Met Office

Environmental prediction

Science and technology in the Met Office

2003–2004

Environmental prediction

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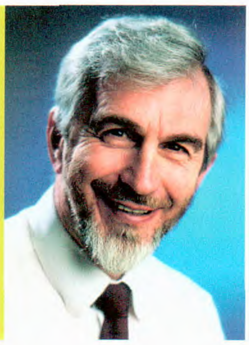
Contents

During 2003, the Met Office moved from Bracknell, Berkshire, to its new, purpose-built headquarters in Exeter, Devon, in the south-west of England

Our work is funded under the National Meteorological Programme, the Defra contract on Climate Prediction, the MOD Programme on Government Meteorological Research and various EU and government contracts

Chief Scientist's introduction

Chief Scientist Professor JFB Mitchell OBE FRS



"The Met Office is best known for weather forecasting. As well as a huge range of forecasts for a wide range of purposes around the globe, the Met Office also provides predictions for the oceans, the dispersion of pollution, rainfall run-off, climate change and other environmental parameters."

This year, I have decided to replace the old Scientific and Technical Report with a shorter brochure. The intention is to give a broad review of science and technology in the Met Office, and to make this information accessible to a wider range of readers. As such, it is not an annual report, but an overview which will be updated from year to year. Those wishing to find more technical, detailed descriptions of Met Office research can access papers and reports on the Met Office websites given below.

The Met Office is, perhaps not surprisingly, best known for weather forecasting, particularly through its radio and television broadcasts. In fact, the Met Office not only produces a huge range of weather forecasts for a wide range of purposes around the globe, but also provides predictions for the oceans, the dispersion of pollution, rainfall run-off, climate change and environmental parameters generally.

These forecasts and predictions are made using numerical models which are constantly being developed and improved by a comprehensive research programme.

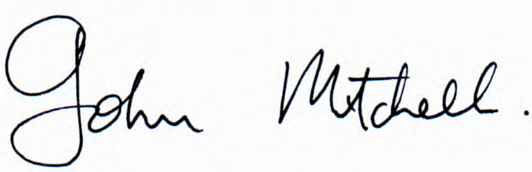
The technology used encompasses everything from weather buoys, satellites and aircraft, to the supercomputers that are an integral part of forecasting and work on climate change. Advancing the development and use of technology is key to the improvement of forecasting techniques.

This brochure describes some of the science and technology underpinning our work, and the improvements and new developments expected from our current work.

The Met Office also produces research papers which appear in mainstream, peer-reviewed scientific publications, as well as many more technical notes.

Technical notes and abstracts of many of the more recent publications can be accessed from the Met Office website at:
http://www.metoffice.gov.uk/research/index.html

For further information on forecast products, please see our website at:
http://www.metoffice.gov.uk



Professor JFB Mitchell OBE FRS

The Met Office is a world-leading centre for short-range numerical weather prediction

What is numerical weather prediction?

It may be simple enough to guess that it is about to rain if you see clouds gathering on the horizon. But what if you have to produce a forecast for several days, or even weeks in advance, covering a whole country or region, predicting quantities such as wind strength and direction, cloud cover and temperature?

The process begins with making observations of temperature, humidity, winds and other parameters around the world **(Fig. 1)**. These are then used as the initial conditions in a numerical forecast model. The behaviour of the atmosphere can be approximated using the equations of fluid dynamics. These include the equations of motion, the thermodynamic and moisture equations, and the continuity equation. These equations form the basis of the numerical weather prediction model. They are solved mathematically, using computer techniques that calculate, step by step, future states of the atmosphere as a set of values on a 3D grid.

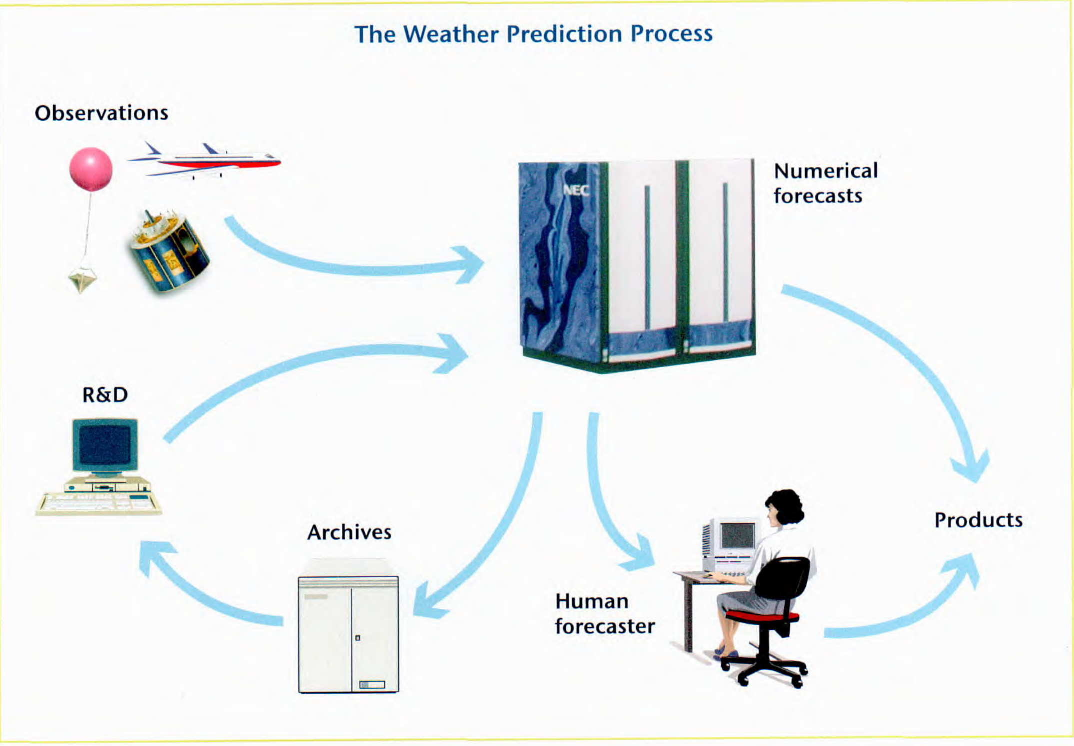
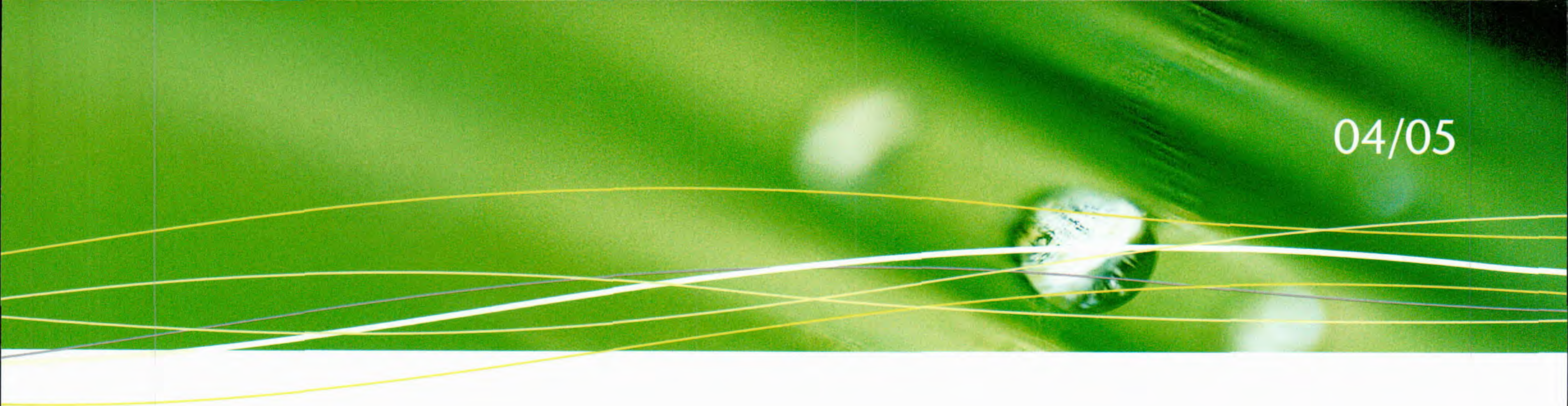


Figure 1: The process involved in forecast production, linking numerical weather prediction and observations to research and the delivery of products to customers



Advancing from one state to the next is called the 'time step' and the gap between the points on the grid is called the 'grid length' or 'spatial resolution'. Observations from satellites, aircraft and weather balloons, as well as from many other sources, are used to determine the initial conditions from which the forecasts begin. This process is called data assimilation. The resulting forecasts may be amended by the human forecaster before being converted into products for use by customers. The data and forecasts are also archived for use in research and to validate the accuracy of the model predictions.

The models of the atmosphere and oceans used in the Met Office are part of the Unified Model system, so-called because it incorporates global and regional components that use the same code for both short-range weather forecasts and longer period climate simulations. Various components of the model are run at regular intervals throughout the day and to tight deadlines in order to provide up-to-date forecast information.

A global configuration provides forecasts up to five days ahead, and higher resolution regional and UK configurations are used to provide more detailed forecasts for Europe and the UK for the period up to two days ahead.

Good initial data are essential in the production of high quality forecasts and continued efforts to make best use of the available observations are required. Satellites have the advantage of global coverage and have become the primary data source for global forecasts. The use of other sources of data, such as those from an enhanced UK radar network, are also still important.

Observations cannot be introduced directly into numerical models and must be passed through an assimilation scheme which handles them in an optimal way, taking account of their error characteristics, consistency with other observations and the state of the model. The development, over the last few years, of new approaches to data assimilation — 4 Dimensional Variational data assimilation (4D-Var) — allows better use to be made of observational data, through improved representation of model errors and the time evolution of observations. 4D-Var became operational in October 2004 and is being developed in the UK to use radar data.

The Unified Model has been re-formulated over the past three years and is now non-hydrostatic. This change allows vertical motion to be modelled properly. This important change, and advances in representation of the physical processes, will allow high resolution models to be developed with hills and valleys represented in detail.

We are developing models to provide forecasts of a wider range of environmental parameters

Getting airborne

Computer models do a very good job of accurately describing the large-scale motion of the atmosphere. But they can't fully describe many of the small-scale phenomena such as convective clouds which affect the large-scale motion.

We overcome this problem by using a technique called parametrization, which simplifies the physics in order to represent the effects of the small-scale phenomena on the larger scale. This technique is dependent on obtaining detailed measurements of specific meteorological conditions that can be used to develop improved parametrization methods.

There are various ways of taking these measurements. One of the most important has been the use of a range of instruments on specially-equipped aircraft – most recently a Hercules that was used for more than 25 years and was retired in 2001.

A new aircraft, a BAe 146-301, has completed an extensive conversion for use as an atmospheric observation platform. It is run

BAe 146 of the Facility for Airborne Atmospheric Measurement. This aircraft participated in an experiment to measure atmospheric aerosols over the Adriatic in August 2004 jointly by the Met Office and the Natural Environment Research Council on behalf of the academic science community.

We have many experiments planned, including a cloud physics experiment in 2005 to study trade-wind cumulus cloud around Antigua. This is run in collaboration with the atmospheric science community in the USA and UK.

We are improving forecasts by making more and better observations, by improving the way we use observations in the model, and by improving the model itself. We are also developing models to provide forecasts of a wider range of environmental parameters.

Improved radar

Localised weather, including rainfall and its subsequent effects, are some of the main concerns of Met Office customers – in particular the general public. To continue improving our services in this area, considerable investment has been made, over many years, in the UK rainfall radar network.

It is well known that rainfall intensities can vary considerably over very short distances, especially in showery weather. The UK network of more than 3,000 daily rain gauges is able to resolve most structure on this timescale, but the relatively sparse real-time hourly network fails to detect a significant proportion of heavy rainfall events.

The national weather radar network of 12 radars was established in the 1980s to map rainfall in real time. In the 1990s, the investment was concentrated on improving data resolution (down to 1 km, available every five minutes).

The data are now being assimilated into numerical weather prediction models. Current investment is towards centralising the data processing and acquiring wind information based upon Doppler radar measurements.

A next-generation dual polarisation radar is also being installed in Kent (with the Environment Agency). This is able to distinguish droplet shape and so infer the size and type of the precipitation – rain, snow or hail.

A Met Office scientist testing the instruments and environmental monitoring systems inside the BAe 146 FAAM

New and improved satellite data

The accuracy of weather forecasts has improved significantly over recent years – to the benefit of everyone who relies on Met Office predictions, from the armed forces and government departments, to business and the general public.

