Climate change science

Some recent results from the Hadley Centre

October 2001

DEFRA
Department for
Environment,
Food & Rural Affairs

Met Office

1 Introduction

The Hadley Centre

The Hadley Centre for Climate Prediction and Research is part of the UK's Met Office, and is charged by government with undertaking research into climate change. Its main aims are as follows.

- To understand the processes which control climate, and represent these with increasing realism in computer models.
- To use the climate models to simulate recent change and natural variability, and to predict change over the next 100 years.
- To monitor global and national climate trends, using observations on land, sea, in the air and from space.
- Using observations and model simulations, to attribute recent climate change to specific causes.
- To communicate results to government, media, industry and, in particular, IPCC/UNFCCC.

The Hadley Centre provides a focus in the UK for scientific issues associated with climate change. It currently employs around 100 scientific, IT and support staff and uses two Cray T3E computers. Most of its funding comes from contracts with the Department for Environment, Food and Rural Affairs (DEFRA), other government departments and the European Commission.

This report

In this report we highlight several areas of recent research at the Hadley Centre:

In 2000, the global mean temperature was almost 0.6° C higher than that at the end of the 19th century. On pages 2–4 we describe recent observations, including changes in extremes of temperature and rainfall over the last 50 years.

On page 5, measurements of the change in the amount of heat stored in the oceans is compared to model simulations. The good agreement provides additional evidence of the role of man in climate change.

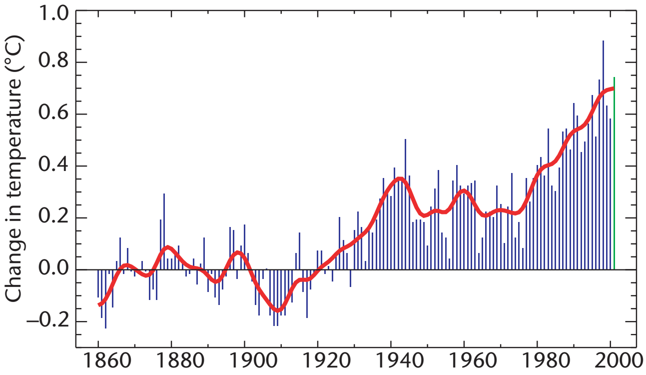
Predictions of change in climate resulting from a range of future emissions scenarios are presented on pages 6–8, suggesting a global temperature rise of between about 2 °C and 5 °C.

In our report to CoP6, we described how the feedback from the carbon cycle is predicted to substantially amplify climate change. On page 9 of this report, we show the effect of feedbacks from chemical cycles in the atmosphere, such as those important for methane and ozone.

2 Observations of climate change

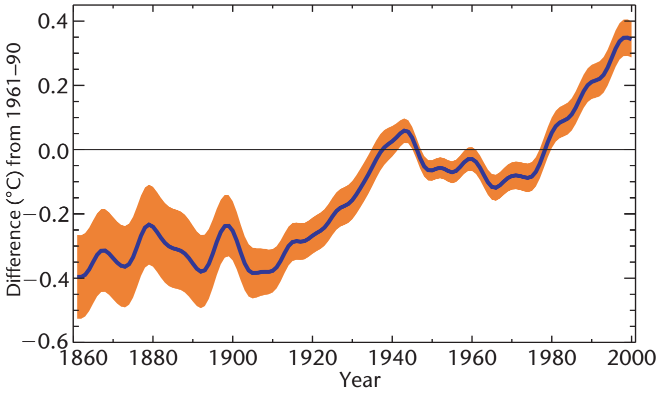
Temperature at the surface

The average global mean surface air temperature in the year 2000 was some 0.6 °C higher than temperatures at the end of the 19th century. The year was cooler than 1999, with temperatures being influenced by the long-lasting (1998–2001) La Niña. However, 2000 was still the seventh warmest year in the record reaching back to 1860. Eight of the warmest years have been since 1990. Because the La Niña has now weakened, and Pacific sea-surface temperatures have returned close to normal, 2001 appears to be warmer than 2000.



Annual average global mean surface air temperature, 1860–2001 relative to the end of the 19th century. A smoothed curve emphasising trends is also shown. The temperature for 2001 (in green) includes data up to August. These observations are collected by national meteorological services all over the world, and have been analysed by the Hadley Centre and the University of East Anglia (UEA).

Uncertainty in the rise in global temperatures is due to a number of factors, for example: changes in number and location of observing sites, urbanisation, and different ways of making the measurements (particularly of sea-surface temperature). Progress has been made in quantifying these errors, and this is illustrated below. The error is greatest at the start, but decreases significantly over the first 70 years as coverage and measurement practice improve. Even with these errors, it is still clear that global temperatures have risen substantially over the past 100 years.

