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UGAMP's objective:
To understand the atmosphere and its links to other systems, such as the oceans, in order to advance the science of climate prediction

The UK Universities Global Atmospheric Modelling Programme (UGAMP) was set up by the Natural Environment Research Council (NERC) as a community research programme, bringing together university centres of atmospheric science, with the aim of addressing high priority issues in climate research. In addition to this collaboration of universities, UGAMP also has close working relationships with some of the world's leading weather centres, including the European Centre for Medium-Range Weather Forecasts (ECMWF) and the UK Meteorological Office.

UGAMP provides an infrastructure of computer models of the atmosphere, datasets and technical support to all its research sites. This infrastructure has allowed research to progress more quickly, enabling UK university groups to lead developments in many areas of atmospheric science.

This report highlights some of UGAMP's achievements during the period April 1992 to March 1997, and notes the practical implications of our findings.

UGAMP is gearing up to meet new challenges in climate modelling. We are building computer models to represent interactions between the atmosphere and oceans. Such models will be the foundation of our attempts to understand climate variability and improve predictions.

UGAMP is also building models that represent the effect of atmospheric chemistry on our environment. New techniques are being used to optimise the use of observational data by assimilating them into atmospheric models.

Alan O'Neill
Scientific Director, UGAMP

Some scientific highlights
UGAMP has:
- shown that the UK's winter storms could get stronger as a result of global warming,
- improved the understanding of natural variability in the atmosphere, thereby aiding the detection of man-made climate change,
- shown how ocean temperatures can affect monsoon rainfall, thereby giving hope that useful seasonal forecasts can be made,
- shown that changes in the strength of the Asian monsoon can have a direct impact on the summertime climate of Europe,
- simulated, for the first time, realistic ice-sheet growth at the beginning of the last ice age. Success in modelling past climates gives confidence in our predictions for future climate change,
- helped to understand what controls motion across the tropopause. This understanding will lead to improvements in the simulation of ozone destruction and the circulation of moisture in the atmosphere,
- confirmed that man-made pollutants are responsible for ozone destruction over the Arctic, thereby adding weight to the argument for curbing chemical emissions,
- made chemical forecasts that were used to guide flight path planning during international observational campaigns.
UGAMP's scientific research is driven by the need for a better understanding of the atmosphere in order to reduce uncertainties in climate forecasting. To this end, it is essential to know what the real atmosphere is like and to develop numerical models that can accurately reproduce its behaviour. These numerical models, known as General Circulation Models (GCMs), represent the processes that can have an influence on the atmosphere. These include: the absorption of the Sun's radiation, the effects of mountains and evaporation from the Earth's surface. We have a model that also simulates the flow in the oceans and chemical transport models that simulate the complex chemistry of the atmosphere.

Besides GCMs, UGAMP's research depends heavily on the use of observational data for the real atmosphere. Global measurements of winds, temperatures, humidity and other parameters are necessary to identify the processes that must be represented in models and to evaluate their performance.

Models

UGAMP has:

• made improvements to many aspects of our GCM. Our improvements to the effects of water vapour on radiation have been implemented in the ECMWF forecast model.
• extended our GCM upwards so that it includes the ozone layer.
• developed some of the world's leading chemical transport models that simulate the chemistry of ozone destruction.
• developed a coupled model of the atmosphere and ocean that captures an important feature of the tropical oceans, the annual cycle in sea surface temperatures in the East Pacific.
• modified some of our models so that they can be run on the new generation of fast 'parallel' computers.
• experimented with using potential temperature as a model vertical coordinate. This theoretically increases accuracy by reducing most atmospheric motion to two dimensions.

Data

UGAMP has:

• developed 'contour advection', a technique now used throughout the world to quantify the movement of chemicals and other parameters in the atmosphere.
• developed the world's first '4-dimensional variational chemical assimilation scheme' which exploits our knowledge of balances between chemicals to make much better use of observations.
• participated in international campaigns and developed a capability to make chemical forecasts to guide the deployment of observational equipment.
• developed innovative methods to analyse data from forecast centres and satellites. Our data products are distributed to colleagues worldwide.
• developed routines to track storms and tropical cyclones and produce statistics about them.
UGAMP’s range of models

UGAMP uses state-of-the-art general circulation models (GCMs) to study the complex processes that occur in the atmosphere. These models show, for example, how the atmosphere may respond to increasing carbon dioxide or changes in sea surface temperatures. Although essential tools, GCMs are expensive in computer time and, at times, are themselves difficult to understand. We can sometimes use simpler models to study particular features of the climate system. In simpler models, results are often easier to interpret and controlled experiments can be made to test specific hypotheses.

The Simple Global Circulation Model (SGCM)
The SGCM was developed at Reading and has formed the basis for several of the World’s leading forecasting models such as that at the ECMWF. This model has helped UGAMP to tackle successfully fundamental questions where very long runs, very high resolution runs or runs with simplified physics are required. These questions include: “What is the natural variability of our climate before the effects of CFCs and carbon dioxide are taken into account?”, “How do cyclones in our storm tracks mix stratospheric and tropospheric air?” and “How does the Asian Monsoon affect European climate?”

General Circulation Models (GCMs)
UGAMP uses several internationally respected GCMs which have a much more complete representation of the atmosphere. These models include the UK Meteorological Office’s ‘Unified Model’ (UM), the ‘Integrated Forecasting System’ (IFS) of the European Centre for Medium-Range Forecasting and our own in-house UGAMP ‘UGCM’. Developments of these models within UGAMP have included extensions into the radiatively important upper atmosphere and changes to the way convection and other physical processes are represented. In addition, UGAMP has invested considerable effort in developing software for analysing the output of these models. With these GCMs, UGAMP has, for example, shown how increasing atmospheric carbon dioxide can strengthen the wintertime North Atlantic storm track, how changes in the Earth’s orbit were partly the cause of the very different climates of the past and how changes in sea surface temperatures due to El-Niño can influence the course of the Asian Monsoon.

Chemical Transport Models (CTMs)
UGAMP is committed to improving the simulation of atmospheric chemistry, particularly that related to ozone loss. We have developed chemistry models which trace the movement of gases and attempt to represent the extremely complex set of chemical reactions that occur in the atmosphere. These models include the emission of pollutants from the Earth’s surface and from aircraft, and also the production of nitrogen oxides due to lightning. The models simulate vertical motion, mixing, deposition and chemistry. Use of UGAMP’s CTMs is helping to explain the complex problem of ozone loss. A forecast made by one of these models was successfully used to plan an observational flight to Antarctica.

Ocean-Atmosphere coupled GCM (OAGCM)
Future progress in seasonal and climate forecasting will rely heavily on advances in understanding the natural variability of the
coupled ocean-atmosphere system. Building on its strong track record in atmospheric modelling, UGAMP is developing a coupled model for NERC researchers. The coupled model comprises an atmospheric GCM, a model of the ocean circulation and an interface, which couples the two together. A ten-year simulation has been completed. A notable success has been that our coupled model has captured the annual cycle in sea surface temperatures in the tropical East Pacific, an important feature that some coupled models fail to capture.

