impacts are likely to arise from changes in the frequency of extreme events, such as high temperatures, strong winds, heavy rains and droughts. Results from previous experiments are being analysed to investigate changes in variability and extremes. In simulations with doubled CO<sub>2</sub> the number of rain days decreases; however, the frequency of heavy precipitation events increases, implying a possible increase in the probability of local flooding. In common with other models, the results indicate more-frequent droughts during summer in southern Europe.

An objective technique for identifying depression centres has been applied to daily northern hemisphere surface pressure fields from a previous coupled model experiment. When CO<sub>2</sub> is increased, the largest changes occur at the eastern extremes of the Atlantic and Pacific storm tracks where the total number of depressions decreases. However, the frequency of deep lows increases, implying fewer but deeper cyclones over the UK and western Europe.

#### Palaeoclimatic simulations

One method of establishing the trustworthiness of predictions of future climate change is to investigate the ability of models to simulate past climates. This is being done for mid-Holocene conditions (6000 years ago) in collaboration with the international Palaeoclimate Modelling Intercomparison Project. Results (Fig. 45) show broad agreement with observed palaeogeographic data.



## Atmospheric model development

Continual refinement and improvement of the formulation of physical processes in the Unified Model are essential tasks. A number of improvements to parametrizations developed over the year are being incorporated into a new model version. Notable changes were to the layer-cloud scheme and the introduction of revised gravity-wave drag and orographic-roughness schemes.

### Large-scale layer clouds (Ref N)

The effects of clouds continue to be one of the main causes of uncertainty in the prediction of climate change. Although the current version of the Unified Model simulates many aspects of the Earth's radiation budget well, it is known to have excessive albedos at the top of the atmosphere over mid latitudes and to underestimate albedo in the tropics and subtropics. The latter is associated, for example, with under-prediction of cloud amount in marine stratocumulus decks under subtropical anticyclones.

Work to reduce some of the errors associated with cloud prediction has progressed. Amounts of modelled subtropical stratocumulus have been shown to increase significantly when boundary-layer resolution is improved by a factor of 3. This reduces albedo errors, and the representation of net surface heat flux over the sub-tropical oceans is improved (Fig. 47, colour section).

The sensitivity of the cloud simulation of the Unified Model to the fraction of cloud which is ice at a given temperature has also been studied. Observations of frontal cloud made by the C-130 of the Met. Research Flight suggest that although the fraction of cloud which is ice varies greatly, many clouds are fully glaciated at  $-9^{\circ}\text{C}$ . Modification of the cloud scheme used in the Unified Model to conform with these observations leads to reductions in cloud amounts, especially over northern latitudes during summer, and over the southern hemisphere depression belt around Antarctica. These changes bring the radiation budget at the top of atmosphere closer to satellite observations.