The use of data from meteorological satellites in numerical weather prediction models, in particular from polar-orbiting satellites, has been a hugely significant factor in delivering these improvements in the quality of forecast performance.

Further improvement is expected with the first of a new series of satellites due for launch in late 2005. It will cover the morning orbit, while US satellites continue to cover the afternoon slot.

This initiative will result in a coordinated system of polar-orbiting satellites carrying the most advanced remote sensing instruments and providing invaluable data. The new satellite collects data at many more wavelengths than previous systems. This will help improve the accuracy of analyses and subsequent forecasts of temperature of the global atmosphere, as shown in **Figure 2**. Several instruments, covering a wide range of wavelengths, will sense the state of the winds, temperature, humidity and clouds throughout the atmosphere.

A major new project has been initiated at the Met Office to make best use of the new data, including reception of data sets, pre-processing, storage and assimilation into numerical weather prediction models. We expect that data from the new polar-orbiting satellites will bring a significant improvement in Met Office forecasts, as new and more accurate data become available.

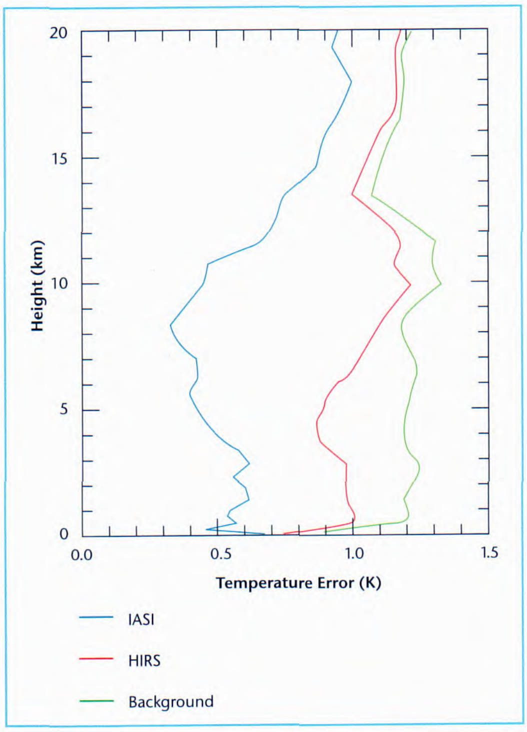


Figure 2: The expected temperature errors from the old (HIRS) and new (IASI) sensors on polar-orbiting satellites

The curve labelled background is the mean error in our knowledge of the atmospheric temperature profile before we have assimilated any new observations

Taking forecasts into a new dimension

To produce an accurate prediction on which governments, business and the public can base their decisions, forecasters need a precise knowledge of the current state of the atmosphere's key variables. These are pressure, temperature, wind, moisture and cloud.

Computers and numerical forecasting methods are now used with these data to predict future patterns, and hence the weather, for several days ahead.

However, detailed observations for all variables are not available at all locations and times, and will sometimes include errors. To make the most of incomplete and imperfect observations, we combine them with the latest model predictions in a process known as data assimilation.

In 1999 the Met Office introduced the three-dimensional variational data assimilation method (3D-Var), which uses a wide variety of observations, distributed in space. A particular feature of 3D-Var is its ability to use the global coverage of observations from satellite radiometers, which give information on temperature and moisture. From the spatial patterns of these observations, 3D-Var can also deduce information about the winds, without measuring the winds directly.

In 2004 the Met Office extended this variational approach to the fourth dimension – time – (4D-Var). Assimilation in four dimensions is able to make effective use of observations distributed in time, as shown in **Figure 3**. This is particularly useful for the continuous stream of data from satellites. It takes account of changes of observations with time to deduce information about the evolution of weather patterns.

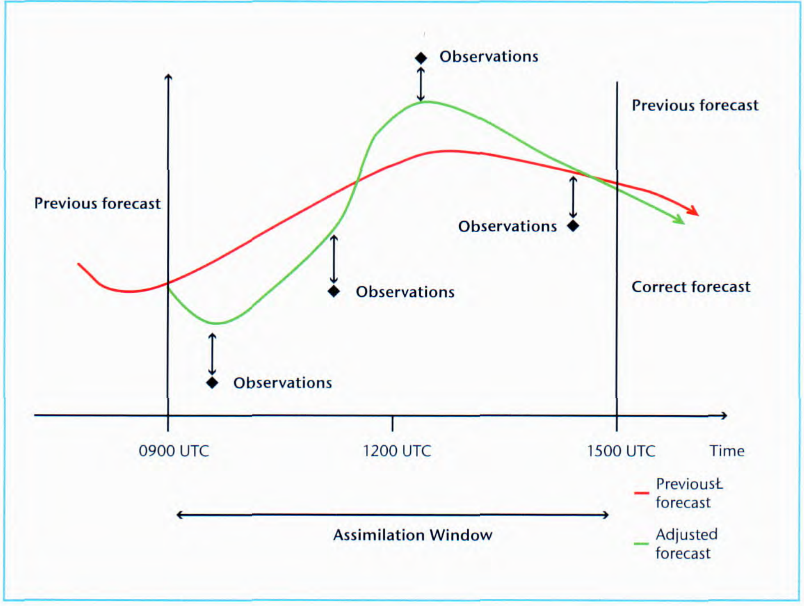


Figure 3: Schematic diagram of 4D-Var. The atmospheric values from the previous forecast are shown in red. 4D-Var uses forward and backward steps of the forecast model to get the best compromise between the most recent observation (diamonds) and the old forecast (red curve) to give the adjusted forecast (green curve). The adjusted forecast then provides the initial conditions for the new forecast

For instance, the assimilation of data will be improved for cases of fast-moving weather systems.

To achieve this, 4D-Var makes even more use of numerical weather prediction models. A sophisticated mathematical process, which involves running the forecast model forwards and backwards in time, then calculates how to alter the estimate of the atmospheric parameters to improve the fit to the observations. This process is repeated about 50 times to give a best estimate, which can then be used to start forecasts of future weather. **Figure 3** shows how a forecast can be amended to take account of more recent observations – while allowing for the fact these observations have errors.

We are currently developing higher resolution versions of our forecast model

The new North Atlantic and European model

When running a computer model, it is necessary to decide what spatial resolution to use. Forecasts at finer resolution provide more accurate information, particularly on forecasts of rainfall and winds. This gives our customers better information on which they can base their decisions, whether it concerns an RAF flight plan, a local authority's decision to grit the roads or a family deciding how to spend their day off. But finer resolutions require more computing power and time. Halving the grid length horizontally and vertically increases computing time by a factor of eight.

The Met Office currently runs three models at different resolutions — a global model, a regional model and a higher resolution UK model. The global model has a grid length of 60 km and the UK model, which also covers the rest of Ireland and the near continent, 12 km. The regional model currently has a grid length of 20 km.

With advances in supercomputing, the Met Office had the opportunity to rethink these configurations. It was decided to expand the 12 km UK model to encompass a substantial part of the North Atlantic, continental Europe and the entire Mediterranean Sea. This will deliver a more accurate representation of the evolving Atlantic systems and should provide improved forecasting of severe weather events as they reach Europe.

The vertical resolution will be increased from 38 to 70 levels, with some of the extra levels concentrated near the surface to provide extra benefit for fog and low cloud forecasts.

The North Atlantic-European model using a 20 km resolution with 38 levels has been running routinely throughout the past year. From April 2004, using the NEC SX6, this model has run four times a day, and following improvements in formulation and in the use of observations it was declared operational from September 2004. Early in 2005 it will run with a 12 km grid.

Producing local forecasts

Meteorologists have to deal with a vast range of space and time scales. These can range from planetary waves covering thousands of kilometres to a localised patch of fog, only tens of metres across. That patch of fog may be small, but if it coincides with an airport or major road, for example, it can have a serious impact.

These parameters are, of course, of particular interest to many people. The problem for meteorologists is that the smallest scales are the most unpredictable.

We are currently developing higher resolution versions of our forecast model. These will be useable over any region of the globe, but will initially be used to improve forecasts for the British Isles. The initial resolution across the UK will be approximately 4 km horizontally with an increased number of vertical levels, many of these especially close to the surface. Forecasts will be produced for up to 36 hours ahead.

At even higher resolution these improvements will also make it possible to provide better information about conditions in our treatment of urban areas, improving our forecasts of temperature and air quality. However, short-range forecasting of severe storms and flash flooding will remain a significant challenge.

Trial runs of the new high-resolution model have delivered much improved fog forecasts, especially at 1 km resolution, using 76 vertical levels (see **Fig. 4**), better wind speed forecasts through the Strait of Dover and the Strait of Gibraltar, as well as improved heavy rainfall and flood forecasting.

Further enhancements to our ability to produce short-range forecasts for 0–6 hours ahead are planned for the end of the decade to further improve local severe weather forecasting. In the longer term, we aim to incorporate a 1 km numerical model into the very-short-range forecasting system. This would produce forecasts for about six hours ahead, updated frequently to use new data, especially from high resolution radar and satellite systems. Work is underway to address the considerable scientific challenge this represents, although it will be some years before increased computer power allows it to be complemented.

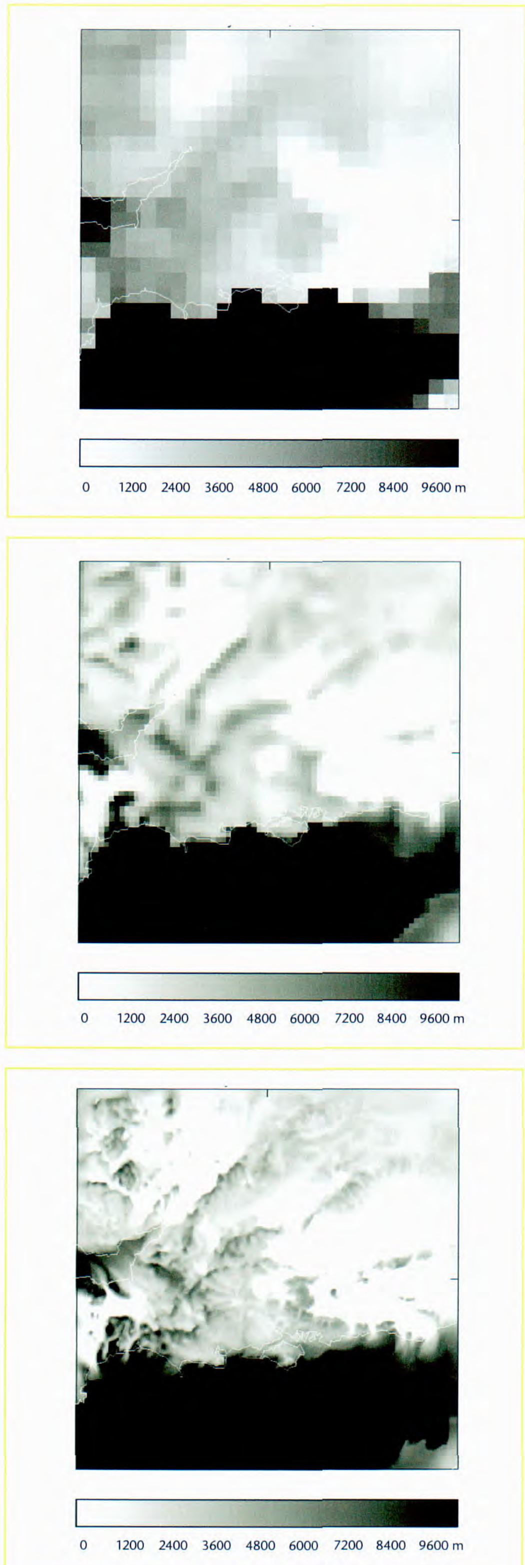


Figure 4: An 8-hour forecast of visibility over central southern England starting from the same initial data, but run at different resolutions

(a) the current 12 km model,

(b) at 4 km and

(c) at 1 km.

Note that both the 4 km and 1 km models add fog in some areas in which it was not forecast in the 12 km model, as well as clearing the tops of hills such as the Chilterns and North Downs

The Met Office is preparing to introduce experimental ensemble probability predictions for short-range weather forecasts

Dealing with uncertainty

To improve their operations, Met Office customers need increasingly reliable short-range weather forecasts. Our new supercomputer will enable what is known as 'ensemble' forecasting techniques to be used for short-range forecasts – allowing customers to assess risks and thus improve decision-making.

Traditionally, a numerical weather prediction model is run only once from a given set of initial conditions to produce a single forecast. However, because of the chaotic nature of the atmosphere, even a tiny error in the starting conditions can be magnified to give a large error in the subsequent forecast.