Understanding model errors
Based on contributions from Mike Blackburn

Most general circulation models still share similar major errors in their simulation of the seasonal climate. Runs of a version of the ECMWF IFS model have revealed that the model exhibits a cold temperature bias at the tropopause in the polar regions, very similar to that in the UK Meteorological Office’s Unified Model (3rd climate version), and in many other GCMs around the World. The evolution of the cold bias is related to errors in the winter polar vortex which lasts too long and whose edge is too far towards the equator. By comparing this simulation with a run of a more recent version of the model, we have shown that the cold bias error is greatly reduced when the method used to transport moisture in the model is improved. This is an important improvement because the distribution of water vapour near the tropopause has a strong influence on climate.

The time evolution of the temperature at about 10km altitude averaged around latitude circles. The model (bottom panel) is unable to maintain warm temperatures at the summer pole. In addition, the model produces a winter vortex which is too extensive and too cold and which fails to break down correctly in the spring.

Improving our models
Based on contributions from Mike Blackburn, Jo Haigh, Julia Slingo, John Thuburn, Stuart Webster and Wenyi Zhang

UGAMP has a continuing commitment to the improvement of models, and almost all physical aspects of models are studied. We have shown how sensitive the variability of convective rainfall is to the choice of representation of the physics of cumulus convection. These differences will have a marked impact, particularly on the forecasting of extreme weather events such as hurricanes.
UGAMP is investigating a new approach to 'gridding' the Earth. Data about the atmosphere are stored at the centres of the nearly uniform pentagons and hexagons. The approach avoids traditional problems at the poles.

Improvements to the absorption of radiation by carbon dioxide and ozone have led to a considerable improvement in the simulation of stratospheric temperatures.

Since the large-scale atmospheric motion is approximately two-dimensional in the sense that air follows closely layers of constant potential temperature, we have experimented with using these layers to store atmospheric data in our model. The idea, which is theoretically appealing, has lead to improvements in the simulation of the tropopause.

Other areas of interest have been the transport of moisture in GCMs and the important representation of breaking waves in the stratosphere.

Improving the representation of radiation in our models
Based on contributions from Jo Haigh, Wenyi Zhong

Water vapour is the most important greenhouse gas in the troposphere so an accurate representation of its effects on radiation is fundamental to a successful simulation of climate. UGAMP has improved the representation of the absorption of radiation by water vapour, and these improvements have been implemented in the ECMWF forecast model. Our work has also indicated the importance of minor greenhouse gases, such as methane, nitrous oxide and CFCs, in the radiation budget of the atmosphere. Our changes to the representation of radiation, which can account for the overlapping of absorption bands, mean that the longwave radiation budget in the UGCM is flexible in terms of the inclusion of different gases and is applicable to much higher altitudes in the atmosphere.

[Images of models with old and new water vapour schemes]

The outgoing longwave radiation (OLR) emitted to space during January in our model with the old and new treatments of water vapour in the radiation calculations. The new water vapour scheme leads to a reduction of OLR in the clear-sky regions over the sub-tropical oceans, in closer agreement with satellite observations. Each colour represents a range of 10 Wm$^{-2}$. 
UGAMP innovations
Based on contributions from Mike Fisher (ECMWF), David Lary and Warwick Norton

Some of UGAMP's ideas have been assimilated into the international scientific community. 'Contour Advection' was developed in UGAMP and independently at MIT, U.S.A. It is now used extensively throughout the world to simulate and understand chemical transport and ozone destruction. Contour advection is a technique for following the very fine structure which develops in chemical concentrations. Particles are placed along a contour of constant concentration and these are then moved by the winds to find the new location of the contour. Accuracy is maintained by redistributing particles along the contour; more particles are added in regions of high curvature.

Another major advance made by UGAMP has been the development of a technique called '4D variational chemical data assimilation'. By incorporating our knowledge about the complex balances which exist between different chemicals species, this technique makes much better use of observations which are irregular in time or space. Similar techniques have been used for meteorological variables but this is the first time that they have been applied to chemical constituents.

The data we help produce and distribute
Based on contributions from Lesley Gray, Brian Hoskins, Paul Berrisford and Dingmin Li

UGAMP plays a major role in acquiring and processing data from the European Centre for Medium-Range Weather Forecasts. Under the 'Joint Diagnostics Project', which is a partnership with the UK Meteorological Office, software has been written to calculate meteorological quantities that give a better understanding of the state of the atmosphere. UGAMP works closely with the British Atmospheric Data Centre in the distribution of the new ECMWF Reanalysis (ERA) data set. Although very new, the ERA data set is becoming indispensable for research and UGAMP uses it for topics as diverse as high resolution chemical forecasts, monsoon research and running our stratospheric model.
The North Atlantic, particularly in winter, is characterized by strong low-level westerly winds blowing between the Icelandic Low to the north and the Azores High to the south, and by mobile weather systems, such as depressions, moving towards western Europe. The average path, or 'storm track', of these weather systems varies from month to month and from year to year. In some winters, a succession of depressions causes severe winds and rain over the UK; in others, the storm track diverts away from the UK, leaving the country to experience more continental-type weather. The reasons for such natural variability need to be better understood if accurate season-ahead forecasts for the UK are to be made, and if the regional responses to man-made climate change are to be determined. Another important question relates to the way mixing of polar and subtropical air within mid-latitude depressions facilitates the transport of chemicals between the stratosphere and troposphere.

UGAMP has:

- shown how global warming can lead to stronger and more frequent wintertime storms affecting the UK and Europe. This is a far more significant change to the local climate than that implied by the average global temperature rise.
- developed methods, now used widely in the atmospheric research community, to track storms in model data and observations. The methods give a new and complementary view of the atmospheric circulation.
- shown that climate variability on time scales as long as several years can arise naturally without the influence of changing ocean temperatures or atmospheric pollution.
- modelled mid-latitude cyclones at unprecedented resolution, showing how cyclones generate small-scale structures that may lead to mixing of air masses and turbulence experienced by aircraft.

Variations in the North Atlantic Oscillation

A measure of the strength of westerly winds over the North Atlantic, which is intimately connected with the storminess affecting the UK, shows that there is natural variability on many timescales. The recent stormy period must be viewed in the context of this longer data record if conclusions about possible man-made climate change are to be drawn.
The effect of global warming on the storm tracks
Based on contributions from Brian Hoskins, Paul Valdes, Nick Hall and Cath Senior (UKMO)

The concentration of atmospheric carbon dioxide, which is a 'greenhouse gas', has been increasing since the beginning of the industrial revolution. Increasing levels of carbon dioxide (CO₂) are thought to lead to a warmer average temperature over the globe. An important question has been how this global warming may affect the strength and number of storms that occur over the North Atlantic during winter.