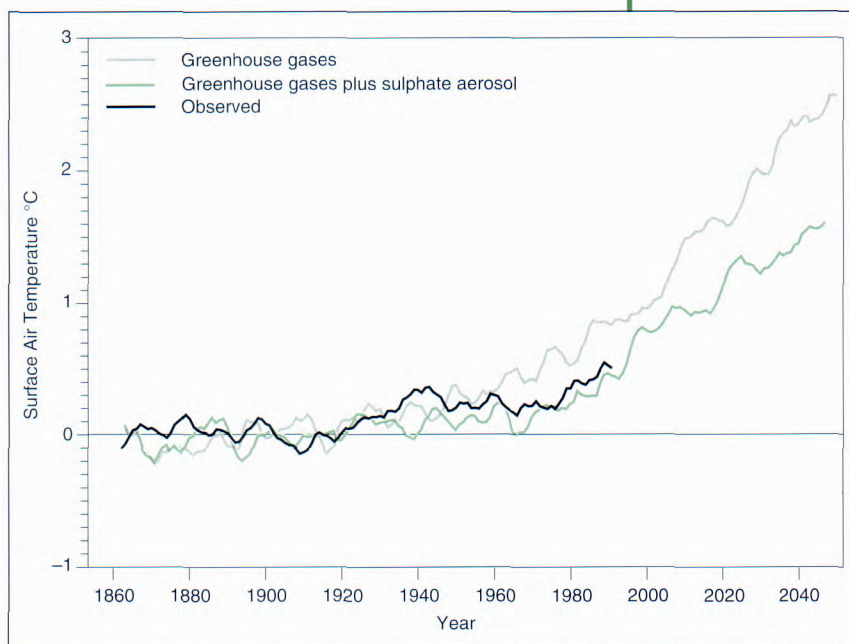


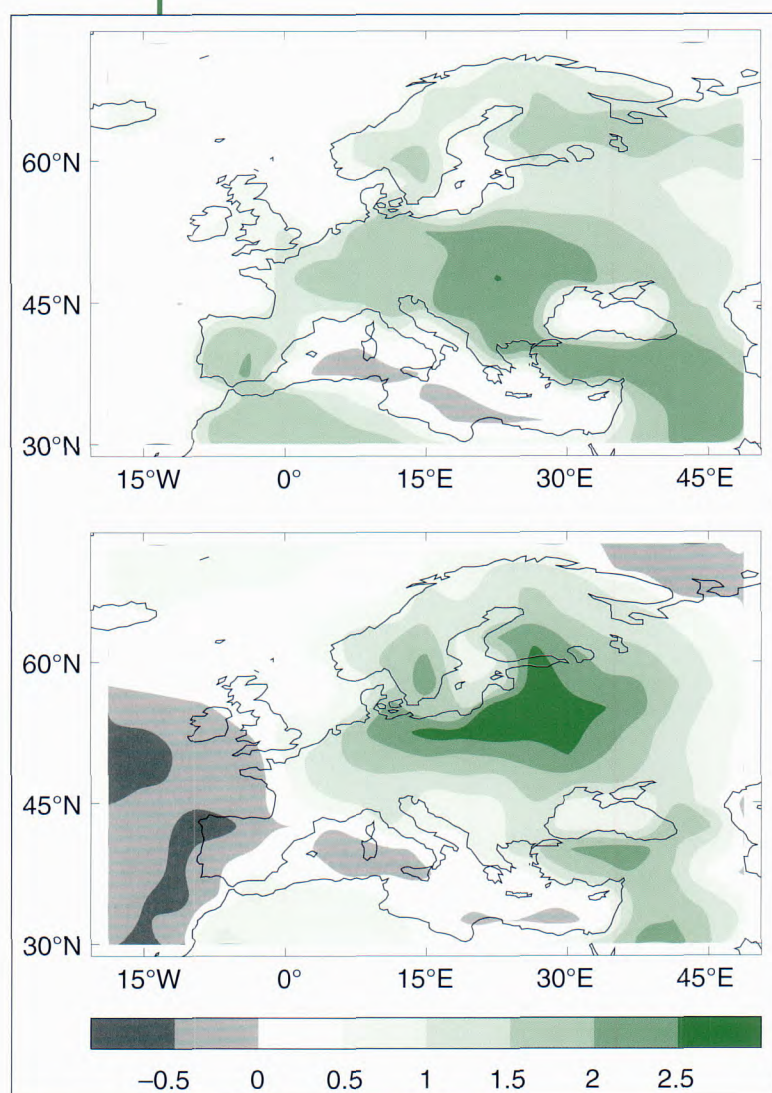
Fig. 43. Simulated global-mean surface air temperature ( $^{\circ}\text{C}$ ) from 1860–2050 for greenhouse gases only (blue curve) and greenhouse gases plus sulphate aerosol (green curve). Observed values (red curve) are shown from 1860–1990.

Sensitivity to ice processes is one motivation for the development of a new cloud scheme for the Unified Model. It incorporates an explicit treatment of ice clouds (rather than by the simple function of temperature used at present) and more-detailed microphysical parametrizations. Tests of the scheme are under way in the mesoscale version of the Unified Model at the Joint Centre for Mesoscale Meteorology (JCMM) at the University of Reading. Aspects of the scheme are also being developed in collaboration with the University of Manchester's Cloud Physics Group. (See also Ref M page 30)

### Convection

Whereas layer cloud has a large impact upon the Earth's climate in the mid-latitudes, deep convection plays a large role in the tropics. Using results from the JCMM detailed cloud model, a simple parametrization of the effects of across-cloud pressure gradients has been developed for the Unified Model





*Fig. 45. Simulated change in July surface air temperature ( $^{\circ}\text{C}$ ) between 6000 years ago and present day. Atmosphere model with fixed (present day) sea surface temperatures (top), coupled ocean-atmosphere model (bottom).*

convection scheme, which then gives better agreement with diagnostics from the detailed model. A comparison of convection schemes in a one-dimensional version of the Unified Model has also been carried out in collaboration with a visiting scientist from the Chinese Academy of Meteorological Sciences. Another collaboration was the use of the Unified Model to study break and active phases of the summer

monsoon over India with a visiting scientist from the Indian Institute of Tropical Meteorology, Pune. Results have shown the model well able to represent the northward shift of the main precipitation region from central India to the Himalayas during a monsoon break.

## Radiation

Work on a new radiation code for use in the Unified Model has included detailed comparisons between the radiation code and observations from the Meteorological Research Flight. (See Ref N page 32). Validation of the code against line-by-line models has been continued and this work has led to the production of a faster version. Initial integrations have shown an encouraging reduction in the cold bias of the model when the new radiation scheme is introduced.