Because it is not possible to know the exact truth of the initial conditions and the model is always approximate, there will always be some uncertainty in the forecast. To combat this, forecasters can run a number of forecasts (an ensemble), each with slightly different initial conditions to reflect this uncertainty. The resulting forecasts can then be compared and combined to calculate a probability for a particular forecast, or to assess the risks associated with a user's decision.

Ensemble predictions for medium-range forecasts have been produced for some years by the European Centre for Medium Range Weather Forecasts, based at Reading.

Now, with the introduction of the new supercomputer, the Met Office is preparing to introduce experimental ensemble probability predictions for short-range weather forecasts from Exeter. This should increase forecast accuracy and enable forecasters to assess risk, in particular the risk of severe weather.

The new computer also enables the increased use of ensemble predictions for climate prediction models (see page 32).

Defining probability

With a probability forecast, it is essential that both the forecaster and the user understand exactly what the probabilities mean. Probabilities must be issued for a clearly defined event which either occurs or does not occur. For example, a statement that there is 'a 30% probability of rain in Scotland' is meaningless because it is not clear whether it is for a specific place or for the whole of Scotland. Also there is no time given, nor the amount of rain.

These are examples of well-defined probability forecasts:

- **30% probability** of more than 5 mm of rain at Edinburgh Airport between 1200 and 1800
- **70% probability** of wind reaching gale force in at least one place in Scotland on Tuesday
- **10% probability** of wind sufficient to cause severe structural damage in London overnight

A probability forecast describes how likely an event is on a particular occasion. If the probability is 10% then the event will only occur on one occasion in every 10. Suppose, for example, an oil company wishing to move a North Sea rig asks the Met Office to warn it every time there is a 10% risk of high waves. It should expect that nine times out of ten the waves will be low enough that the tow could have gone ahead safely. However, since the rig is worth many millions of pounds, the company may well benefit from accepting nine missed opportunities in order to avoid the one-in-ten occasion when it was likely to lose the rig.

To make best use of the probability forecasts, the user must choose a probability threshold which gives the correct balance of alerts and false alarms for their particular application.

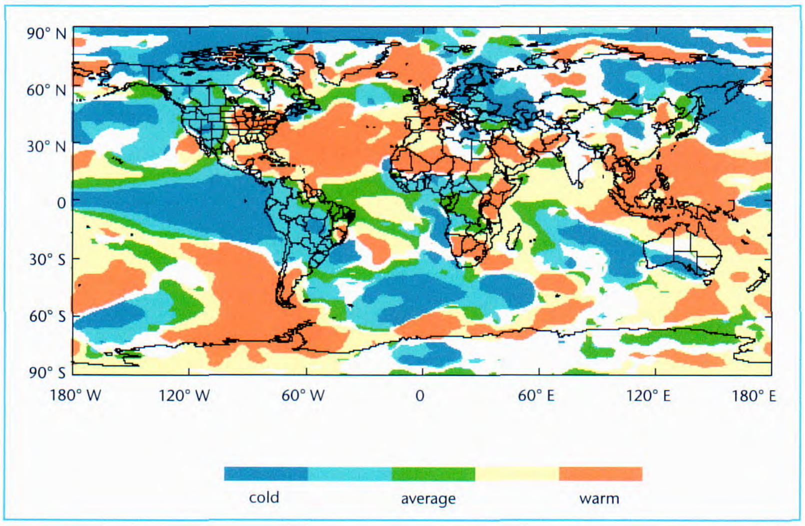
Seasonal prediction

Although it is not generally possible to forecast individual weather events further than several days in advance, it is possible to provide useful predictions of conditions averaged over weeks or months and over large areas. We provide experimental seasonal predictions, covering all areas of the globe, to UK government departments, United Nations organisations, and national meteorological services worldwide.

The Monthly Outlook provides more detailed information for up to one month ahead and is used by the commercial sector.

Our seasonal predictions are produced using the Global Seasonal (GloSea) forecast system (**Fig. 5**). The GloSea system uses an adapted version of the Met Office's coupled ocean-atmosphere general circulation model. Each forecast starts from prescribed ocean, land and atmospheric conditions. The sensitivity to initial conditions is quantified by making a number of predictions with slight initial variations, thus producing an ensemble forecast with individual forecast 'members'. Forecast products are then created by analysing the output from the whole ensemble.

Figure 5: Seasonal prediction of global anomalies of surface air temperature using GloSea



Warning of air pollution, disease and severe weather

Tracking pollutants

If a volcano erupts, there is a nuclear accident or there is an outbreak of an airborne disease such as foot and mouth, it is vital to be able to track airborne pollutants.

The Met Office uses a dispersion model, known as NAME (Numerical Atmospheric dispersion Modelling Environment), to track plumes of pollution. It was originally developed after the *nuclear accident at Chernobyl in 1986*, which highlighted the need to predict the spread and deposition of radioactive material released into the atmosphere.

Over the years, NAME has been applied to a number of atmospheric releases, including radioactivity, oil fires in Kuwait, major industrial fires and chemical spills, and two major volcanic eruptions in Iceland.

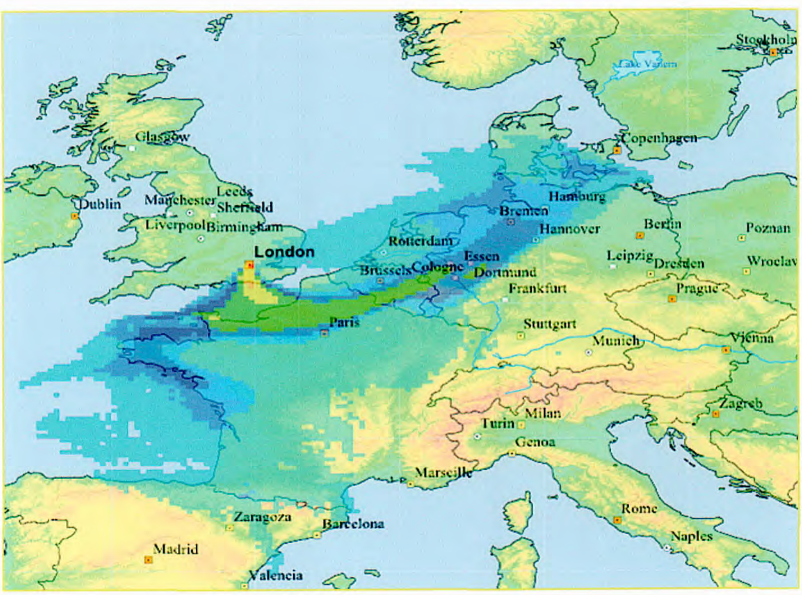


Figure 6: The NAME model can be used to identify pollution sources. This map was generated by running the model 'backwards' in time to show all possible source regions that could have affected London at midday on 6 August 2003, during the summer heatwave. The various shades represent the percentage contribution to concentrations at London. Air reaching London has clearly been transported over a number of highly populated and industrialised regions, resulting in poor air quality

Recently, the model has been adapted to run backwards (**Fig. 6**). This is designed to help *forecasts of air quality* and identify the source or causes of a pollution incident, where an area may be affected by poor air quality but the source of the pollution is unclear.

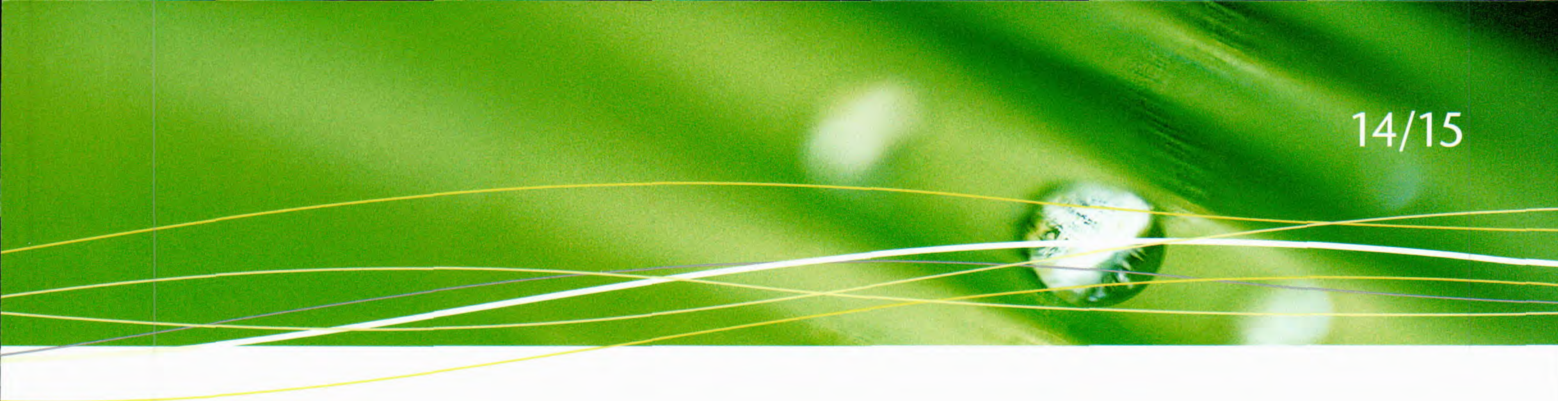
The major development of the last few years has been the next version – NAME III. This version integrates both short and long-range capabilities, traditionally treated separately. Plans are in place for this to become the operational version.

Researching the spread of foot and mouth

In the 2001 foot and mouth disease epidemic, 80% of transmissions were classified as 'local spread' without the actual mechanism being known.

Met Office scientists have carried out a number of detailed studies which have shown that airborne transmission may have been more significant than at first thought (**Fig. 7**).

The Department for Environment, Food & Rural Affairs (Defra) recently commissioned a three-year joint research project with the Institute for Animal Health and the Met Office. The operational service offered to Defra in the event of foot and mouth cases has also been reviewed and upgraded. The aim is to understand airborne-spread disease better, to enable more focused targeting of resources during an outbreak.



A European severe weather warning system

There have been many episodes of damaging weather to parts of Europe in recent decades. It has become clear that there is a need for early warnings of probable damage to be exchanged across the continent, so that the risk of damage can be minimised.

The network of European Meteorological Services has developed the European Multiservice Meteorological Awareness (EMMA) system to help deal with these risks, and trials were carried out at the Met Office between March and June 2004.

To allow easy interpretation and receipt of warnings across the continent, a geographical information system is used. Colour coding of the warnings show their expected severity and the area affected.

The system will be available to the general public, government authorities and European forecasters to provide a useful tool for the timely preparation of those likely to be affected. Warnings will be easily accessible through the internet, on display in the user's language. More detailed information will also be accessible from the originating national meteorological and hydrological services.

Data are received and held on a server at the Met Office in Exeter, where we have designed and built the EMMA reception, storage and visualisation system.

Predicting flooding

When flooding occurs, it is important not only to predict how much water is involved and where it is going to appear, but also where it is likely to go. Predicting water run-off during flooding events will enhance our ability to support the Environment Agency and water utilities in providing effective, pro-active responses to reduce damage and disruption.

The Met Office has been working in collaboration with the Centre for Ecology and Hydrology at Wallingford, to develop and implement a scheme to route water run-off. This builds on the ability to provide a real-time soil moisture and run-off diagnosis on a 5 km resolution grid, which has been in use since late 2002.

Digital terrain elevation data at 1 km resolution is used to generate flow paths. A kinematic wave model calculates the propagation of river flow downstream. **Figure 8** shows a map of the Thames catchment flow on a 1 km grid.