UGAMP has compared two experiments using the UK Meteorological Office model, one with doubled CO₂ in the atmosphere and the other with present day CO₂ values. We found that, in the northern hemisphere, winter storms strengthened on average by 10% and were displaced northward by about 500 km in response to global warming. The intensification of storms over the North Atlantic was particularly marked. The implication is that increasing levels of carbon dioxide in the atmosphere may lead to an increase in the number of strong winter storms affecting the UK and Europe, such as the infamous 'October Storm' of 1987 which did many millions of pounds worth of damage in southern Britain. Such a change in the storm tracks is a far more significant change to the local climate than that implied by the average global temperature rise.

Global warming may lead to stormier winter-time weather for Europe

Increasing levels of carbon dioxide in the atmosphere may lead to an intensification of the winter-time storm tracks. The most noticeable change over the globe is an increase in storms reaching the UK.

Natural variability in the storm tracks
Based on contributions from Keith Haines, Brian Hoskins, Ian James, Chris Folland (Hadley Centre) and Kevin Hodges

In addition to their influence on the local climate of the UK, the mobile weather systems of the mid-latitude storm tracks play a central role in the global circulation, facilitating the poleward transport of heat and momentum. Storm track strength is therefore of great importance to the question of global climate change. There have been changes in the average strength of mid-latitude storms. For example, the recent stormy period from 1988 to 1995 was characterised by stronger than normal westerly winds and more
intense storms over the wintertime North Atlantic.

UGAMP has developed methods, now used widely in the atmospheric research community, to automate the tracking of individual storms as they cross the ocean. During the winter of 1984/85, before the recent stormy period, there were relatively few storms crossing the North Atlantic and most of these diverted away from the UK. In the winter of 1988/89, by contrast, the storm track was much more active with numerous storms affecting the UK. The diversion of storms is related to a phenomenon known as blocking, when high pressure resides over the UK and western Europe for several days. Generally climate models do not simulate enough blocking. Using both simple models and GCMs, UGAMP has identified features in the large-scale flow that favour the development of blocking, which may provide useful information for forecasting.

The tracks of depressions over the North Atlantic during two recent winters. In the winter of 1984/85, the North Atlantic storm track was weak, with a 'blocked' situation preventing depressions passing over the UK. In 1988/89, the storm track was much stronger. These differences are due to natural variability in the atmosphere and must be taken into account when attempting to identify climate change.

In addition to variability on the timescales of weeks and months, a measure of the westerly winds for each winter in the last 130 years (displayed at the beginning of this section) shows the year-to-year variability and variability on longer, decadal, timescales. The decadal variability in storminess is part of a large-scale oscillation in pressure over the North Atlantic called the North Atlantic Oscillation (NAO).

It is clear that there is considerable natural variability in the westerly winds and the storm tracks. In fact, the recent period of increased storminess was matched by a similar period during the earlier part of the 20th Century. It is crucial to be able to discriminate between such natural variability and climate change induced by man, so we must also understand the processes that govern natural variability.

UGAMP has made a number of long simulations, up to 100 years long, with a simplified model of the atmosphere to identify some of the mechanisms of natural variability.
The results confirm that some long-term variability can arise from natural processes entirely within the atmosphere. There is strong evidence that decadal variability over the North Atlantic involves interactions between the atmosphere and ocean. UGAMP is building coupled models of the atmosphere and ocean to understand these interactions and to determine whether the variability is predictable so that climate forecasts can be made.

### Very high resolution modelling of mid-latitude cyclones
*Based on contributions from Brian Hoskins and John Methven*

A simple model of a depression in the storm track region shows it as a wave-like disturbance to a jet-stream. Many studies have examined the evolution of these waves and have shown that the structures which develop are similar to those found in real weather systems, over the North Atlantic for example. UGAMP has studied this wave evolution at very high resolution, about eight times higher resolution than is generally used in climate models. Small-scale structures, embedded within cyclones, are represented in much more detail than previously seen. Folds in the tropopause bring stratospheric air, with its trace chemicals such as ozone, deep down into the troposphere. The development of such folds would lead to the exchange of gases, including pollutants, between the stratosphere and troposphere. The folds might also be associated with atmospheric turbulence and this information may be useful for routing commercial flights. Campaigns such as the Fronts and Atlantic Storm Track Experiment (FASTEX) are seeking to study such folds in the real atmosphere.

**High resolution reveals small scale structures which can affect air turbulence and chemical transport**

The spiralling of air in a modelled cyclone stirs up subtropical tropospheric air with polar stratospheric air. As these air masses interleave, the polar air descends into the subtropical air in what is known as a ‘tropopause fold’. The fold can lead to turbulence for aircraft and mixing across the fold facilitates the transport of pollutants into the stratosphere.
Over half the world's people live within the influence of the Asian summer monsoon where the reliable return of summer rains is essential for life. From June to September monsoon rainfall provides the main source of fresh water for the millions of people who live in India, Bangladesh, China and other countries of South East Asia. The effect of the monsoon on climate is not confined to this region, but extends to distant parts of the Earth. In some years the monsoon is much weaker than normal, and this has severe social and economic consequences. It is therefore important to understand the factors that affect the monsoon, so that we can forecast its likely intensity some months ahead.

UGAMP scientists have studied other features of the tropical weather such as the so-called Madden-Julian Oscillation (MJO). The MJO is a pulse of strong rains and winds that travels eastward around the equator in about 30 to 60 days. It pumps enormous amounts of heat into the atmosphere, affecting the circulation far away.

**Monsoons**

UGAMP has shown that:
- Our atmospheric model can reproduce the observed effect of temperatures in the Pacific Ocean on the overall strength of the monsoon.
- Warmer than normal temperatures in the West Pacific Ocean favour an earlier and stronger monsoon.
- Storms far away in the Southern Hemisphere can lead, about a week later, to a cessation of the monsoon for several days.
- Changes in the strength of the monsoon can have a direct impact on the climate of Europe.

These findings are important steps toward developing a capability to predict the monsoon and its remote influences.

**Other tropical weather**

UGAMP has:
- Identified a mechanism for the eastward progression of the Madden-Julian Oscillation (MJO) into the south Pacific.
- Shown that atmospheric models do not accurately simulate the MJO, and that better simulations may require improved representations of the oceans.
- Shown how convective rainfall over the Pacific can be triggered by surges of cold air from Siberia.

By increasing understanding of tropical weather, UGAMP has contributed to the quest for better simulations of the tropics within climate models.
Seasonal prediction of the Asian monsoon
Based on contributions from Julia Slingo, Jianhua Ju and M.K. Soman

Year to year variations in the surface temperature of the Pacific Ocean have a major impact on the strength of the Asian monsoon. During so-called El-Niño years, which have

Ocean favour an earlier and stronger monsoon. These findings will enable forecasters to make more reliable predictions of the monsoon some months ahead.

Pacific sea surface temperatures may hold the key to seasonal forecasts

Warm East Pacific temperatures in spring (yellow and red) tend to precede weak summer monsoons. The reverse is true when the East Pacific is cold

higher than normal sea surface temperatures over the eastern Pacific, the monsoon is weaker. During La-Niña years, when sea surface temperatures are lower than normal in the eastern Pacific, the reverse is true.