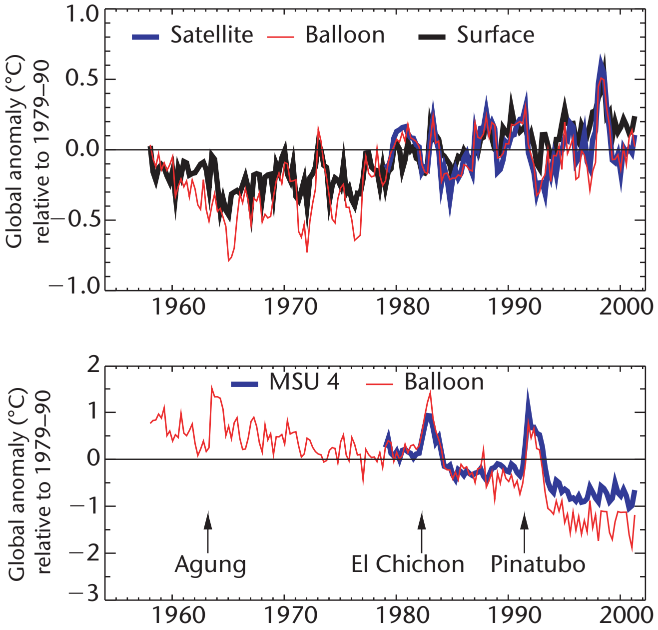


The overall error in surface temperature estimates, 1861–2000. (work done in collaboration with UEA and NCDC).

Temperatures in the atmosphere

In the first few kilometres of the atmosphere, temperatures are measured by instruments on routine weather balloons, and also (since 1979) derived from satellite observations, for example the NASA Microwave Sounding Unit (MSU). Atmospheric temperatures in 2000 were similar to those in 1999, and are at a level about 0.3 °C higher than those in the 1960s when global measurements began.

In the stratosphere (above 10–15km) measurements continued to show a long-term cooling trend. This is caused partly by a loss of stratospheric ozone, and partly because increased carbon dioxide radiates heat away from the stratosphere and thus cools it.



Changes in atmospheric temperatures at 1–8 km (top) and in the stratosphere (bottom).

Changes in extremes of climate

Even in today's climate, extremes of temperature and rainfall often result in considerable damage, loss of life and financial cost. To see if extremes in climate are becoming more severe or frequent, we (in collaboration with colleagues from around the world[1]) have collected and analysed several decades of daily observations from all over the world, a considerable task. Because raw observations are not always available, results have been combined into climate indicators such as the number of frost days per year and the number of days of heavy rain.

Different regions of the planet will undergo climate change at different rates; for instance the land will warm at a faster rate than the ocean. In addition to these expected differences, natural variability causes the climate to vary from place to place and over time, hence, it is not surprising that there are areas of the globe that show different trends (in some cases opposite trends) from the rest of the world.

The number of frost days shows a near uniform global decrease over the second half of the 20th century, although a few stations in south-eastern United States show an increase. The length of the growing season has increased across large parts of the northern hemisphere mid-latitudes, with the notable exception of Iceland. Significantly longer heat waves have occurred in Alaska, Canada, central and eastern Europe, Siberia and central Australia. Heat waves have become shorter in south-east United States, eastern Canada and Iceland (see diagram on facing page).

The length of dry spell has shown a reduction over most of the globe, except in South Africa, Canada and eastern Asia. The number of wet days, with precipitation greater than 10 mm/day, has increased over Russia, the United States, parts of Europe, South Africa and most of Australia. The maximum five-day precipitation total, a good indicator of potential flood events, has increased as a global average, with particularly large increases over Russia and the United States. Some areas (such as eastern China) have seen a decrease in this indicator.

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[1] *Bureau of Meteorology, Australia*
National Climate Data Center, United States
Royal Netherlands Meteorological Institute (KNMI), Netherlands

Annual climate indicators

Number of frost days

This is the number of days for which the minimum air temperature falls below 0 °C. It is important because of its effects on agriculture, gardening and transport. The indicator is also easily understood by the general public.

Growing season length

The growing season is considered to start when the daily mean temperature rises above 5 °C for more than five days. It ends when the daily mean temperature falls below 5 °C for more than five days. It is important for agriculture. This indicator is most useful in the mid-latitude regions.

Heat wave duration

A heatwave is defined as a period of at least six consecutive days when daytime maximum temperatures are at least 5 °C above the (1961–90) climatological average. This index shows the maximum heatwave period for a given year.