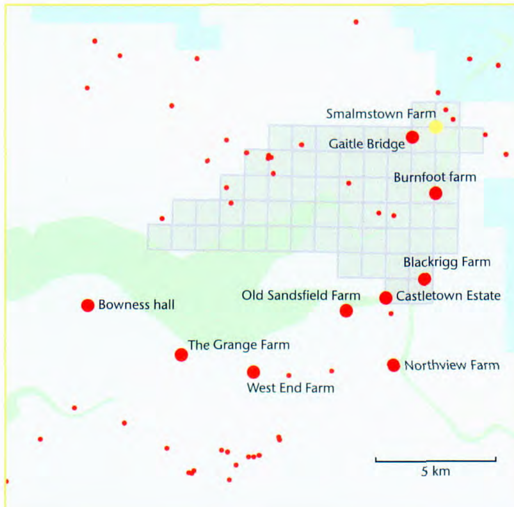


Figure 7: Farms under investigation for the possible airborne spread of foot and mouth disease around Longtown, Cumbria – yellow for the virus source, red for farms that might have been affected by airborne transmission of the disease. Smaller red dots show other infected farms where there was an alternative mechanism for the introduction of the virus. The shaded squares show the spread of the virus plume modelled by NAME

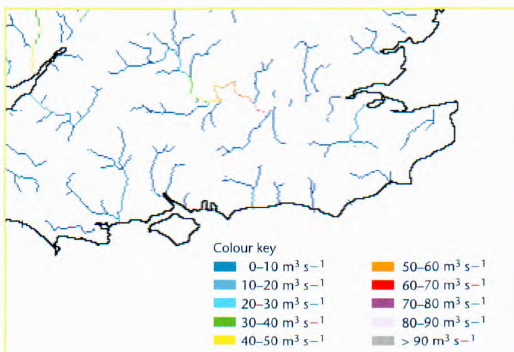


Figure 8: This figure shows flow rates for all the major rivers of south-eastern England. The rate of flow is colour coded, so that areas where there may be a risk of flooding, such as the middle and lower reaches of the River Thames, may be easily seen

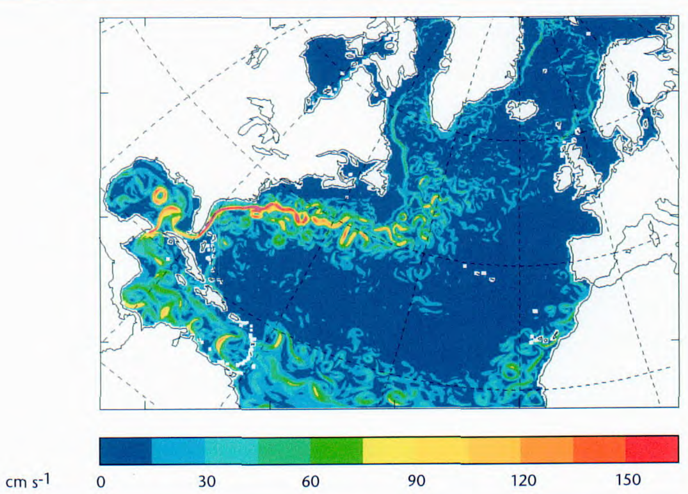
Ocean observations are essential for accurate analysis

New ocean observing network

Ocean observations are essential for accurate analysis and forecasting of ocean conditions, seasonal prediction and understanding, and the prediction of climate variability and change. As part of our work improving ocean observations, the Met Office is a prominent member of an international programme called Argo, to deploy 3,000 free-drifting profiling floats to measure the temperature and salinity of the upper 2,000 m of the ocean. The Met Office coordinates the UK contribution, and over the last three years more than 100 UK floats have been deployed.

Satellite observations of the ocean are an essential component of the ocean-observing systems and UK support for the Jason-2 satellite altimeter — which will deliver high accuracy sea surface height information — is being channelled through the Met Office. The Global Ocean Data Assimilation Project High Resolution Sea-Surface Temperature (GHRSST) pilot project aims to deliver a new generation of highly accurate worldwide sea-surface temperature products with a resolution of less than 10 km every six hours. As an important step towards achieving this goal, we are hosting the GHRSST International Project Office which coordinates sea-surface temperature data merging and analysis activities in the UK, Japan, USA, Australia and France.

Figure 9: FOAM analysis of surface current speed in the North Atlantic Ocean



Modelling the oceans

The Met Office routinely runs a range of ocean models to make predictions up to five days ahead. These were developed to help organisations such as the Royal Navy and oil companies plan their operations at sea. They include sea-state forecasting with ocean wave models, the Forecasting Ocean Assimilation Model (FOAM) — a global real-time ocean analysis and forecast model — and regional modelling of the shelf seas around the UK. In operational oceanography we have a leading capability in Europe.

The deep ocean

FOAM is an ocean model and assimilation system that produces real-time daily analyses and forecasts of temperature, salinity and currents for deep oceans, for up to five days ahead (**Fig. 9**). Using the FOAM system it is possible to set up high-resolution (1/9° or better) configurations for any deep ocean region.

Shelf seas

For nowcasting and short-period forecast modelling of the north-west European shelf seas and UK coastal waters, the Met Office runs the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS). The Atlantic Margin Model covers the north-west European continental shelf, and much of the shelf break to the west of the British Isles, with approximately 12 km resolution. We also run a nested model for the Irish Sea at one-nautical-mile resolution and output from this model is available through the Proudman Oceanographic Laboratory Coastal Observatory. We are developing a nowcasting capability for the marine ecosystem of the north-west European shelf jointly with the Proudman Oceanographic Laboratory (POL) and the Plymouth Marine Laboratory.

The research groups developing future configurations of the shelf seas model work closely with the POL. **Figure 10** shows the domain of the medium-resolution continental-shelf version of POLCOMS, which has a 6 km grid length. The coupled marine physical ecosystem model (POLCOMS with the European Regional Seas Ecosystem Model (ERSEM)) is being applied to this grid and the Met Office has run hindcast simulations for 2002 and 2003 and will bring the model to near real-time in 2004.

Figure 10 shows the domain of the one-nautical-mile Irish Sea POLCOMS. Nested within this model it is possible to run an estuary-scale model at approximately 200 m resolution, as shown for Liverpool Bay (inset). Future plans include enlargement of the area covered by the one-nautical-mile POLCOMS to cover more of the UK coastline and eventually the full north-west European continental shelf.

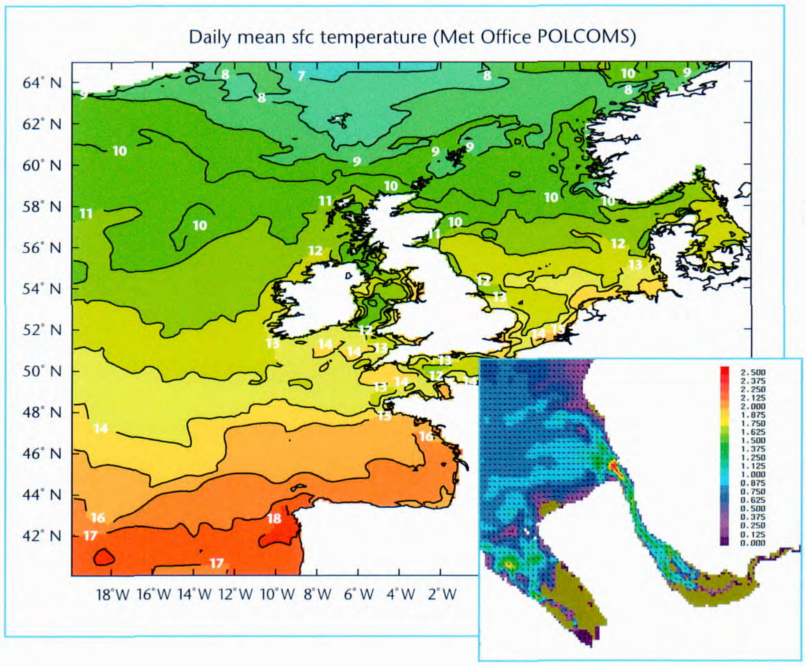


Figure 10: Coverage of the shelf seas models, developed with the Proudman Oceanographic Laboratory, for operational application over the north-west European shelf. At present, the estuary-scale model is in a pre-operational development stage. The inset shows Liverpool Bay

Waves

For many years we have run spectral wave models to provide forecasts of sea state, supporting a range of user applications. There are three operational wave-model configurations – global, European and UK waters. Wave-model data are compared with observations from the Envisat environmental satellite and the WAVENET moored buoy network.

In collaboration with HR Wallingford (an independent company that carries out research and consultancy in hydraulics, civil engineering and the water environment), we are able to provide site-specific near-shore wave forecasts for a range of coastal applications. Work carried out under the European MaxWave project has led to the development of preliminary diagnostics of the likelihood of occurrence of extreme or damaging waves.

Scientists at the Met Office are using climate models to understand the causes of global warming

Climate prediction

So far, we have looked at how we are improving short-range forecasts. The Met Office produces forecasts for days, months and the season ahead. It also produces predictions of longer term climate change. This requires the addition of chemical and biological processes into the model.

There is good scientific evidence that the Earth's temperature is rising and that most of the warming over the last 50 years has been caused by human activities. These activities have altered the chemical composition of the atmosphere through the build-up of certain greenhouse gases.

The Earth's climate is driven primarily by heat from the sun. Ultra-violet radiation from the sun warms the Earth's surface. Infra-red radiation is emitted from the surface and atmosphere, back to Space. Some of this radiation is absorbed by the greenhouse gases (such as water vapour, carbon dioxide, methane and nitrous oxide) and re-emitted to Space.

In this way, they trap heat rather like the glass of a greenhouse – hence the name 'greenhouse effect' — and raise the surface temperature. This is a natural effect and without it, the Earth would be much too cold to support life. However, by changing the balance of gases in the atmosphere, human activities appear to be causing a rise in temperatures which could have serious consequences for future generations.

It is believed that greenhouse gas concentrations in the atmosphere are increasing largely because of the combustion of fossil fuels such as oil and coal.

"The year 2003 was the third warmest globally in the 143-year global temperature record, 0.49 °C above the 1961–90 average. Only 1998 and 2002 were warmer, at 0.54 and 0.50 °C above average."

The global mean temperature record

The Hadley Centre for Climate Prediction and Research, in collaboration with the University of East Anglia Climate Research Unit, has produced a comprehensive record of surface temperature which has been used to show that climate is indeed changing **(Fig. 11)**.

Data exist from measurements of both the sea water temperature near the surface and the air temperature just above it. Both data sets show similar evidence of ocean warming. Since 1975, the warming over the land has been greater than that over the oceans. Evidence for this warming is supported by observations of retreating glaciers.

Global surface temperatures have risen about 0.7 °C in the past 100 years. We are confident that this is evidence of global warming because the rise in temperature is much greater than the uncertainties in the record. The evidence indicates that both the land and the oceans have warmed.

Scientists at the Met Office are using climate models to understand the causes of global warming.

The year 2003 was the third warmest globally in the 143-year global temperature record, 0.49 °C above the 1961–90 normal. Only 1998 and 2002 were warmer, at 0.54 and 0.50 °C above normal.

All the ten warmest years globally since 1861 have occurred in the past 13 years, including every year since 1997.

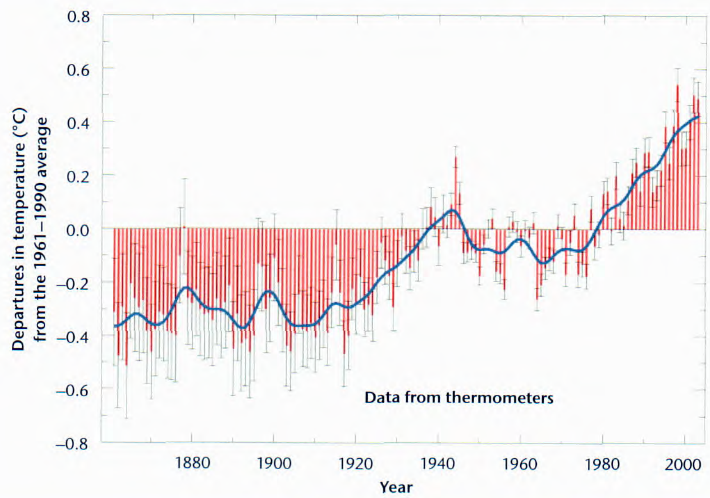


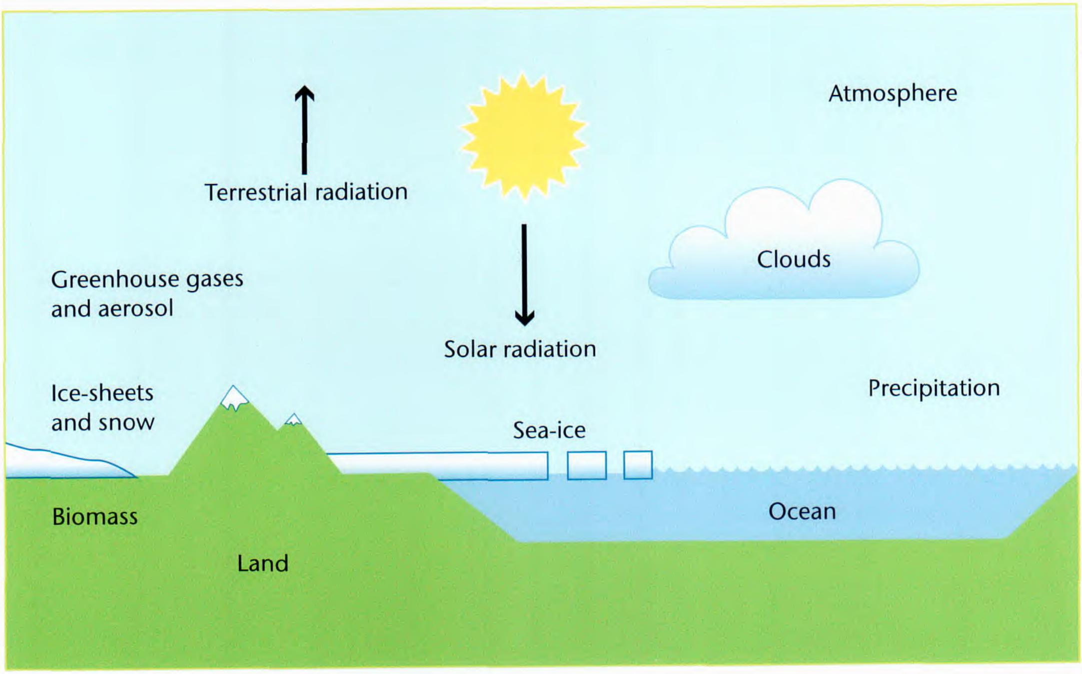
Figure 11: Global mean air temperature relative to a 1961–90 average. Comparing one year to the next, the bars show significant inter-annual variability. The blue line is the 5-year running mean, which shows that, in general, the temperature has been rising in the last few decades

We also make predictions of global temperature using physical factors that influence it. Our prediction of +0.55 °C for 2003 was well within our uncertainty range, but was too warm because a weak warm-water 'El Niño' event in the tropical Pacific did not persist as expected. For 2004, we predict a value of +0.50 °C ± 0.12 °C.