UGAMP has developed a model of the global atmosphere that reproduces this effect. UGAMP has also shown that warmer than normal temperatures in the West Pacific

The UGAMP model shows skill simulating monsoon winds when given the observed sea surface temperatures.

Predicting breaks in the monsoon
Based on contributions from Brian Hoskins, Julia Slingo, Mike Blackburn and Mark Rodwell

The monsoon rains are often punctuated by break spells lasting a week or so, when rainfall is sharply reduced. A sequence of breaks can lead to the 'failure' of the monsoon, affecting agriculture and the economy. Until now the reasons for these breaks have not been well
Air flowing into the monsoon system normally originates over the tropical Indian Ocean. When a weather system passes South Africa, trajectories show that the air can originate from much further south, resulting in weaker, drier winds over India.

India and South East Asia follows a curved track over the tropical Indian Ocean. The development of a weather system near South Africa may alter this track dramatically. Drier air is fed over India and winds are weakened in the region, reducing monsoon rains by up to a half. These results imply that forecasters need access to good data for the Southern Hemisphere in order to improve three to ten-day forecasts of the monsoon.

The period when the countries surrounding the Mediterranean are at their driest (June to August) coincides precisely with the time when South Asia is wettest. We have identified a mechanism that links these two very different climates. During the monsoon, huge amounts of heat are released into the atmosphere as air rises over India and water vapour condenses. This heating generates a large scale wave.

**The impact of the monsoon on the climate of Europe and North Africa**

Based on contributions from Brian Hoskins, Julia Slingo, Mike Blackburn and Mark Rodwell

Changes in the strength of the monsoon can have a direct impact on the climate of Europe.
pattern that propagates towards the west, causing dry air to descend and sharply reduced rainfall over the Mediterranean and North Africa. This shows that changes in the strength of the monsoon can have a direct impact on the climate of Europe. It may also explain a fact, which has long puzzled scientists, that high lake levels and lush vegetation in North Africa over the last 140,000 years tended to occur when the Asian monsoon was weak for long periods of time.

The Madden-Julian Oscillation (MJO)

Based on contributions from Julia Slingo, Brian Hoskins, Mike Blackburn and Adrian Matthews

The MJO is a pulse of strong rains and winds, seen as a rapid increase of convective cloud that travels eastward around the equator in about 30 to 60 days. It is at its strongest from December to May, when it is one of the most intense weather systems in the tropics, pumping enormous amounts of heat into the atmosphere.

Model Intercomparison Project), UGAMP has analysed the results of experiments made with the World's leading climate models. We have identified key features that are needed to represent the MJO. One of the most important is the way convection is represented in models, and we have identified the better of two

UGAMP has explained why convection often intensifies over the South Pacific as the MJO passes Indonesia

Just after the convective cloud associated with the MJO (seen here in purple and blue) passes over Indonesia, a line of convection is often seen to flare in the South Pacific along the South Pacific Convergence Zone (SPCZ).

Despite the MJO's importance for the climate of the tropics, it is not well represented in climate models. If we could represent the MJO better, weather forecasts for the tropics could be improved for a week or more ahead. As part of an international collaboration (the Atmospheric commonly used methods. Our findings also imply that improved treatment of the MJO in climate models may require a better representation of the oceans.

As the MJO moves around the equator, it is boosted when it arrives over the Indian Ocean.
UGAMP has shown how higher frequency atmospheric waves, associated with mid-latitude weather systems, can re-energize the MJO, enabling it to make another circuit of the equator.

When the MJO passes over Indonesia, convection is often seen to develop along the so-called South Pacific Convergence Zone (SPCZ). UGAMP has proposed a mechanism, supported by studies with atmospheric models, to explain this behaviour. We propose that the convection modifies the air-flow aloft, leading to the development of a low-pressure system to the south east and further convection.

The initiation of Pacific convection

Based on contributions from Julia Slingo

A feature of the winter circulation over Siberia is that there are occasional surges of cold air toward the South China Sea. UGAMP has shown that these surges can lead to extreme weather events in the tropical western Pacific. In the UGAMP model, the cold surge excites a wave train in the upper troposphere that travels from midlatitudes into the tropics over the eastern Pacific, triggering enhanced convection about four days after the cold surge. Knowledge of this time delay can be used for weather forecasting.

The atmospheric model developed by UGAMP has successfully reproduced the structure and frequency of these cold surges, giving confidence that their effect on tropical weather can be forecast.
The ability to simulate past climates with our atmospheric models is important if we are to have confidence in our predictions of future climate change. For the last 700 thousand years or so, the climate of the Earth has experienced large fluctuations. The climate has oscillated between relatively warm periods such as the present climate, lasting for approximately 10 thousand years, and much cooler glacial periods, lasting for approximately 90 thousand years when ice sheets covered most of Northern Europe and North America up to a depth of several thousand metres, and winter sea ice extended to the UK and beyond. Important information about the UK’s future climate can be obtained from a better understanding of past changes in the behaviour of storms over the North Atlantic. During the earlier Mesozoic era, 220-65 million years ago, the climate was much warmer than it is today, and this would have affected the rate of build-up of mineral reserves. A better understanding of regional variations in climate during the Mesozoic and other periods would help to locate these mineral deposits.

UGAMP:

- was the first to simulate realistic ice sheet growth at the beginning of the last ice age.
- has shown that the character of the storms occurring over the North Atlantic and Europe was very different during glacial periods.
- has linked the past climate of the Sahara with changes in the monsoon climate of southern Asia, thereby explaining previously contradictory geological dating estimates.
- has successfully simulated and explained the warmer temperatures of the Mesozoic climate (220 - 65 million years ago); the simulated climate is in accord with that inferred from geological data.

The formation of commercially important mineral reserves was influenced by past climates.
Glacial storm tracks and ice-sheets

Based on contributions from Paul Valdes and Buwen Dong

Climate simulations have been completed for 6,000, 21,000 and 115,000 years ago using the UGAMP model (UGCM), run at relatively high resolution. These were the first ever high resolution simulations for these periods. The increased resolution allowed us to study mid-latitude storms which are vital for precipitation. Our results indicate that during the last glacial maximum, 21,000 years ago, the behaviour of storms occurring over the North Atlantic was very different from the present, and would have resulted in greater storminess for the UK and Europe.

Around 115,000 years ago was a time of glacial inception, when ice-sheets began to grow. The UGCM successfully simulated the initiation of this growth of ice in north-east Canada and north-east Siberia. This is the first time that this has been achieved in a global atmospheric model.

The formation of many economically important mineral reserves was influenced by past climates. UGAMP has focused on the Mesozoic era, 225-65 million years ago, when rich mineral deposits were laid down. During this period, the amount of carbon-dioxide in the atmosphere, the geometry of the continents, sea-level and the Earth's orbit around the sun were different from what they are today. Model simulations have been made taking account of these different conditions. The climate simulated by our model was warmer and more equable than that of today, with much less ice, as has been inferred from geological data.