## Orography

The climatology of general circulation models is improved by the inclusion of drag associated with the breaking of gravity waves forced by low-level flow over mountains. A new representation of this processes has been developed with the Atmospheric Process Research Division. Together with a representation of drag due to the roughness of orography developed within the Forecasting Research Division, this provides an improved simulation of the flow in mid-latitudes at both climate and operational forecast resolution. These schemes were introduced into the operational forecast model early in 1995. (See also Ref L page 26)

## Atmospheric model validation

Simulations of present-day climate provide a stringent test of a general circulation model. Multi-year runs of the atmospheric model, where the interaction with the oceans is prescribed using observed sea-surface temperatures, have been validated against a wide variety of data. Temperature, wind and moisture at upper levels have been compared with operational analyses and



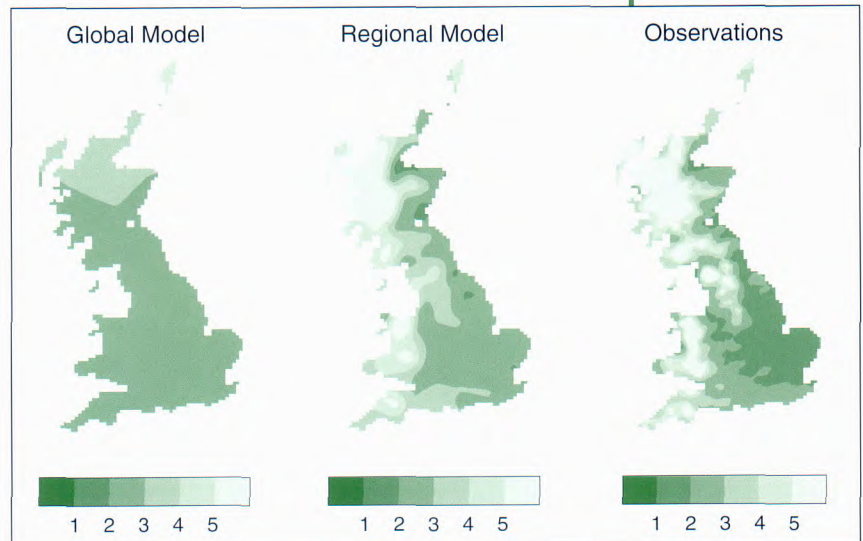
radiosonde observations; surface parameters have been compared with reports from ships and land stations. Satellite data have provided information on clouds and the radiation budget. Fig. 48 provides an illustration of the good agreement that has been found with the current version of the climate model.

Valuable insights into the nature and cause of systematic errors can be gained by comparisons between different models. For this reason particular importance has been attached to the Hadley Centre's participation in the Atmospheric Model Intercomparison Project (AMIP), sponsored by the World Climate Research Programme, and a second parallel project into high-resolution models sponsored by the National Meteorological Services' European Climate Support Network.

The system for the Simulation and Analysis of Measurements from Satellites using Operational analyses (SAMSON) uses global analyses produced by weather forecast models combined with the new radiation code to simulate clear-sky long-wave radiative fluxes and heating rates. Development work is now complete for CLERA (Clear-sky Long wave from the ECMWF Re-Analysis), which aims to provide improved clear-sky simulations for the 15-year period 1979–1993. Comparisons of early results with satellite data from the Earth Radiation Budget Experiment (ERBE) show agreement to within  $5 \text{ W m}^{-2}$  over large regions of the oceans, with discrepancies appearing mainly over land (see Fig. 49). Preliminary comparisons with the Hadley Centre climate model show the potential for CLERA as a useful tool for validation of the model's clear-sky long-wave fluxes and heating rates, and hence its atmospheric temperature and humidity structure.

### Developments in modelling of land-surface processes

Land-surface processes play an important role in simulations of weather and climate through their modulation of the surface radiative heat transfer and the turbulent transfers of heat and water vapour into the atmosphere. Further advances have been made this year in representing the interactions between



*Fig. 46. Ten-year mean precipitation (mm/day) for December, January and February simulated by the global general circulation model (left) and the nested high-resolution regional model (middle) over Great Britain, compared against a high-resolution observed climatology for 1961–90 (right).*

vegetation and evaporation, and the dependency of the stomatal conductance of Thetford Forest on environmental variables have been reanalysed in collaboration with the Institute of Hydrology. A number of models which include an explicit coupling between stomatal conductance and photosynthesis are being tested; each of these provide a representation of the effect of increasing  $\text{CO}_2$  on transpiration. This is potentially important in the response of climate to increasing  $\text{CO}_2$  through its effect on soil moisture and rainfall in middle latitudes in summer.

Interactions between vegetation and climate have been investigated during the year as part of a collaboration under the Terrestrial Initiative in Global Environmental Research (TIGER) programme. The Dynamic Global Vegetation Model developed at the University of Sheffield has been run to assess the feedback caused by the response of vegetation to the climate changes simulated by the coupled model with doubled  $\text{CO}_2$ . An important feature of the response is a warming over eastern Asia associated with the decreased surface albedo in snowy conditions, caused by increased vegetation which masks the underlying snow.