However, not all results show this clear increase in temperature. For example, a major puzzle is that temperatures up to 15 km altitude in the tropics appear not to be warming as expected from the evident surface warming there.

A possible reason is that these temperatures are influenced by cooling of the layer immediately above most weather — the lower stratosphere. This cooling is occurring because of reductions in ozone and increases in some greenhouse gases, such as carbon dioxide, at these levels. As climate models do not show this behaviour, we are working to improve our understanding of the physical mechanisms.

Figure 12:
The climate system



Introduction to modelling climate change

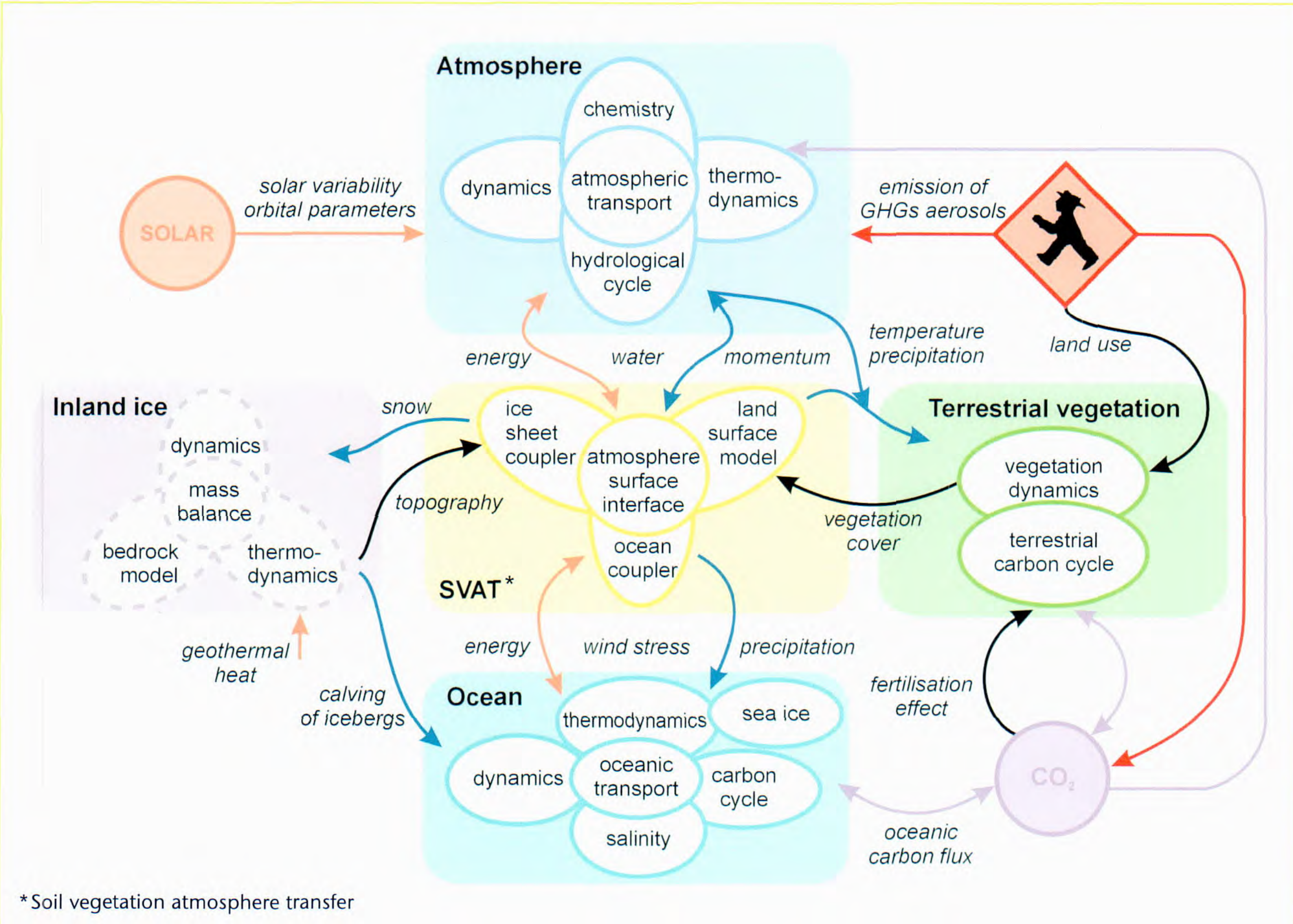
By creating complex climate models using the most powerful computers, scientists are able to provide vital information for the global community.

When policymakers come to make crucial decisions relating to climate change, they need the best possible information to hand. They need to understand what has happened in the past, what is happening now, and what is likely to happen in the future and why. If they don't know the likely changes in climate, as well as the consequences of these changes, there can be no decision made about how to tackle them.

Met Office scientists in the Hadley Centre use computer models to simulate the complexities of the world's climate to provide accurate information to governments, business and the global community as a whole.

The quality of the complete model depends on the accuracy with which the important physical processes within the sub-models can be captured. These include the factors shown in **Figure 12**, such as the dynamics of the atmosphere and oceans, the processes that form clouds and precipitation, turbulence, radiation, sea-ice, and surface exchanges of heat, moisture and carbon dioxide between the atmosphere and land surface and ocean.

Over the last four years a major development project has led to the creation of the new Hadley Centre Global Environment Model (HadGEM1), part of the Unified Model (**Fig. 13**). This will be used for many years to come.



Virtually every subcomponent of the old model, HadCM3, has been improved. New sub-models have been incorporated more closely into the model to include feedbacks between more processes in the earth system. The impact of these improvements is summarised in **Figure 14**.

Improving the realism of such climate processes remains the most productive way to make significant improvements in future generations of model.

Figure 13: The Met Office Hadley Centre climate model HadGEM. Dashed lines indicate that these processes are not included in the model.

GHG = greenhouse gases

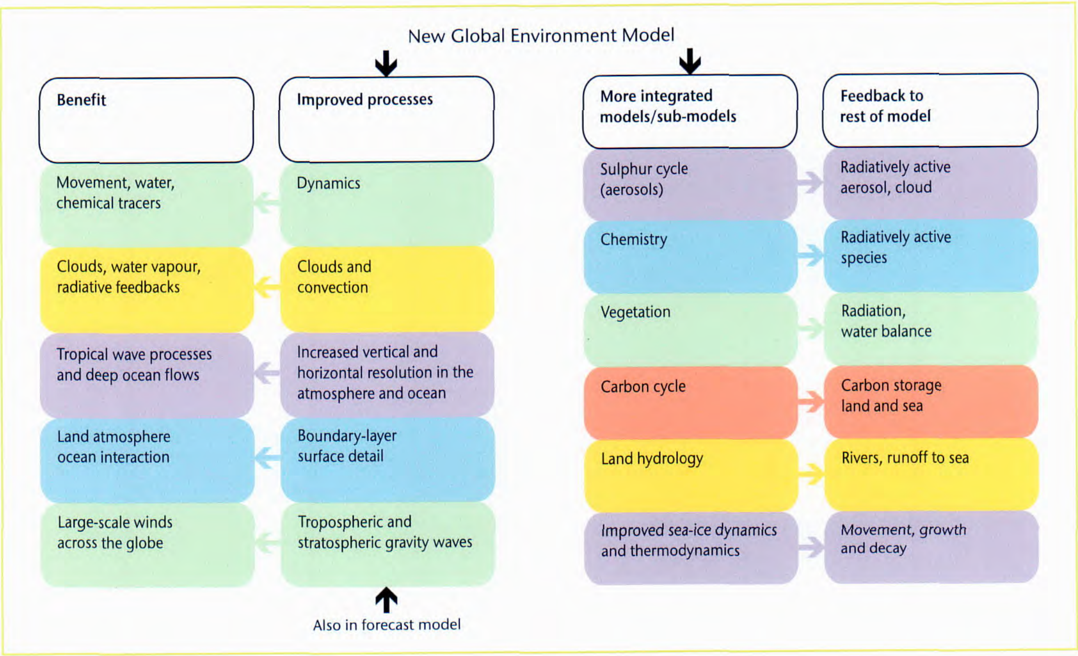


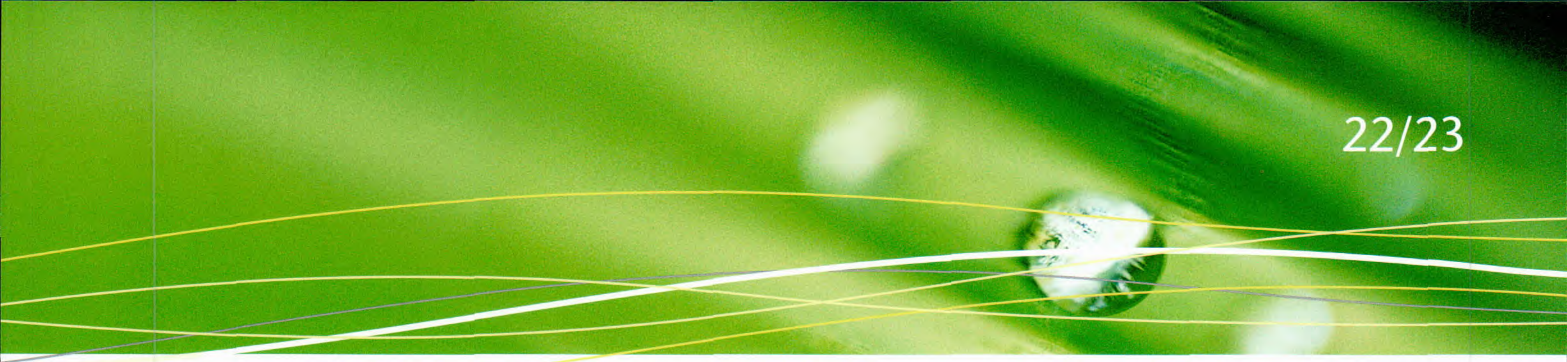
Figure 14: The impact of improvements in the new Hadley Centre Global Environment Model (HadGEM1)

Evaluating and improving models in comparison with observations is vital. Met Office scientists are always looking out for new and improved forms of data (e.g. from sophisticated new Earth-observing satellites or autonomous submarines roving the deep oceans) to improve understanding of the real world and check the performance of models.

"It is important that we demonstrate that models represent processes accurately."

Comparison with current climate

Climate observations from numerous sites around the world are available for recent decades, while some go back several hundred years. Model performance is compared against a range of different indicators, including temperature, rainfall and surface pressure.



Do climate models produce credible results?

Comparison with observed climate variability
Natural climate variability occasionally leads to extremes of temperature or precipitation. An important test of a climate model is whether it can credibly reproduce the observed natural variability.