Palaeoclimate research has led to improvements in our present-day climate A measure of the storminess shows that the storm tracks, particularly the one over the north Atlantic, were very different during the last glacial maximum, when there was extensive sea-ice and large mountains of land-ice.

UGAMP was the first to simulate realistic growth of glacial ice sheets

The increase in snow depth over a ten year model simulation of the climate 115,000 years ago. Much of the winter snowfall lasts through the summer, resulting in a year-on-year accumulation of snow and growing ice sheets.
Exchange of air between the troposphere and stratosphere is of fundamental importance for climate. Pollutants, such as CFCs, rising into the stratosphere are responsible for the 'ozone hole', and the transport of ozone down from the stratosphere affects the oxidising and pollutant-destroying capacity of the troposphere. The tropopause (the interface between the stratosphere and troposphere) is a fundamental feature of the atmosphere, forming a partial barrier to vertical movement of air and chemicals. Despite its importance, we still do not understand fully what determines the location and structure of the tropopause. A better understanding of the tropopause and of the ways that air can pass through it is essential if we are to reduce the uncertainties concerning chemical transport and climate change.

UGAMP has:

- helped establish that a wave-driven 'pump' in the stratosphere controls the average circulation of air through the tropopause.
- used a high-resolution UGAMP model to obtain a three-dimensional picture of the penetration of stratospheric air into the troposphere along tropopause folds.
- obtained images, at unprecedented resolution, of filamentation and mixing of tropospheric and stratospheric air at mid-latitudes.
- found that moist and dry layers alternate with height in the lower stratosphere, and explained this phenomenon.
- shown that the height of the mid-latitude tropopause is sensitive to changes in surface temperature, and has explained this sensitivity.

From our work, a much clearer picture has emerged of the exchange of air between the stratosphere and troposphere.

The layers of the atmosphere are characterised by the way the temperature changes with height.
The tropopause
Based on contributions from John Thaburn and George Craig

The tropopause marks the boundary between the troposphere, where our weather systems occur, and the stratosphere above, where the ozone layer resides. The reasons for the existence and location of the tropopause are still not fully understood. A number of theories have been advanced to explain the structure and height of the tropopause. We designed a series of experiments with the UGCM to discriminate between these theories. These experiments show that the height of the tropopause is insensitive to the Earth's rotation rate, somewhat sensitive to the concentration of stratospheric ozone, but highly sensitive to changes in temperature at the Earth's surface. We have explained the mid-latitude sensitivity to surface temperature in terms of related changes in humidity and in the radiation balance.

A 'snap-shot' of the height of the tropopause in a run of the UGCM. Deep convection in the tropics leads to a higher tropopause at the equator than at the poles.

Troopopause folds in the mid-latitudes
Based on contributions from David Andrews, Lesley Gray, Mike Bithell and Warwick Norton.

Vertical transport of water vapour and other gases from the troposphere into the stratosphere is very important for the chemistry of stratospheric ozone. The downward movement of ozone-rich air from the stratosphere into the troposphere is important for the oxidation of pollutants in the troposphere.

We have used a high-resolution UGAMP model to obtain a detailed three-dimensional picture of this exchange of tropospheric and stratospheric air. Mid-latitude weather systems can, as shown in the Storm Track chapter, fold the tropopause, bringing stratospheric air deep into the troposphere and tropospheric air up into the stratosphere. The structure of folds simulated in our model is in good agreement with that deduced from satellite data and from ground-based observations.

Once the fold has developed, air within it might subsequently return to its region of origin or it might be mixed irreversibly into its new environment. We have used our contour advection technique to investigate these two possibilities. This technique has given us an

A three-dimensional picture of a modelled tropopause fold over the UK, with stratospheric air, green shading, plunging downwards. The structure of this modelled fold can probably only be verified using aircraft observations.

A model simulation of a depression over the UK has given a three-dimensional picture of the descent of stratospheric air.
The mixing of stratospheric air (coloured) with tropospheric air (blank) at a level close to the tropopause. This mixing conveys CFCs up into the stratosphere and ozone down to the troposphere.

The tropical ‘tape-recorder’

Based on contributions from Bob Harwood, Michael Mcintyre and Phil Mote

Measurements of water vapour concentrations can indicate the strength of the circulation in the stratosphere and also the degree of mixing that occurs. By using data from the Upper Atmosphere Research Satellite, we have shown that water vapour in the tropical stratosphere exhibits alternating layers in the vertical of relatively wet and dry air. UGAMP scientists, as part of an international collaboration, have explained this phenomenon. There is an annual cycle in temperature at the tropical tropopause, with the lowest temperatures during the northern winter, for reasons mentioned in the next section. Since temperature controls the amount of moisture that air can hold, this temperature cycle imparts a seasonal cycle on the humidity of the air ascending into the stratosphere. In northern winter, when the tropical tropopause is cold, the air entering the tropical stratosphere carries relatively little moisture and produces a dry layer in the lower stratosphere. This dry layer moves upward and in the following northern summer, when the tropical tropopause is warmer, a moister layer enters the stratosphere from below. In this way, tropical temperatures impart a moisture signal on the air ascending in the tropical stratosphere, much as the head of a tape-recorder imparts a signal to the moving tape.

The moisture signal of a layer is slowly erased over a period of about 18 months as the layer rises upwards through the stratosphere and mixes with air from outside the tropics. The rate
of erasure enables one to quantify the degree of mixing that occurs in the tropical stratosphere. From this, we can determine the rate of spreading of pollutants in the stratosphere that have been emitted from aircraft, volcanoes and other sources.

A new understanding of stratosphere-troposphere exchange

Historically, studies of stratosphere-troposphere exchange have focused on two small-scale processes: tropopause folding in middle latitudes, and the penetration of the tops of cumulonimbus clouds across the tropical tropopause. It has turned out, however, that very many more processes are involved, over an enormous range of scales, locations and times.

UGAMP, in collaboration with international colleagues, has begun to put the large and small scale processes involved into a far clearer perspective. The picture that has emerged is that extratropical wave breaking in the stratosphere and mesosphere acts as a giant atmospheric 'suction pump', controlling time-averaged, area averaged, transport through the tropopause and overlying layers quite independently of the local dynamics of tropical convection and also, to a large extent, independently of the local dynamics of tropopause folding. In the tape-recorder analogy mentioned earlier, the pump acts as the tape motor.

The pumping action is the result of complicated and subtle fluid-dynamical processes: the interplay between wave propagation, wave breaking and the Earth's rotation. UGAMP has a special expertise in studying such fundamental fluid dynamics.

Changes during the year in the strength of pumping - it is strongest in the winter hemisphere - can affect the temperature and moisture bearing capacity of the stratosphere. Strong pumping means lower temperatures and drier air.