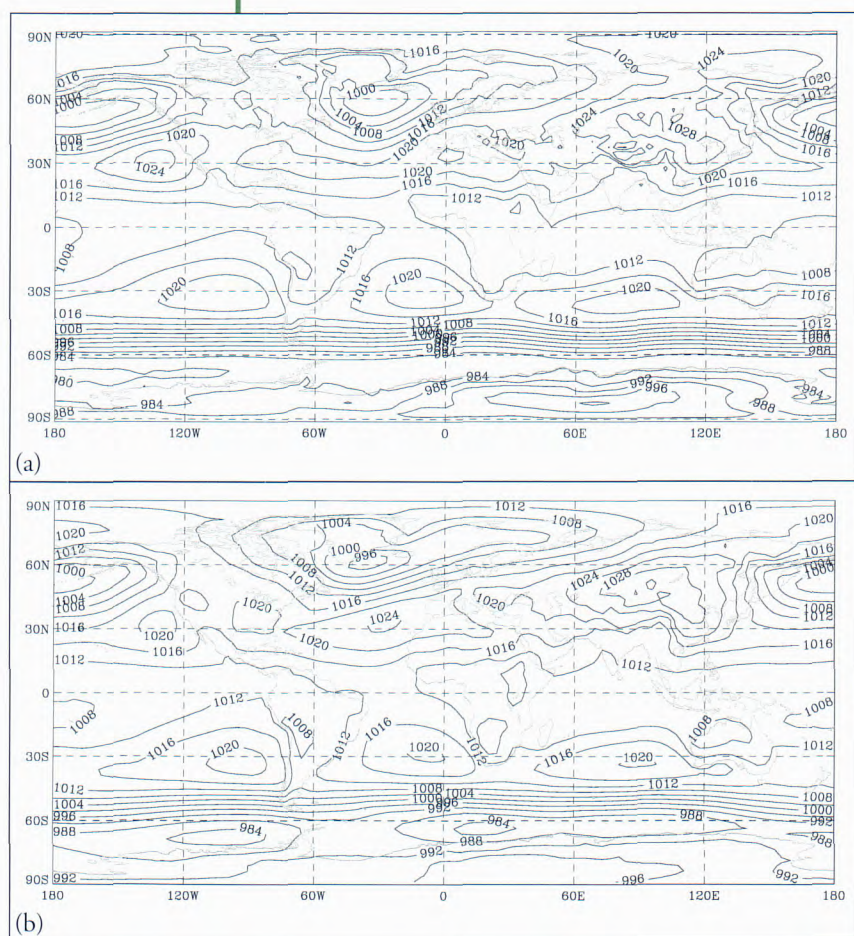


Fig. 48. Mean-sea-level pressure (hPa) for December, January and February from, (a) 10-year simulation with the climate model, and (b) Met. Office analyses 1983–94.

Surface turbulent fluxes are also modulated by the transfer of water in the soil and the modelled snow cover. The multi-layer soil hydrology scheme has been tested further and is being used to include the effects of soil moisture on soil thermal processes in the model, together with a representation of the freezing of soil. Methods of representing a patchy snow cover are being investigated using the APR Division's two-dimensional boundary layer model. Preliminary tests against data from observational studies of surface processes in Canadian boreal forest regions show quite good agreement over a frozen snow-covered lake.

Assessments of the model have also been made using measurements from forested and deforested regions of Amazonia as part of the collaborative studies with the Institute of Hydrology and the Instituto Nacional de Pesquisas Espaciais, Brazil to estimate the climatic effects of deforestation of Amazonia. Results of ten-year simulations, in which the whole of the Amazonian forest was replaced by pasture, have allowed a more confident assessment of regional effects. A series of companion experiments have allowed clearer identification of the mechanisms involved and have highlighted the large sensitivity of regional changes to the specification of these parameters. The results of full deforestation show rainfall increases over the north-west of the deforested area and decreases over other parts of Amazonia. An experiment with deforestation confined to a more realistic reduced area has shown rainfall changes similar to, though smaller than, those with full deforestation (Fig. 50, colour section).

Validation of the land-surface parametrizations has continued through the Project for Intercomparison of Land-Surface Parametrizations, in which model-generated data was used to force stand-alone versions of the surface parametrizations schemes of over 20 participating groups. Intercomparison of the results has shown the Unified Model scheme to lie close to the centre of the surprisingly widely scattered distribution of results. The project has now moved into the second phase in which models are to be tested against observational data.

### Development of ocean, sea ice and ocean carbon cycle models

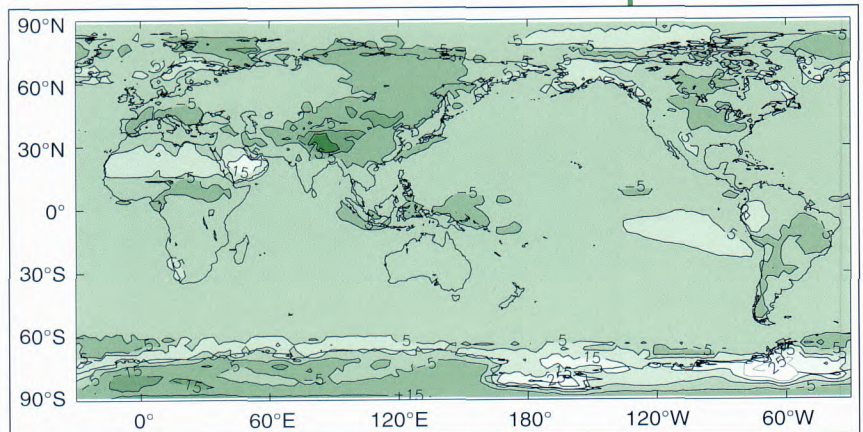
One of the restrictions of the current generation of coupled models is their relatively low resolution. The addition of a simple parametrization of ice dynamics completed a version of the coupled ocean–atmosphere model with a higher-resolution ocean component. In this an ocean resolution of  $1.25^\circ \times 1.25^\circ$  is used, compared to the  $2.5^\circ \times 3.75^\circ$  of the current coupled model. Various intercomparison experiments have been performed with the 'high'