Comparison with palaeoclimates
Climate models can be used to simulate climates in the distant past, such as the Last Glacial Maximum – the peak of the last ice age, c. 21,000 BC. The model results are compared with proxy 'measurements' of past climate changes, such as the width and density of tree rings, or layer thickness from laminated sediment cores.

Understanding climate processes

As well as simulating observed climate, it is important that we demonstrate that models represent processes accurately. For example, one of the main uncertainties in climate change is the interaction between clouds and climate. Increased high cloud tends to warm the climate, since high cloud absorbs outgoing infrared radiation. Increased low cloud tends to cool the climate as incoming ultraviolet radiation is reflected back to Space from its top.

It is likely we have detected a 'forced change' in climate

Weighing the evidence

Detection of climate change involves showing that a particular change in climate is unusual relative to the natural variations in climate.

Attribution involves demonstrating that a detected change is due to a particular cause (for example, human activity).

The recent warming is so large that it is unlikely to be due to natural (unforced) variations in climate. Hence it is likely that that we have detected a 'forced change' in climate. Potential explanations for the change are natural factors (changes in solar intensity, a reduction in the cooling associated with major volcanic eruptions) or human influences. Model simulations indicate that the natural factors fail to explain the recent warming whereas human influences — through increases in greenhouse gases — can. Indeed, it is likely that most of the warming over the last 50 years can be attributed to human activity.

The methods used in detection and attribution can also be used to calibrate the size of the climate model's response against observations.

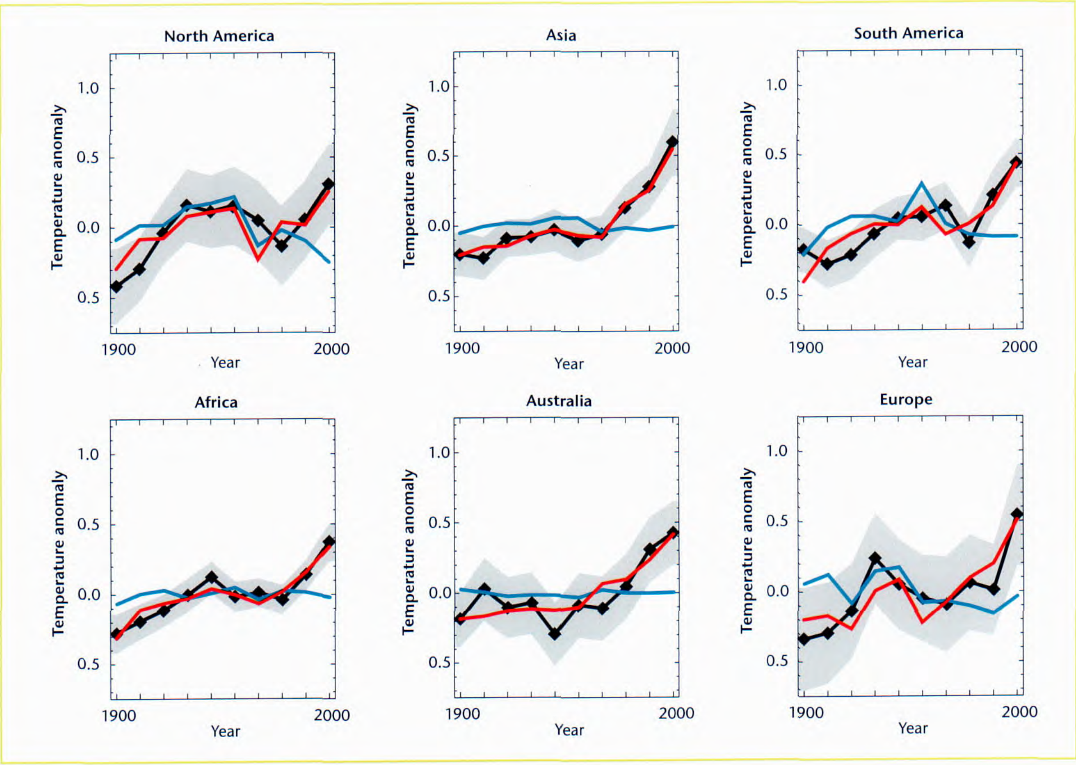


Figure 15: Indicators of climate change on a continental scale, showing the effects of greenhouse gas emissions, modified by volcanic activity, sulphate emissions and changes in solar forcing (red is all factors, blue is just natural forcing, black is observations)

This allows the possibility of correcting the size of the model's predictions, with estimates of uncertainty. Predictions corrected in this way lie within the range of those given by the third IPCC (Intergovernmental Panel on Climate Change) assessment.

An added bonus of the attribution methodology is that it provides a measure of how well the climate model simulates the magnitude of the response to different forcing. This helps validate the climate model and can highlight which parts might benefit most from improvement.

Climate change on a continental scale over the past 100 years

Observations of temperature show that on average the globe has warmed substantially over the 20th century but that there have been large regional variations in the amount of warming.

Previous analyses have looked at temperature changes over the globe as a whole rather than over individual continents, but recently the Hadley Centre has examined the causes of 20th century temperature change on a continental scale.

The modelling study investigated the historic impact on the climate system of the combined effect of greenhouse gases, anthropogenic sulphate aerosol, lower atmosphere and stratospheric ozone and the effects of volcanoes and changes in the output of the sun. The study compared this with the climate change that would have been expected if only natural factors from volcanoes and changing solar output were important (**Fig. 15**).

There is a much better agreement with the observed climate change in all six continents when anthropogenic factors are included.

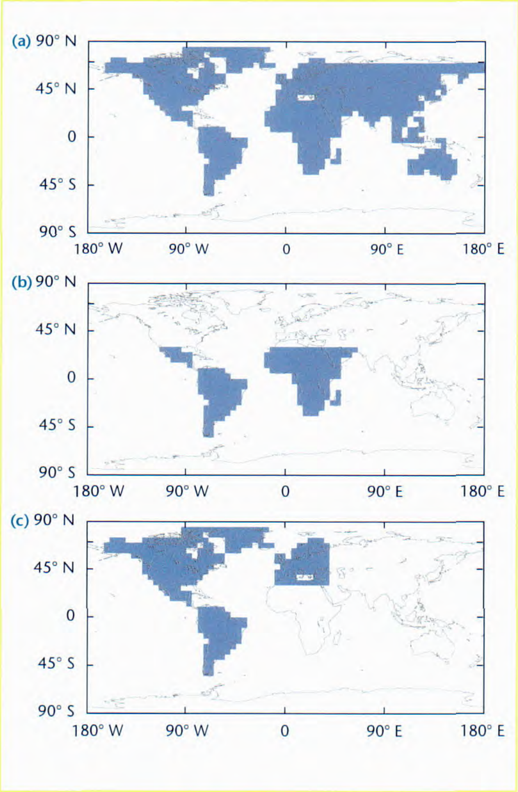


Figure 16: Regions where we detect the impact of

(a) greenhouse gases

(b) sulphates

(c) natural factors

Warming observed in the last two decades can only be explained by increasing concentrations of greenhouse gases.

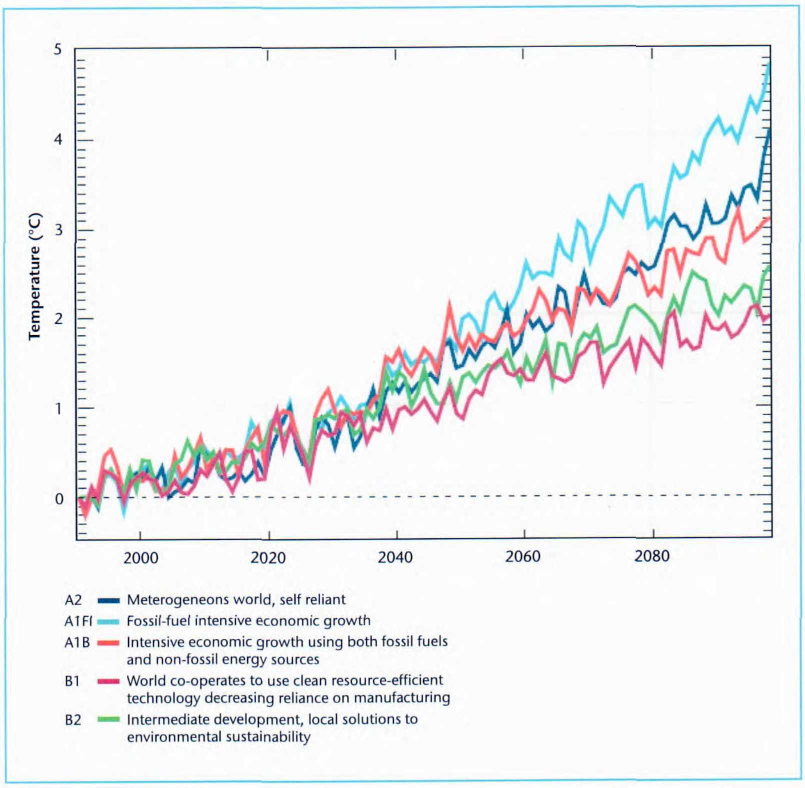
The 'optimal' detection method shows there is a significant greenhouse gas warming signal in all of the continental regions we looked at: the Americas, Asia, Africa, Australia and Europe (**Fig. 16**).

Temperature changes from other human activity and from natural factors are detected in some but not all of the continental areas, since these factors are weaker and more uncertain than the effects of greenhouse gas.

Therefore, scientists have more confidence in attributing a man-made greenhouse gas component to continental-scale temperature changes than in attributing other factors.

Changes in the latter half of this century depend on the choices made in the next 20 to 50 years

Figure 17: Predicted 21st century global mean surface temperature rise for five emissions scenarios



Predictions of future climate change are a vital input to the strategic plans made by governments and many private companies. These predictions depend on factors such as politics, population growth, economic growth, technological development – and so on.

The scientific community works with a number of carefully developed scenarios which take into account as many of these factors as possible.

These scenarios were developed by the Intergovernmental Panel on Climate Change. They are described in detail in the IPCC Special Report on Emissions Scenarios.

New predictions of future climate change have been produced by the Hadley Centre for five scenarios of future emissions. The projections shown were made using the Hadley Centre coupled ocean-atmosphere climate model.

The global mean temperature rise over the 21st century is predicted by the model to be 4.5 °C for the highest emissions (A1FI) and 2 °C for the lowest (B1). The mid-range A1B scenario projects a global mean temperature rise of 3 °C.

As can be seen in **Figure 17**, over the next 40 years the warming predicted for the five scenarios is similar. This is because much of the change over the next few decades is already built into the climate system from present day emissions and those from the last few decades.

The climate outcome for the latter half of the 21st century will strongly depend on the emissions over the next few decades.

Global rainfall increases by around 1% for every 1 °C of warming in the climate model for all the scenarios. In the case of A1B, the rainfall increase during the 21st century is predicted to be almost 3.5%.

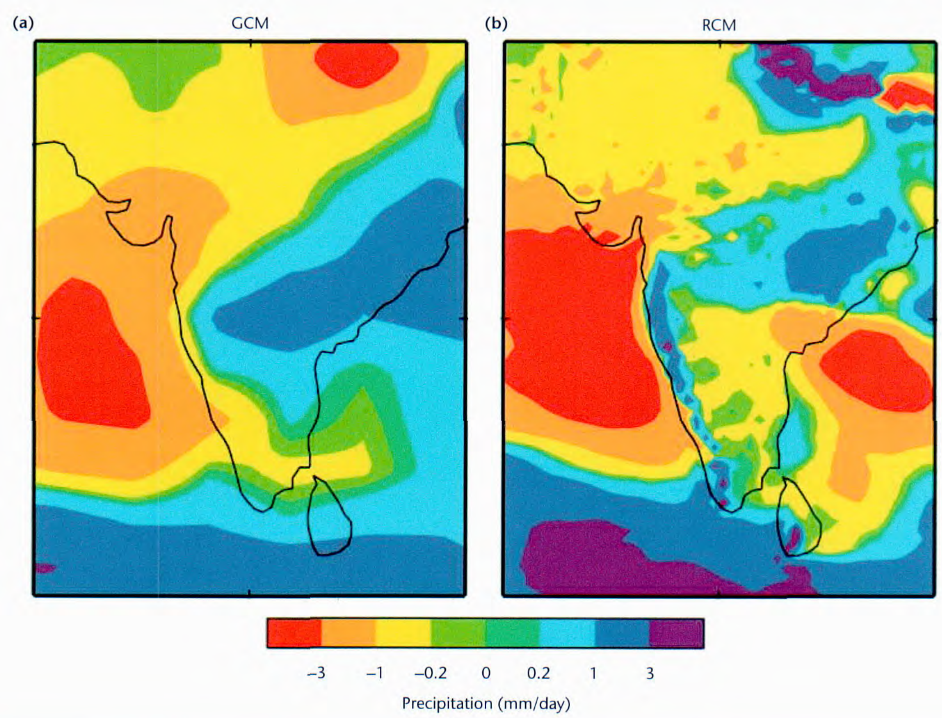


Figure 18: Changes in summer rainfall due to a gradual increase in atmospheric carbon dioxide, around the time of doubling carbon dioxide concentrations using

(a) a global coupled ocean-atmosphere model and

(b) a regional atmospheric model driven by changes in the global model

Getting in close – regional climate modelling

Societies need detailed predictions of regional climate change and its impacts to assess their vulnerability and decide how they will adapt to the coming changes.