A giant wave-induced 'suction pump' (green region) controls the chemically important time-average upward mass transport across the tropopause (thick blue line) in the tropics. The downward return flow across the tropopause in the mid-latitudes can take place both across and along surfaces of constant potential temperature (black lines), for instance in tropopause folds (wiggly arrows). The broad red arrows show the time-average transport controlled by the pumping.

An important implication of this work is that GCMs will have to be extended vertically if they are to represent this high altitude pump and thereby simulate the fate of, for example, aircraft emissions released in the lower stratosphere. Another implication is the recognition of a new possibility; the 'hyperventilation' of the tropical lower stratosphere by cumulonimbus turrets.

This research is being acknowledged as a major step toward a definitive and coherent picture that is consistent with what is known about both small-scale and large-scale processes in the atmosphere.
The Antarctic ozone hole was discovered by NERC scientists in 1985. Since then, observations in both hemispheres have shown a more widespread depletion of stratospheric ozone. The most immediate implication of ozone loss is an increase in harmful ultraviolet (UV-B) radiation reaching the ground. However, ozone chemistry is complicated because it is sensitive to atmospheric conditions and these can themselves be altered as ozone is destroyed. The polar regions are susceptible to ozone loss because the wintertime ‘Polar Vortex’ acts as a containment vessel where air is chemically primed to destroy ozone when the sun re-emerges above the horizon in spring.

Lower down in the atmosphere, surface and aircraft emissions can change the amount of tropospheric ozone. High ozone amounts in the urban environment can be harmful to health but ozone is also important for the removal of other atmospheric pollutants.

UGAMP is addressing the important scientific questions concerning ozone chemistry and is developing methods to predict ozone concentrations.

UGAMP has:

- Combined diverse data sets to form an ozone ‘climatology’ which gives our best estimate of the time development of the actual distribution of ozone.
- Confirmed that Arctic ozone loss has occurred following chemical reactions involving chlorine and bromine compounds, similar to the process that leads to the massive depletions seen over Antarctica.
- Simulated the increasing yearly loss of Arctic ozone that has occurred during the 1990s. As much as 50% loss is modelled inside the polar vortex at low altitudes, in good agreement with observations.
- Shown that air from the polar regions can contribute to stratospheric ozone loss over midlatitude regions including Europe.
- Developed techniques that are successful in estimating the mixing of chemicals in the atmosphere, thereby improving the forecast rates of chemical reactions.
- Successfully simulated the chemistry that acts on air in the lower atmosphere as it flows across Europe. This includes the increase in ozone levels due to photochemical reactions.
- Modelled the ozone distribution well in the aircraft flight corridors around the tropopause.

These findings represent major advances in our understanding of atmospheric chemistry and are leading to improvements in the forecasting of ozone and other chemical species.
Observations of ozone and other chemical species
Based on contributions from David Andrews, Lesley Gray, Keith Shine and Dingmin Li

Ozone is an important climate gas whose distribution helps determine the atmospheric temperature and wind pattern. No single satellite or ground-based instrument can measure ozone at all heights and at all latitudes. Hence UGAMP has combined data from a variety of sources to produce a single 3-dimensional map of ozone for each month from January 1985 to December 1989. This data set is widely used in climate models that do not include chemistry and provides an invaluable set of observations to test models that do simulate the ozone distribution.

An understanding of ozone-related chemistry relies on good quality data sets of other chemicals in the atmosphere. With this aim in mind, work within UGAMP using data from the Upper Atmosphere Research Satellite has helped provide a more accurate picture of the concentrations of nitrous oxide and methane. These chemical measurements have identified features that are also apparent in other independent data sets and they therefore validate our present understanding of the motion and chemical composition of the stratosphere.

The Polar Vortex
Based on contributions from Alan O'Neill, Lesley Gray, Bob Harwood and William Lahoz

The Polar Vortex, which develops during the winter season, effectively confines air in the polar region for several months. In the lower stratosphere, this air can be chemically processed when it comes into contact with droplets and ice-crystals in high altitude (polar-stratospheric) clouds so that high concentrations of ozone-destroying chlorine monoxide build up. In spring, when sunlight returns to the polar region, this chlorine monoxide destroys ozone.

Particle tracking highlights the merger, seen here at about 30 km altitude, of two anticyclones (yellow) south of Australia which helps precipitate the final breakdown of the polar vortex (seen here in blue and displaced away from the pole).

A better understanding of the dynamics of the Polar Vortex is essential for the forecasting of ozone trends. UGAMP has studied the polar...
vortex using satellite water vapour measurements and by tracking air particles. The boundary between descending air within the vortex and well-mixed air outside is clearly depicted by the water vapour data. Particle tracking has given a clearer picture of the way interacting anticyclones can weaken, or even break-down completely, the polar vortex.

Using our upper atmosphere model, we have been able to simulate both vortex weakening and its final break-down in spring. The spring breakdown is especially important because this is when ozone values are at their lowest.

Modelling polar ozone depletion
Based on contributions from John Pyle, Martyn Chipperfield, Adrian Lee and Robert MacKenzie

Low temperatures, within the lower stratospheric polar vortex, provide the conditions for ozone depletion. Temperatures are lower within the Antarctic than the Arctic but, nevertheless, in some winters it is clear that Arctic ozone loss can occur. We have used UGAMP chemical transport models to simulate and study every Northern Hemisphere winter since the winter of 1991/92. All winters show some ozone loss, but it has been most pronounced in the last three, the coldest Arctic stratospheric winters on record.

The inclusion of chemistry in our model improves seasonal simulations of ozone

The model with chemistry (red line) simulates well the observed total ozone when given the observed winds. A model which does not include chemistry (green line) does progressively less well - implying the importance of the chemical removal of ozone.

UGAMP's results have confirmed the importance of the chemical destruction of ozone with as much as 30% of column ozone being destroyed chemically during a winter season. We have shown that Arctic ozone depletion occurs by similar mechanisms to those that operate in the Antarctic. The modelled loss agrees well with observations.

An important outstanding question concerns the degree to which an ozone - climate feedback loop exists whereby the ozone loss can affect polar temperatures and this in turn can lead to a more persistent polar vortex and greater ozone loss.

Percentage change in ozone since 12 December 1994 at an altitude of 20 km, calculated by the 3D model with chemistry. Initially, ozone loss occurs at the edge of the Polar Vortex (light blue region in top picture). Later, up to 45% depletion occurs within the vortex.
Erosion of ozone depleting air from the polar vortex
Based on contributions from David Andrews, Bob Harwood, John Pyle, Glenn Carver, Martyn Chipperfield, Adrian Lee, Warwick Norton, Anne Pardaens, Kate Searle, Peter Stott and Gordon Watson

When air comes into contact with polar stratospheric clouds, it can be chemically altered so concentrations of ozone-destroying chlorine monoxide are increased. Trying to quantify how much of this chemically altered air is transported out of the Polar Vortex into mid-latitudes is an important issue because it has a bearing on the northern mid-latitude ozone loss observed over the last fifteen years. Results using the highly accurate contour advection technique developed within UGAMP indicate that, in some years, as much as 45% of the mass of the Polar Vortex can be transported into mid-latitudes. An understanding of the conditions that lead to this large transport of polar air is essential for both short-term forecasts and long-term climate prediction.