and 'low-' resolution ocean versions of the model. In the equatorial oceans the 1.25° model provides a considerably more realistic simulation of the underlying dynamics associated with the El Niño Southern Oscillation (ENSO). The higher resolution model is also capable of a more realistic simulation of, for example, the high horizontal thermal gradients associated with the major ocean currents such as the Gulf Stream (Figs 51 (colour section) and 52) and Kuroshio. The precise positioning of these currents is an important factor in determining the mid-latitude sea surface temperature distribution and a number of investigations have been performed, initially concentrating on the Gulf Stream, to understand the dynamics of these currents within the model. Further analysis of the Meteorological Office ship drift current data has been carried out to produce improved estimates of the climatological currents to provide verification data.

A comparison of the surface fluxes from the atmospheric model with observed estimates has shown that, over most of the world's oceans, the 'flux corrections', necessary in coupled models to overcome drifts in the modelled climate, arise from inadequacies in the positioning of the major current systems by the ocean model. They can also arise as a consequence of a small number of known systematic errors in the atmospheric model simulation. Long integrations are needed in the ocean model for equilibrium to be reached. Techniques originally developed and used in purely dynamical versions of the ocean model have been extended to the current generation of models in which many physical processes are represented with greater realism.

Collaboration with the James Rennell Centre on a comparison of the Hadley Centre ocean general circulation model with the newer isopycnic coordinate model has continued. A controlled comparison of the two types of model configured for the Atlantic Ocean, has led to new understanding of the ways in which models handle the flow of dense currents over ridges, an important part of the global ocean circulation. A comparison of global versions of the two models is now under way.



*Fig. 49. Annual mean clear-sky outgoing long-wave radiation for 1979: CLERA minus ERBE climatology. Contour interval is 10 W m<sup>-2</sup>; regions with differences of more than 5 W m<sup>-2</sup> are shaded.*

The inorganic carbon cycle model, developed in the Hadley Centre, has been used to simulate the oceanic uptake of CO<sub>2</sub> for the period 1760–1990. The model has been validated using the tracers carbon-14, tritium and the freons F-11 and F-12 (Fig. 53). This model was also used to investigate the response to possible future emissions.

Investigations with the biological ocean carbon cycle model, developed at the James Rennell Centre, have demonstrated the importance of representing the horizontal advection of zooplankton in biological ocean modelling. Work is currently in progress to couple the inorganic and organic carbon cycle models, and to establish the optimum parametrization to use for the ecological processes on the global scale.

## ENSO and seasonal variability and prediction

ENSO is the largest climate fluctuation on interannual time-scales. It is generated by strong ocean–atmosphere interaction in the tropical Pacific region and has worldwide impact via its effect on atmospheric circulation. It is now becoming clear that under some circumstances ENSO is predictable at lead times of several seasons.