Predictions are required at scales of tens of kilometres or less. Global climate models are too expensive to be run at this resolution so we bridge the gap using regional climate models run at a resolution of 25 km or 50 km over areas covering whole continents.

The Met Office uses regional climate models in conjunction with sub-models to determine the impacts of climate variability and change. However, the accuracy of these models is limited by the accuracy of the global model used to produce the atmospheric conditions at their boundaries.

Monsoon rainfall over the south-west coast of India is predicted to reduce in the global model due to increased greenhouse gas concentrations, with a large area of increases further to the east (**Fig. 18a**) as the model does not represent the Western Ghats (the coastal mountain range). However, in the regional model, the coastal range is resolved, leading to increased rain along the coast where the monsoon flow rises over the mountains, and reductions further downstream in the south-east (**Fig. 18b**).

Hadley Centre models suggest a reduction in the strength of the Gulf Stream

Will the Greenland ice sheet melt?

Recently, the Hadley Centre has used its climate model to simulate and predict the evolution of the Greenland ice sheet over several thousand years. This experiment is novel in that changes in the ice sheet, such as the height of the ice or whether the ground is covered in reflective ice or dark soil, are fed back into the climate model.

The results show that over the 3,000 years following a quadrupling of atmospheric greenhouse gas concentrations, the ice sheet recedes from most of Greenland. By the end of the simulation, it exists only on the mountainous ground of the east (**Fig. 19**). The fresh water released from this loss would cause a sea level rise of around seven metres.

Earlier results suggested that if the ice sheet is removed in this way it would not recover, even if greenhouse gas concentrations were significantly lowered. The next task is to understand at what point the melt down of Greenland becomes irreversible.

Will the Gulf Stream collapse?

A key question in climate research concerns the stability of the thermohaline circulation, a system of large scale currents including the Gulf Stream in the North Atlantic Ocean, which carries heat from the tropics to higher latitudes as cold salty water sinks near the pole, drawing warm water north-eastwards.

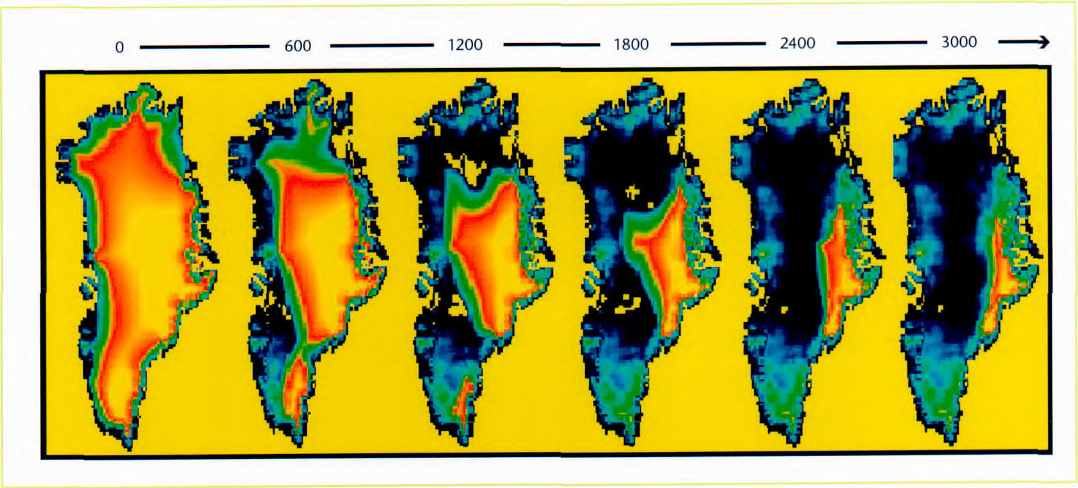


Figure 19: The Greenland ice sheet will melt over the course of 3,000 years. Red indicates thick ice while blue indicates thin (or no) ice

Recent observations have shown a reduction in the amount of salt in the seawater deep in the north-west Atlantic, and this has been interpreted by some as an early sign of a weakening thermohaline circulation.

The HadCM3 climate model shows that the observations are, in fact, consistent with a slight strengthening of the thermohaline circulation since the 1960s. Nevertheless, the model predicts that in future it will weaken somewhat as a result of global warming (**Fig. 20**).

Hadley Centre models suggest a reduction in the strength of the Gulf Stream by as much as a quarter, but not a collapse. However, even with this reduction in the Gulf Stream, the net result of climate change will be a warmer Europe.

Will coastlines flood?

Coastal populations are growing faster than those inland and there is a concern that many will be vulnerable to flooding. The most serious coastal flooding comes from storm surges.

Hadley Centre scientists have been working with the Proudman Oceanographic Laboratory in Liverpool to predict how the storm surge height around the United Kingdom coastline will change over the 21st century (**Fig. 21**).

If defences are not raised then some regions may experience coastal flooding much more frequently in the future than they do today.

A new system that will improve our predictions of storm surges and enable detailed prediction of other quantities in European coastal waters is now being developed.

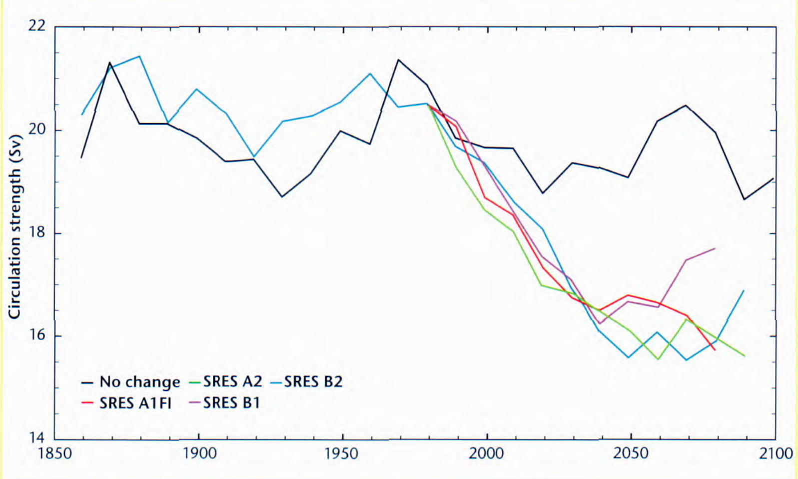


Figure 20: Simulations using the HadCM3 climate model of the strength of the Atlantic thermohaline circulation from 1860–2000 (using historical variations of greenhouse gases, sulphate aerosol, solar radiation and volcanic dust). The simulations show a freshening of the Labrador Sea from 1950–2000, as has been seen in observations, but this is associated with a slight strengthening of the thermohaline circulation over the same period, rather than a weakening as has sometimes been suggested. When the simulations are extended forward from 2000–2080 (using a projection of future greenhouse gases and aerosols), both trends are reversed, with a salting in the Labrador Sea and a weakening thermohaline circulation

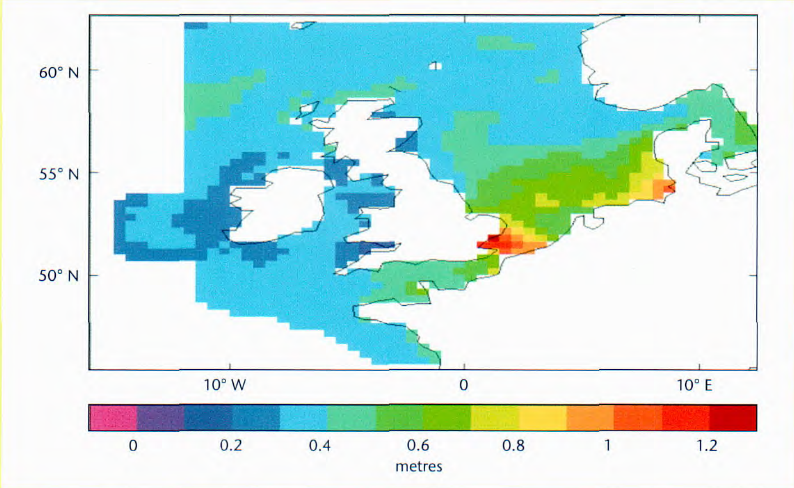


Figure 21: Predicted changes in storm surge height (m) around the coasts of the British Isles, English Channel and North Sea during the 21st century

The chemistry of the atmosphere will change as the climate changes

The effect of the carbon cycle

As the atmospheric concentration of carbon dioxide (CO_2) increases, so does the ability of vegetation to take up CO_2 from the atmosphere.

However, the increase in CO_2 leads to changes in temperature and rainfall, which can affect natural carbon sinks. For example, the coupled climate-carbon cycle model predicts a dying-back of the vegetation in northern areas of South America — one of the most significant carbon sinks.

Climate change also affects the amount of CO_2 emitted by bacteria in the soil. In the ocean, changes in circulation and mixing alter the ocean's ability to take up CO_2 from the atmosphere. In addition, the warmer oceans absorb less CO_2.

To include all of these feedbacks it is necessary to treat the carbon cycle and vegetation as interactive elements in full global climate modelling experiments (**Fig. 22**). This approach was pioneered by the Hadley Centre.

The Hadley Centre climate-carbon model suggests that the land-surface as a whole could switch from being a weak sink of CO_2 to become a strong source from about 2050, under a 'business as usual' emissions scenario. This result implies that there may be a well-defined 'dangerous level' of CO_2 – beyond which the land-carbon cycle begins to accelerate climate change – and also that stabilising CO_2 below this level may be more difficult than previously thought – because feedbacks lead to less anthropogenic CO_2 being absorbed by ecosystems.

Getting a reaction

The chemistry of the atmosphere will change as climate changes. Predicting how these processes will interact is a significant scientific challenge.

Some greenhouse gases, such as methane, and ozone are controlled by chemical reactions in the atmosphere. These reactions depend on the emissions of natural and man-made pollution and are strongly affected by climate change. To take account of these complexities, comprehensive models of atmospheric chemistry calculate future concentrations of reactive greenhouse gases and the results are passed to climate models to calculate their warming effect.

These chemicals are not only important from a greenhouse gas point of view. For instance, ozone is poisonous to human health (causing respiratory distress) and crops (reducing the yields). However, ozone high up in the stratosphere protects the surface from harmful UV radiation.