NASA's ASHOE field campaign to understand Southern Hemisphere ozone loss over the Antarctic made use of UGAMP ten-day chemical forecasts when planning aircraft flight paths. We forecast the presence of a 'streamer' of air south of New Zealand and Australia that had been eroded from the polar region. This air was forecast to have a high ozone destroying potential. Observations made by the aircraft did indeed reveal the presence of such a streamer, and validated the accuracy of our forecast.

UGAMP's ability to make such forecasts will inform scientists of the most important regions to take measurements.

As much as 45% of the air within the Polar Vortex can mix into the midlatitudes, resulting in ozone depletion over Europe.

The highly accurate contour advection technique, developed within UGAMP, shows chemically altered air with the potential for destroying ozone extending over much of Europe.

Our chemical forecasts have aided in flight path planning and have proved accurate.

UGAMP forecast of N₂O made for a day during an aircraft observational campaign in the Southern Hemisphere. The green streamer south of Australia indicates air of polar origin with the ability to reduce ozone. The arrow shows the actual flight path on this day. A flight track comparison between forecast and observed N₂O does indeed reveal the presence of such a streamer.
The role of mixing in ozone chemistry

Based on contributions from Peter Haynes, Robert MacKenzie, Kate Searle, David Tan and John Thuburn

The grid-boxes used in atmospheric climate models are typically a few hundred kilometres across and a few kilometres deep. When these models calculate the results of chemical reactions, they often assume that each chemical species is uniformly distributed within a grid-box. This assumption that the air in each grid-box is well mixed means that models tend to overestimate the speed of some chemical reactions. We have shown that this error may have important consequences for the accuracy of ozone forecasting. We have also developed techniques which are successful in more accurately estimating the real mixing rate within a grid-box. The outcome of this work is significant progress towards reducing the uncertainties in modelling atmospheric chemistry.

By increasing the amount of mixing in a model, some reaction rates are increased. Here, strong mixing leads to an unrealistically large production of ClONO₂ from NO₂ and ClO. With too little ClO left to destroy ozone, ozone loss is underestimated.

Tropospheric ozone chemistry

Based on contributions from John Pyle, Glenn Carver, Martyn Chipperfield, Mathew Evans, Kathy Law, Paul-Henri Planton, Claire Reeves, Dudley Shallcross, Zoe Stockwell and Oliver Wild

The concentrations of major tropospheric oxidants (such as ozone and OH), which remove many pollutants from the atmosphere, are changing with time. The reasons for these changes are not fully understood but could include changing emissions from the surface and by aviation. Near the ground, high levels of ozone can be harmful to health. Sometimes ozone levels exceed the 50 ppbv agreed level above which air quality is described as poor. UGAMP has worked closely with international field campaigns, including NERC’s AGSOE programme, to address these issues.

Using data from ECMWF and BADC, we have used a chemical trajectory approach to investigate the transport and chemistry of atmospheric compounds. The model has been used to simulate the chemical composition of air flowing over Mace Head, on the remote west coast of Ireland. The model agrees reasonably well with the measurements showing that, when the air-flow is from

During periods when the air is flowing from Europe, photochemistry of man-made nitrogen oxides and hydrocarbons leads to high levels of ozone and poor air quality at remote locations. When the source of the flow is from elsewhere, low ozone values are observed and modelled. Ozone data courtesy of Peter Simmonds, Bristol.
industrialised Europe, photochemical reactions that take place along the path of the flow lead to high levels of ozone.

A global chemistry transport model for the troposphere has also been run using wind data from ECMWF. The calculated ozone distribution has been compared with observations made by the EU MOZAIC (Measurement of Ozone by Airbus In-service Aircraft) project. MOZAIC has been making continuous measurements of ozone and relative humidity worldwide since 1994 on five Airbus passenger aircraft. The model has been compared to seasonally averaged data at cruise altitudes (8-13 km) and directly against data collected along particular flights. In both cases, simulated ozone shows an encouraging degree of agreement with the measurements, confirming that our chemical transport model is a powerful tool for studying tropospheric chemistry issues.

Chemistry - climate feedbacks
Based on contributions from David Andrews, Lesley Gray, Jo Haigh, John Pyle, Slimane Bekki, Martyn Chipperfield, Kathy Law, Warwick Norton, Sarah Ruth, Raif Toumi and Wenyi Zhong

Changes in the chemical composition of the atmosphere can lead to changes in the absorption of infrared and solar radiation and therefore changes in the heating of the atmosphere. Through this mechanism, chemistry can alter the motion in the atmosphere.