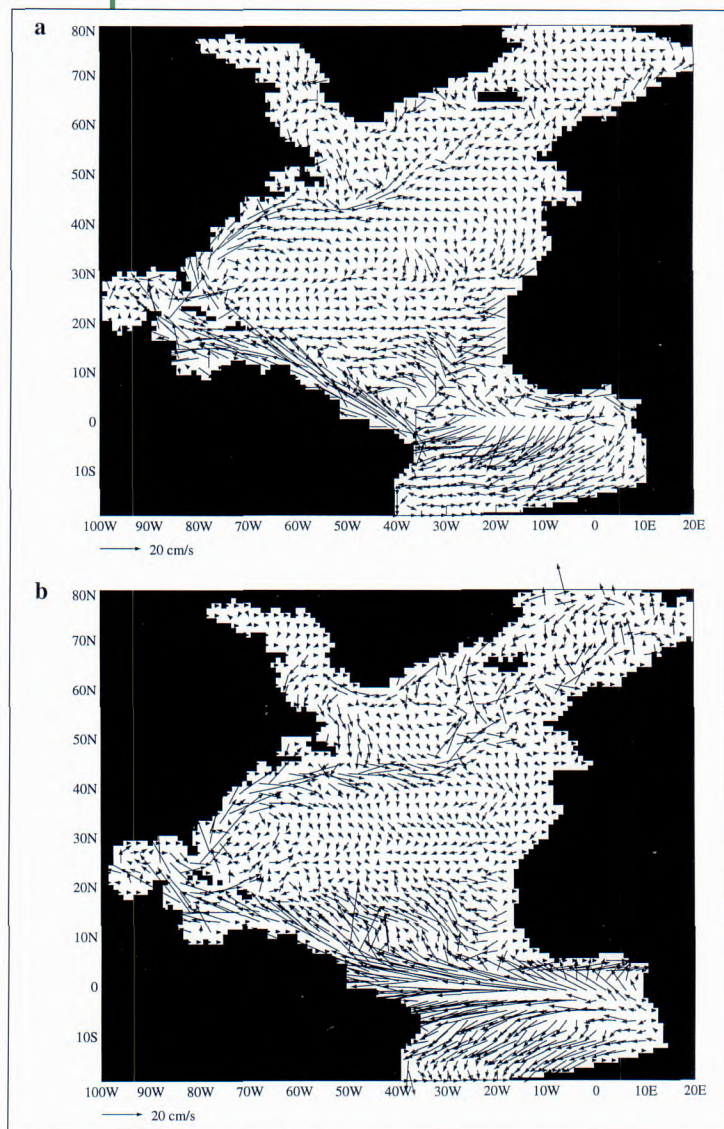


Fig. 52. North Atlantic surface ocean currents ( $\text{cm s}^{-1}$ ) from the  $2.5^\circ \times 3.75^\circ$  and  $1.25^\circ$  ocean models.

A high-resolution tropical Pacific Ocean model, developed at The Met. Office, has been shown, when forced with observed winds, to simulate El Niño events over the last three decades quite realistically. When run coupled to the climate resolution atmospheric model, integrations for several decades show interannual variability which includes several realistic ENSO events. A standard measure of the

pattern of variability is the correlation of pressure around the globe with that at Darwin. Fig. 54 shows such a map calculated from coupled model data. The model compares well with observed behaviour over the Pacific and Indian Oceans.

Such coupled models have the potential for ENSO prediction, given the appropriate initial conditions. The initial ocean state can be estimated by forcing the OGCM with observed winds, at the same time assimilating direct observations such as ocean temperature. The ocean assimilation scheme developed in Forecasting Research Division has been adapted for the tropical Pacific Ocean model for this purpose, and trials are in progress. Apart from the prediction application, assimilation is also a useful way of assessing the strengths and weaknesses of the ocean model.

While ENSO prediction with the coupled general circulation models is being developed, simpler, and computationally much cheaper, models have been used in collaboration with a group at Oxford University to investigate ENSO mechanisms and predictability. For example, a substantial difference between behaviour in the 1970s and 1980s has been found.

The close connection between sea-surface temperature anomalies and atmospheric circulation can be exploited to predict seasonal rainfall in certain sensitive areas. Indeed, it is now becoming apparent that models show a remarkable ability to reproduce the interannual changes in rainfall in certain sensitive regions when forced by observed sea-surface temperature fields. Real-time statistical forecasts have been issued for NE Brazil and tropical North Africa since the mid 1980s, with a high success rate. Such forecasts were again issued in 1994/95, with the addition of atmospheric general circulation model-based extended-range forecast information from the Forecasting Research Division; more recently neural net methods supplied by the tropical modelling group at Oxford University have been used. A forecast for East Africa was also issued for the first time in 1994. Training of African meteorologists in the development



and use of seasonal forecasting techniques was also undertaken. Modelling work has recently been extended to investigate European seasonal climate predictability. Initial indications are that this will be much lower than for North East Brazil, but some predictability seems likely.

## **Middle atmosphere research**

Analyses of the middle atmosphere (i.e. the stratosphere and mesosphere) carried out using a version of the Unified Model data assimilation scheme, are being used in a variety of applications. Many of these use data from the Upper Atmosphere Research Satellite (UARS) and are providing new insights into the dynamics and chemistry of the stratosphere. These analyses are produced daily, and during the year were adapted to run as part of the operational suite. They are supplied, in particular, to the UARS science team via the National Aeronautics and Space Administration Goddard Space Flight Center. This year were also supplied to the ASHOE aircraft campaign, together with trajectory calculations carried out in collaboration with Reading University.

The stratospheric data assimilation system has also been used to analyse some of the measurements from UARS. Experimental retrievals of stratospheric winds measured by the High Resolution Doppler Imager (HRDI) on board UARS have been successfully assimilated. The Met. Office UARS analyses themselves have been used for a number of studies of the stratospheric circulation. One was for the winter 1993/94 during which a number of interesting dynamical phenomena occurred, especially the splitting of the polar vortex into two distinct centres (which later recombined) several times; one such episode is illustrated in Fig. 55 (colour section).

In another recent collaborative study with NASA/JPL, The Met. Office stratospheric analyses have been used to help interpret observations of ozone depletion over the northern hemisphere, as measured by the Microwave Limb Sounder on board UARS during winter 1992/93. These have confirmed that the observed ozone decrease

could not have been caused by transport processes alone. Several model integrations are being carried out with a configuration of the Unified Model that extends through the troposphere and stratosphere up to the lower mesosphere. In this model, gravity-wave breaking in the lower mesosphere is parametrized by a simple Rayleigh friction scheme. Following recent changes to the formulation of this scheme and the treatment of radiation, improvements have been made to the stratospheric climatology of the model. We have now completed two integrations of over a year.