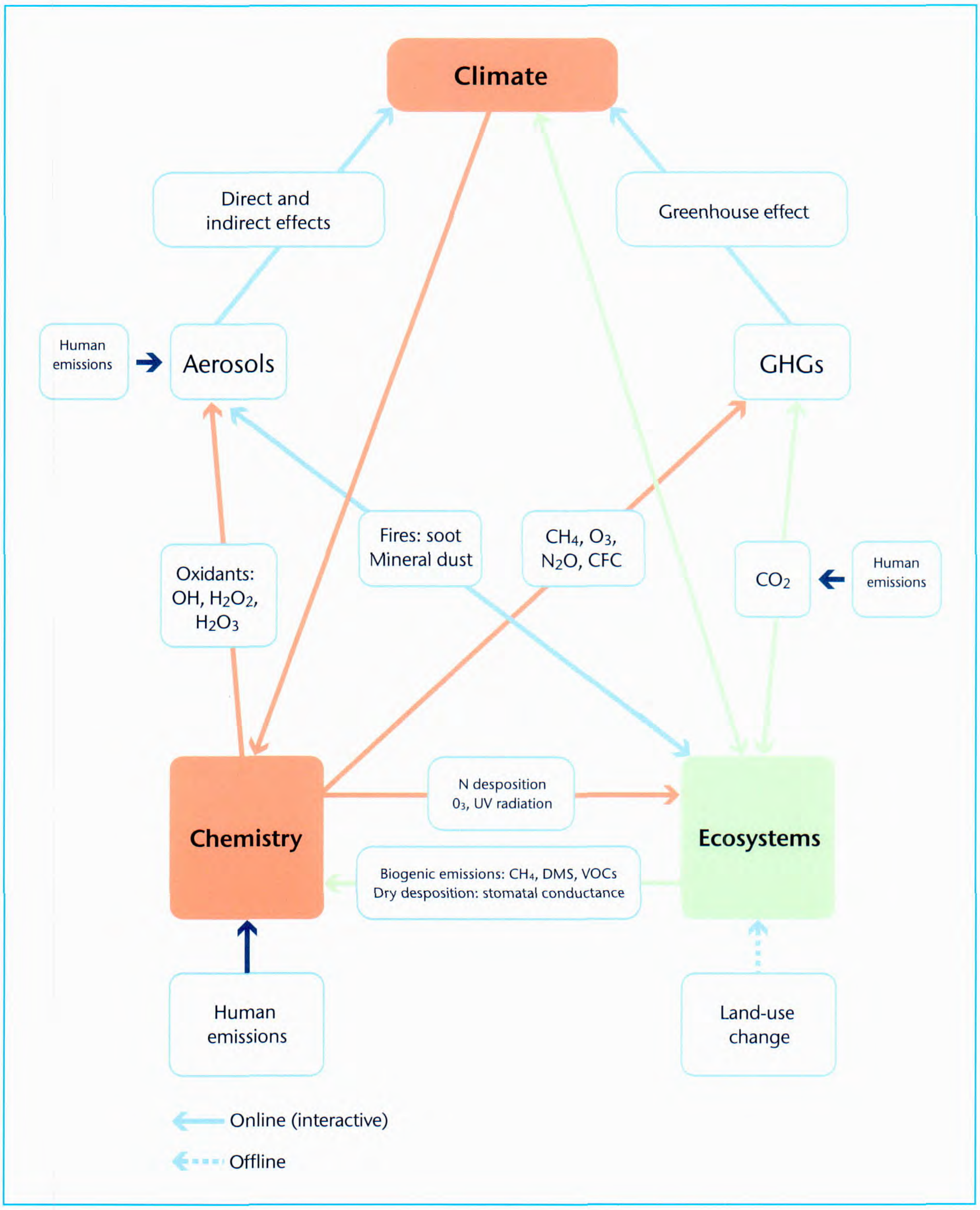


Figure 22: The inter-relationship between climate, chemistry and ecosystems

"Through climate change, mankind may be altering the strengths of what are normally thought of as 'natural' sources of chemicals, with consequences for the production of greenhouse gasses and air pollution."

Ensemble predictions of time-dependent climate changes during the 21st century

Ensemble climate prediction

One of the ways in which scientists are improving our climate modelling techniques is through the use of ensembles. Ensemble climate modelling uses similar principles to ensemble forecasting (see page 12) to span the uncertainties due to errors in initial conditions and shortcomings in the model formulation.

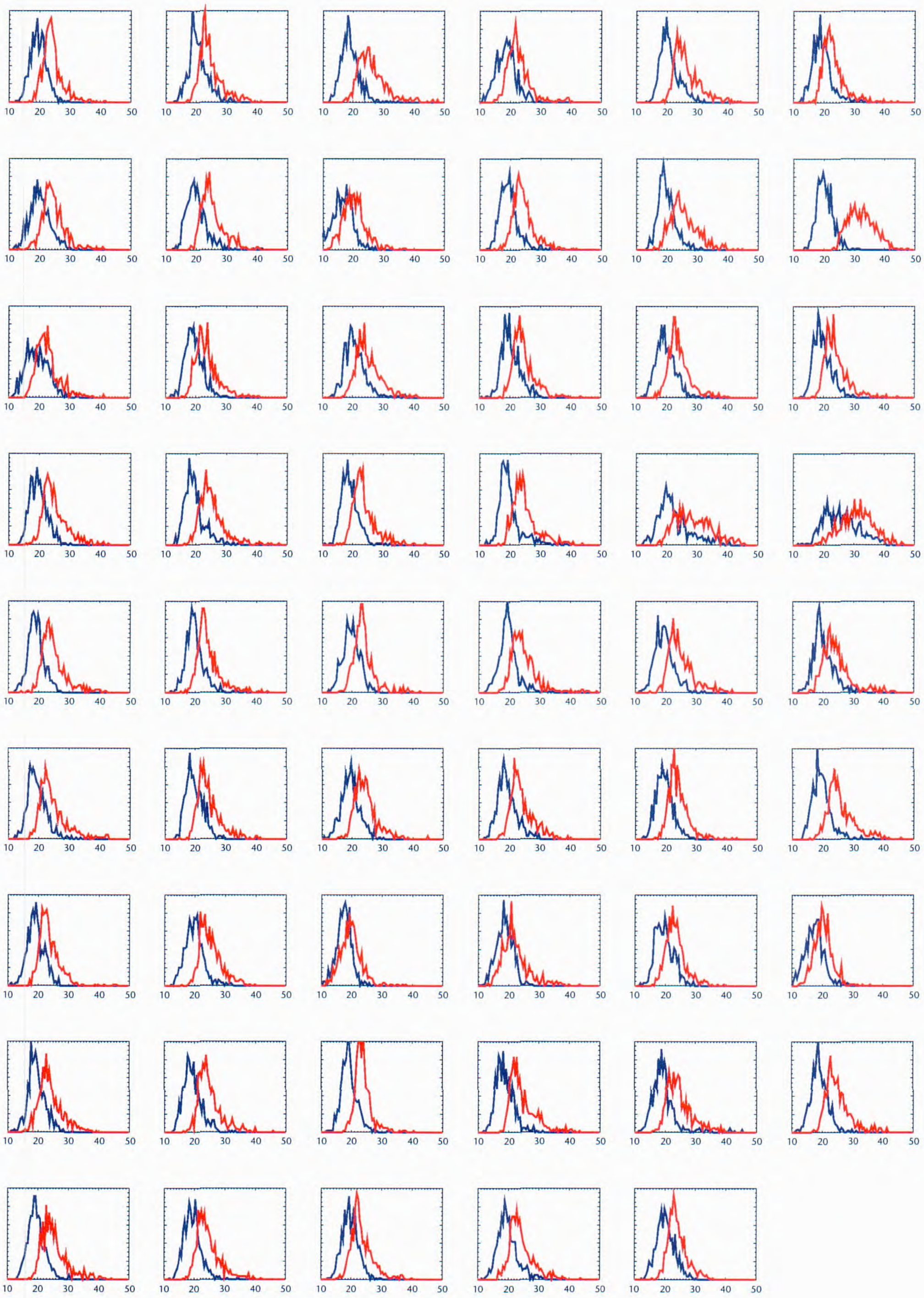
Global climate model predictions are subject to the considerable uncertainties in the modelling process; ensemble techniques help to quantify the uncertainty present in any model.

As a first attempt, Met Office scientists have produced a 53-member ensemble simulating the long-term response to a doubling of atmospheric carbon dioxide, as shown in **Figure 23**. It was created by varying parameters in the model physics whose values cannot be accurately specified on the basis of theory or observations, and are therefore subject to an uncertainty range.

This initiative is being developed to produce ensemble predictions of time-dependent climate changes during the 21st century. This will allow us to produce estimates of the evolving uncertainty range for global and regional climate changes in response to a given greenhouse gas emissions scenario which are consistent with the uncertainties arising from the range of surface and atmospheric parameters.

It will also be possible to cater for key uncertainties associated with other aspects of the climate system, such as physical processes in the ocean, the atmospheric sulphur cycle and the terrestrial carbon cycle.

In future, a climate index will provide a measure of how well the model reproduces present climate or recent changes in climate. This will be used to weight the predictions of different model versions and will provide an improved basis for the assessment of climate-related risks.



The vertical axes show frequency and the horizontal axes show temperature.

Figure 23: Distributions of daily maximum surface air temperature over south-east England simulated by 53 alternative versions of the Hadley Centre climate model. The **blue lines** show present-day distributions and the **red lines** show distributions in a climate with doubled carbon dioxide. In each plot the vertical axis shows relative frequency and the horizontal axis shows maximum temperature in °C. All models show an increase in frequency of high temperatures, but there are variations in the magnitude of the increase from model to model

The Met Office has always used computers that are among the most powerful available

Introduction of the NEC SX6

To improve the reliability and accuracy of weather forecasts and climate predictions, it is necessary to continue improving the Unified Model. There are many ways to do this and they all involve using more computer power. For example, we can make the numerical model more detailed, which means making more calculations. We can run a series of forecasts from slightly different conditions (ensembles) to help assess the robustness of the forecast. Climate predictions can be run further into the future. For short-period forecasts, we can increase the amount of observed data used by the model, as well as its quality.

The Met Office has always used computers that are among the most powerful available, so it features high in the list of the top 500 supercomputing sites in the world.

During 2003, NEC installed twin SX6 supercomputers. The SX6 is built on similar technology to the Earth Simulator that NEC has built and installed in Japan, which is one of the fastest supercomputers in the world. It uses parallel processing to increase the speed at which data can be processed. The new Met Office system is six times more powerful than our previous Cray T3E supercomputers. It will be used to improve forecasting and climate models. Using the computer system for both short-period forecasts and climate simulations makes the most efficient use of the available computer time. Weather forecasting requires short bursts of very powerful computer usage to produce forecasts quickly, whereas climate prediction requires long periods of powerful computer time, without short deadlines.

In moving from the T3E to the NEC, we have moved to a cluster of machines, each cluster member containing a number of processors that share a single, very high performance memory. This new system allows real applications to use far more of the peak performance than the previous T3E system.

Specification of the new computer

Each SX6 comprises a 15-node cluster with eight processors per node. The vector processors within each node share a single 32 Gigabyte memory and have a theoretical peak performance of 8 Gigaflops. The combined 2-cluster SX6 has a total peak performance of 1.9 Teraflops with a total memory of near one Terabyte. (Flop stands for 'Floating Point Operation' – or arithmetic instruction).

One of the SX6 supercomputers in an IT Hall at the Met Office headquarters, Exeter

Before taking advantage of this extra performance to build bigger and better models, it was necessary to make sure the existing operational numerical weather prediction and climate systems could be correctly transferred (from the Cray T3E to the NEC SX6) while delivering the same forecast accuracy.

Transferring operation to the next-generation computer can be problematic, because the code needs to be adapted and optimised for the new system and verification of the results is complex. This can be a particular problem when using parallel processing – the scheme that the NEC SX6 uses. Parallel processing involves use of different processors of the computer to work on different aspects of the model at the same time. These components must be combined effectively and be delivered together, if the maximum efficiency and computational stability are to be realised. All the major application codes were designed and developed with portability in mind to simplify installation of new computers. However, with several million lines of computer code, even changes which involved less than 1% of that code were a substantial task. A team of Met Office computer analysts concentrated on this task during the transition to Exeter. After four months of validation and testing, we were able to declare the system operational at the end of April 2004. At the same time, a new climate model has been developed and tested on the new system.

There is an ambitious programme of change over the next two years to use the additional computer capacity, not just of the installed SX6 but also of the planned upgrade in 2005 which will double the available computing power.

The planned operational system is geared to providing what customers want – more accuracy, more detail and a quantification of risk, with a particular emphasis on severe weather.

The new climate model will deliver better representation of physical processes, more confidence in results and better analysis of uncertainty.

Collaboration

Met Office research scientists are involved in a wide range of collaborations with universities and government research laboratories, both nationally and internationally

There are joint centres for mesoscale meteorology and data assimilation, as well as a Hadley Centre unit at the University of Reading. We also jointly fund a unit at the Centre for Ecology and Hydrology, Wallingford. We have strong links with the European Centre for Medium-Range Weather Forecasts.

We have a large number of formal and informal collaborations with university groups and government institutes.

We also take part in European Union Framework programmes as coordinators or participants. For example, we lead the Framework VI integrated project on ensemble-based predictions of climate change and their impacts.

We engage in and take the lead in a number of projects within the European meteorological satellite programme. The Hadley Centre and the Centre for Global Atmospheric Modelling have set up a joint modelling project with the University of Tokyo using the Earth Simulator.

Met Office scientists also play a leading role in many of the World Meteorological Organization programmes, in particular those of the Commission for Atmospheric Sciences and the World Climate Research Programme.

Further copies of *Environmental prediction: Science and technology in the Met Office 2003/04* can be obtained from our Customer Centre on 0870 900 0100, or +44 (0)1392 885680 if calling from outside the UK

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