Volcanic eruptions, which deposit large quantities of sulphur dioxide (SO$_2$) into the atmosphere, lead to particularly abrupt changes in atmospheric chemical composition. The eruption of Mt. Pinatubo in the Philippines in 1991 injected approximately 20 Mega tonnes of SO$_2$ into the stratosphere. Our calculations have shown that absorption by SO$_2$ is important for the heating budget of the stratosphere as well as the troposphere. The oxidation of this SO$_2$ led to enhanced stratospheric ozone depletion and reduced absorption of ultraviolet radiation. UGAMP model results suggest that in the troposphere, there could have been an equally important indirect effect of stratospheric ozone loss. The increased ultraviolet radiation entering the troposphere may have led to increased OH production and thus destruction of methane and carbon monoxide, both of which are greenhouse gases. In addition, increased OH may have led to increased oxidation of SO$_2$ to produce sulphate aerosol. Higher aerosol concentrations lead to smaller droplets in clouds, making the clouds reflect more solar radiation.
### Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACMSU</td>
<td>Atmospheric Chemistry Modelling Support Unit</td>
<td>Cambridge University</td>
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<tr>
<td>ACSOE</td>
<td>Atmospheric Chemistry Studies in the Oceanic Environment</td>
<td>a NERC funded programme.</td>
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<td>AMP</td>
<td>Atmospheric Model Intercomparison Project</td>
<td>A programme to compare the performance of GCMs.</td>
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<td>ASHOE</td>
<td>Airborne Southern Hemisphere Ozone Experiment</td>
<td>An observational field campaign to Antarctica.</td>
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<td>BADC</td>
<td>British Atmospheric Data Centre</td>
<td></td>
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<tr>
<td>CFC</td>
<td>Chlorofluorocarbon</td>
<td>Man-made chemicals which are catalysts for ozone destruction.</td>
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<tr>
<td>CGAM</td>
<td>The Centre for Global Atmospheric Modelling</td>
<td>Reading University, the coordinating centre for UGAMP.</td>
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<tr>
<td>CH₄</td>
<td>Methane</td>
<td>A greenhouse gas.</td>
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<tr>
<td>ClO</td>
<td>Chlorine monoxide</td>
<td>A catalyst for ozone destruction.</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
<td>A greenhouse gas.</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
<td>A major greenhouse gas.</td>
</tr>
<tr>
<td>CTM</td>
<td>Chemical Transport Model</td>
<td>A computer representation of the chemistry occurring in the atmosphere.</td>
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<tr>
<td>DAMTP</td>
<td>Department of Applied Mathematics and Theoretical Physics</td>
<td>Cambridge University.</td>
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<tr>
<td>Dobson Unit</td>
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<td>A measure of the amount of ozone above a point on the Earth's surface. Typical values are about 260 DU near the tropics and higher elsewhere, though there are large seasonal fluctuations.</td>
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<tr>
<td>ECMWF</td>
<td>The European Centre for Medium-Range Weather Forecasts</td>
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<tr>
<td>El-Niño</td>
<td>El Niño</td>
<td>A particular pattern of anomalously warm sea surface temperatures in the eastern tropical Pacific.</td>
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<tr>
<td>ERA</td>
<td>European Centre Re-analysis data</td>
<td>An improved analysis of atmospheric observational data for the period 1979 - 1993.</td>
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<tr>
<td>FASTEX</td>
<td>The Fronts and Atlantic Storm Track Experiment</td>
<td>An observational campaign over the Atlantic during winter 1996/97.</td>
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<tr>
<td>GCAM</td>
<td>Global Circulation Model</td>
<td>A numerical representation of the atmosphere on a computer.</td>
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<tr>
<td>H₂O</td>
<td>Water</td>
<td>Water vapour is a major greenhouse gas.</td>
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<tr>
<td>Hadley Centre</td>
<td>The UKMO's Centre for Climate Prediction and Research</td>
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<tr>
<td>hPa</td>
<td>Hectopascal</td>
<td>A unit of pressure. 1 hPa = 1 mb.</td>
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<tr>
<td>IFS</td>
<td>Integrated Forecasting System of ECMWF</td>
<td>Including their forecasting model.</td>
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<tr>
<td>ISAMS</td>
<td>Improved Stratospheric and Mesospheric Sounder</td>
<td>A device on board UARS to measure chemical concentrations and temperatures in the atmosphere.</td>
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<tr>
<td>JDP</td>
<td>The Joint Diagnostics Project</td>
<td>A partnership between UGAMP and the UKMO to analyse and distribute atmospheric data.</td>
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<tr>
<td>La-Niña</td>
<td>La Niña</td>
<td>A particular pattern of anomalously cold sea surface temperatures in the eastern tropical Pacific.</td>
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<tr>
<td>mb</td>
<td>Millibar</td>
<td>A unit of pressure. Pressure decreases with height and can be used as a height coordinate. At the surface, the air pressure is about 1000 mb, at the tropopause it is about 200 mb.</td>
</tr>
<tr>
<td>MJO</td>
<td>Madden Julian Oscillation</td>
<td>A pulse of strong rains that travels around the equator in about 30 to 60 days.</td>
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<tr>
<td>Monsoon</td>
<td>Monsoon</td>
<td>Strong and persistent seasonal winds and rains that occur in some tropical countries.</td>
</tr>
<tr>
<td>MOZAIc</td>
<td>Measurement of Ozone by Airbus In-service Aircraft</td>
<td>A programme that has installed equipment on five passenger planes to give worldwide measurements of ozone and humidity.</td>
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<tr>
<td>N₂O</td>
<td>Nitrous Oxide</td>
<td>A gas sometimes used to trace the origin of air parcels.</td>
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<tr>
<td>NASA</td>
<td>National Aeronautical and Space Administration</td>
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<tr>
<td>NERC</td>
<td>Natural Environment Research Council</td>
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<tr>
<td>NO₂</td>
<td>Nitrogen dioxide</td>
<td>An important gas for ozone chemistry.</td>
</tr>
<tr>
<td>O₃</td>
<td>Ozone</td>
<td>A gas that absorbs harmful UV radiation from sunlight, but is itself harmful to health near the ground.</td>
</tr>
<tr>
<td>OAGCM</td>
<td>Ocean - Atmosphere GCM</td>
<td>A GCM that includes a representation of the oceans.</td>
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<tr>
<td>Polar Vortex</td>
<td></td>
<td>The westerly circulation of cold air around the winter pole in the stratosphere.</td>
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<tr>
<td>Potential temperature</td>
<td>A measure of temperature that makes allowance for cooling due to expansion as air rises, enabling easier comparison of air at different heights.</td>
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<tr>
<td>Vorticity</td>
<td>A measure of the spin of the air. It is conserved by a parcel of fluid under certain conditions. Abbreviated to PV.</td>
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<tr>
<td>ppbv</td>
<td>Parts per billion by volume.</td>
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</tr>
<tr>
<td>ppmv</td>
<td>Parts per million by volume.</td>
<td></td>
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<tr>
<td>Tropopause</td>
<td>The boundary between the troposphere and the stratosphere, varying in altitude between 15 km (tropics) and 8 km (poles).</td>
<td></td>
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<tr>
<td>Troposphere</td>
<td>The part of the atmosphere below about 15 km altitude, characterised by complex motions and cloud processes constituting &quot;weather&quot;.</td>
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<tr>
<td>SGCM</td>
<td>UGAMP's Simple Global Circulation Model</td>
<td></td>
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<tr>
<td>SPCZ</td>
<td>South Pacific Convergence Zone</td>
<td>A region of enhanced convection over the south west Pacific.</td>
</tr>
<tr>
<td>Stratosphere</td>
<td>The part of the atmosphere between about 15 and 50 km above the Earth's surface, where ozone destruction takes place.</td>
<td></td>
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<tr>
<td>UARS</td>
<td>Upper Atmosphere Research Satellite</td>
<td>A satellite mainly making observations of the chemical composition of the stratosphere.</td>
</tr>
<tr>
<td>UGAMP</td>
<td>UK Universities Global Atmospheric Modelling Programme, funded by the NERC</td>
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<tr>
<td>UGM</td>
<td>UGAMP's own GCM</td>
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<tr>
<td>UKMO</td>
<td>United Kingdom Meteorological Office</td>
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</tr>
<tr>
<td>UM</td>
<td>Unified Model, the forecasting model of the UKMO</td>
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Refereed Publications

UGAMP refereed publications have shown a rising trend from an average of 20 papers per year in 1991/1992 to over 80 in 1996. In total, 275 publications have appeared between 1991 and February 1997 (a full list is available). The pie chart shows the journals that we have published in, including 'Nature' and the 'Quarterly Journal of the Royal Meteorological Society'.

Cover: Hurricane Bertha, greatly magnified on the globe. The remnants of hurricanes represent perhaps the most extreme weather experienced in the UK. The factors that could have affected Bertha's strength and path include the polar ice sheets, deserts, tropical monsoons and interactions with the sea. There is also a chaotic 'butterfly effect'. The strong interaction between many features of the atmosphere means that a truly global perspective to climate research is essential. The orbiting 'planets' show our range of computer models of the global atmosphere from the simple to the highly complex.

Editors: Dr. Mark Rodwell, Prof. Alan O'Neill and Dr. Julia Slingo
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