## **External liaison**

Strong links are maintained between the Hadley Centre and other groups involved in research on climate change, both in the UK and throughout the world. Some of these have already been indicated above, and there is an active programme of exchange visits, mainly as part of the DoE-funded Climate Prediction Programme within the Centre. Active involvement with other European groups is maintained, especially by participation in the CEC Environment Programme, the European Climate Support Network and the European Climate Computing Network.

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

The Hadley Centre hosts the Technical Support Unit for the Scientific Assessment Working Group (WG I) of the IPCC. The unit, which is funded by the DoE, co-ordinates the planning, preparation, review and publication of periodic IPCC reports. It also provides a central reference point for IPCC activities.

Much of the work of the IPCC is aimed at supporting implementation of the Framework Convention of Climate Change (FCCC), originally signed by around 150 countries at the earth Summit in Rio de Janeiro in June 1992. Developed



countries are required by the FCCC to submit national inventories of greenhouse gas emissions. IPCC, with the assistance of the Organization for Economic Co-operation and Development and the International Energy Agency has developed Guidelines for the calculation and reporting of these inventories. Both the Guidelines and the IPCC 1994 WGI report on the radiative forcing of climate, which includes the most recent and reliable calculations of the greenhouse warming potential of a wide range of gases and a detailed review of the global carbon cycle, atmospheric chemistry and aerosols, were published in time for the first Conference of the Parties to the FCCC (Berlin, 28 March to 7 April 1995).

Work has begun on the second IPCC Scientific Assessment of Climate Change. This will assess developments across the whole range of topics concerning physical understanding of climate change. It is due to be completed in late 1995.

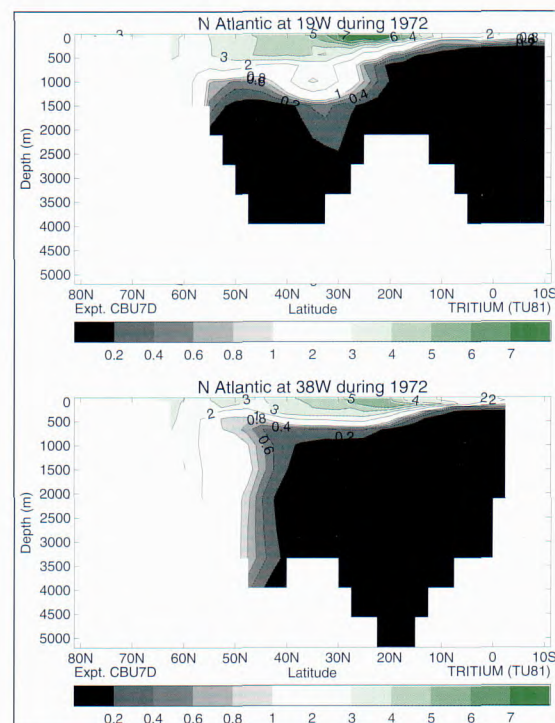


Fig. 53. Western North Atlantic tritium concentrations for 1972, (a) observations from the GEOSECS programme; (b) model results.

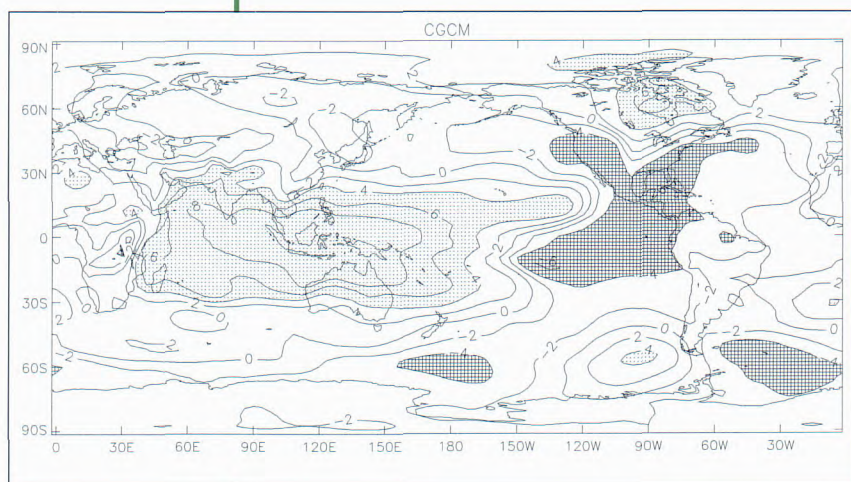


Fig. 54. Correlations ( $\times 10$ ) of the coupled model annual mean-sea-level pressure. Time-series at each grid point are correlated with the time-series at Darwin. The model pattern is similar to that observed.



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## Acronyms

ADMS — Atmospheric Dispersion Modelling System	FWOC — Fleet Weather and Oceanographic Centre
AGCM — Atmospheric General Circulation Model	GANDOLF — General Advanced Nowcasts for Deployment in
ALFENS — Automated Low Flying and Enquiry Notification System	Operational Land surface Flood forecasting
AMIP — Atmospheric Model Intercomparison Project	GCOS — Global Climate Observing System
AMPA — Advanced Mission Planning Aid	GISST — Global sea-Ice and Sea Surface Temperature
AMSU — Advanced Microwave Sounding Unit	GMS — Geostationary Meteorological Satellite (operated by the Japanese at 140° E)
AMT — Air Mass Transformation	GPS — Global Positioning System
APP — Acoustic Prediction Package	GTS — Global Telecommunications System
APR — Atmospheric Processes Research division	hPa — hectopascal
ARIES — Airborne Research Interferometer Evaluation System	HQSTC — HQ Strike Command
ASDAR — Aircraft to Satellite DATA Relay	HRDI — High Resolution Doppler Imager
ASHOE — Airborne Southern Hemisphere Ozone Experiment	HYREX — hydrology and radar experiment
BMETS — Battlefield METeorological Systems	IASI — Interferometric Atmospheric Sounding Instrumentation
CAMOS — Computer Aided Meteorological Observing Systems	ICAO — International Civil Aviation Organization
CBDE — Chemical & Biological Defence Establishment	IFU — International Forecasting Unit
CEC — Commission for the European Community	INTELSAT — International TELEcomms SATEllite
CEPEX — Central Equatorial Pacific EXperiment	IPCC — Intergovernmental Panel on Climate Change
CFO — Central Forecasting Office	IT — Information Technology
CLERA — Clear-sky Long-wave from the ECMWF Re-Analysis	IWP — International Weather Productions
COSMOS — the Met. Office central computer system	JCMM — Joint Centre for Mesoscale Meteorology
CS — Commercial Services Division of The Meteorological Office	LAM — limited area model
dam — decametre	LCBR — Laser Cloud Base Recorder
DGTE — Directorate-General of Tests & Evaluation	LES — Large Eddy Simulation
DGVM — The Dynamic Global Vegetation Model	LORAN — LOng RANGE Navigation
DMSP — (US) Defense Meteorological Satellite Program	MACSI — Microwave Airborne Campaign over Snow and Ice
DRA — Director Royal Artillery	MDD — Meteorological Data Distribution
DRAL — Daresborough Rutherford Appleton Laboratory	METOP — Meteorological OPERations satellite
DS — Defence Services Division	MIR — Microwave Imaging Radiometer
EC — European Commission	MIST — Meteorological Information SysTem
ECMWF — European Centre for Medium-range Weather Forecasts	MMU — Mobile Meteorological Unit
ENSO — El Niño Southern Oscillation	MODS — Mobile Outstation Display System
EPS — Ensemble Prediction System	MOS — Model Output Statistics
EPS — European Polar System	MOSS — Met. Office observing System for Ships
ERBE — Earth Radiation Budget Experiment	MSG — Meteosat Second Generation
ETEX — European Tracer Experiment	MST — Mesosphere-Stratosphere-Troposphere
EUCREX — EUropean Cloud and Radiation EXperiment	MUM — Mesoscale Unified Model
EUMETSAT — European Meteorological Satellite organisation	NAME — Nuclear Accident ModEl
f — prefix femto, 10 <sup>-15</sup>	NERC — Natural Environment Research Council
FCCC — Framework Convention of Climate Change	NVG — Night Vision Goggles
FLIR — Forward Looking InfraRed	NWP — Numerical Weather Prediction
FOAM — Forecasting Ocean Atmosphere Model	OCTA — Oxidizing Capacity of the Tropospheric Atmosphere
FR — Forecasting Research division	ODS — Outstation Display System
FRONTIERS — Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite	OGCM — Oceanic General Circulation Model
FSR — Flood Studies Report	OPUS — Outstations Production Unified System
	PE — Parabolic Equation
	PFO — Principal Forecast Office
	PILPS — Project for Intercomparison of Land Surface Parametrizations



PMP — Probable Maximum Precipitation  
PMSL — Pressure at Mean Sea Level  
RAFC — Regional Area Forecast Centre  
RN — Royal Navy  
RSI — Remote Sensing Instrumentation branch  
RSMC — Regional Specialized Meteorological Centre  
SAMOS — Semi-Automatic Meteorological Observing System  
SAMSON — Simulation and Analysis of Measurements from  
Satellites using Operational Analyses  
SAWS — Synoptic Automatic Weather Station  
SBMM — Standard Ballistic Met. Message  
SCMM — Standard Computer Met. Message  
SIGWX — Significant Weather  
SOI — Southern Oscillation Index

sst — sea surface temperature  
SSU — Stratospheric Sounding Unit  
TDA — Tactical Decision Aids  
TIGER — Terrestrial Initiative in Global Environmental Research  
UARS — Upper Atmosphere Research Satellite  
UKMO — UK Meteorological Office  
VSAT — Very Small Aperture Terminal  
WAFC — World Area Forecast Centre  
WAFS — World Area Forecast System  
WG1 — Scientific Assessment Working Group of the IPCC  
WIN — Weather Information Network  
WMO — World Meteorological Organization  
WSA — Weather Sensitivity Analyses  
W'W'W — World Weather Watch

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