Length of dry spell

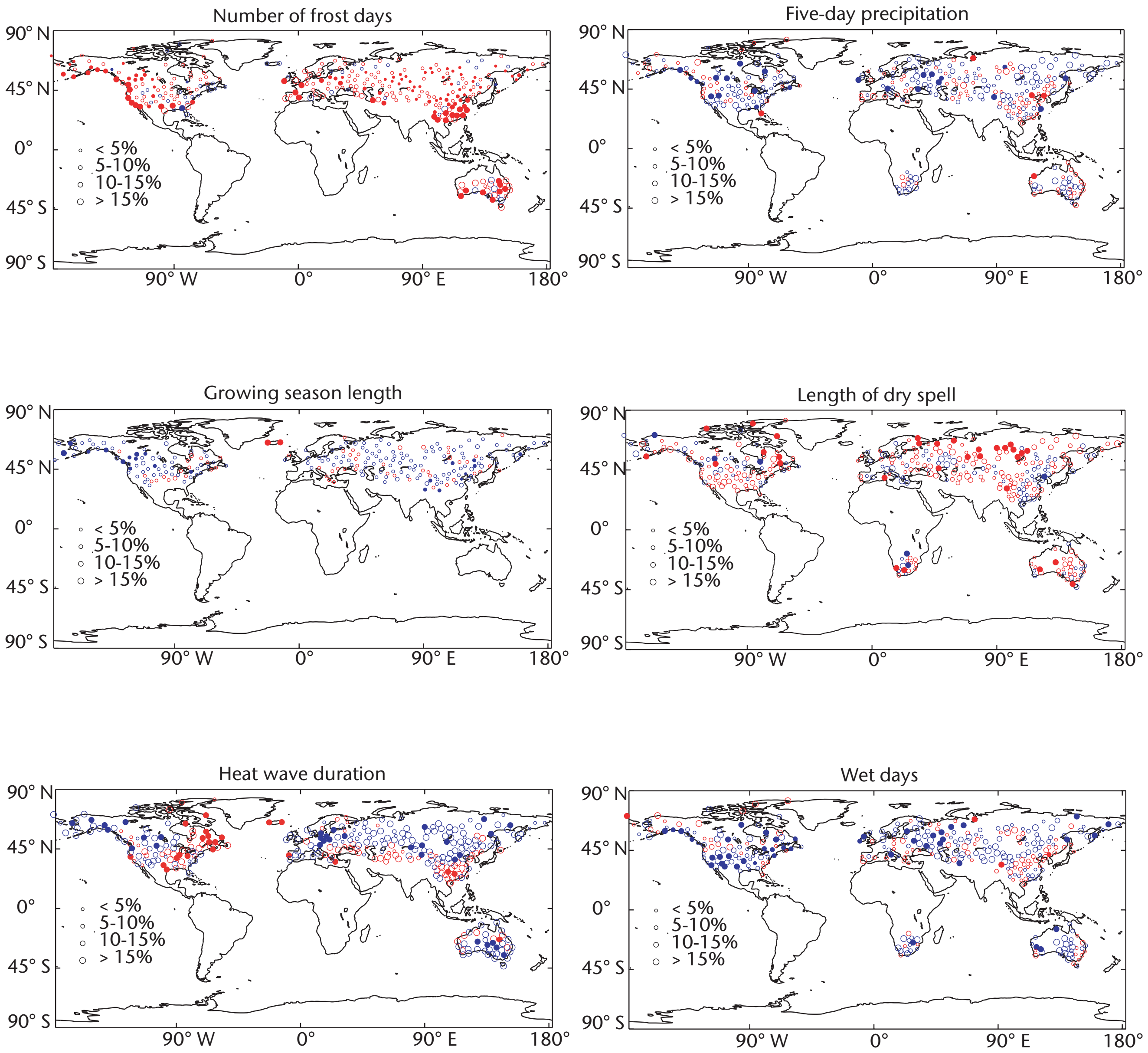
This is the maximum number of consecutive days for which the daily average rainfall is less than 1 mm. It has important consequences for vegetation and ecosystems and is a potential drought indicator.

Wet days

Number of days with precipitation greater than 10 mm/day:

Five-day precipitation

The maximum precipitation falling in any continuous five-day period in a given year. This measure provides a good indicator of the potential for floods.



Changes in extreme indicators of temperature (left) and precipitation (right). The changes are averaged over the second half of the 20th century. Positive changes are shown in blue. Filled circles are significant at the 95% level of confidence.

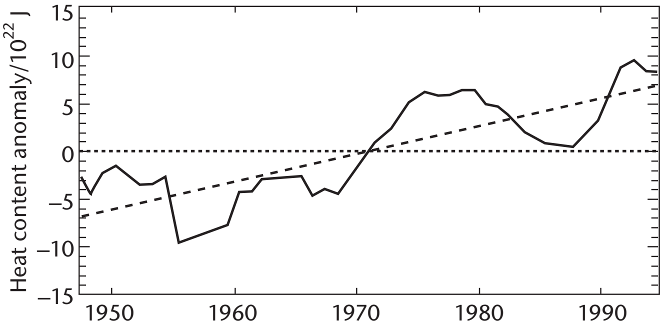
3 Changes in ocean heat storage

Observed changes in heat storage

A full understanding of how the global climate will warm in response to increased atmospheric greenhouse gas concentrations must be able to explain the response of all the major stores of heat in the climate system. It must account for observed changes in atmospheric warming, land surface and the upper ocean warming, melting of land and sea ice, and changes in the deep ocean heat storage.

A very large amount of the extra heat trapped in the climate system by increased atmospheric greenhouse gas concentrations will be stored in the deep ocean (100 m to 3,000 m). This has the capacity to store an enormous amount of heat with relatively little increase in temperature.

Until recently sufficient observations of deep ocean temperature have not been available. However, researchers in the United States have used the results from many of the numerous measurement campaigns that have taken place over the last 50 years in order to produce a global data set of ocean temperature from which the changes in heat storage can be estimated (see below). The results show a substantial increase in deep ocean heat storage between 1950 and the mid 1990s.

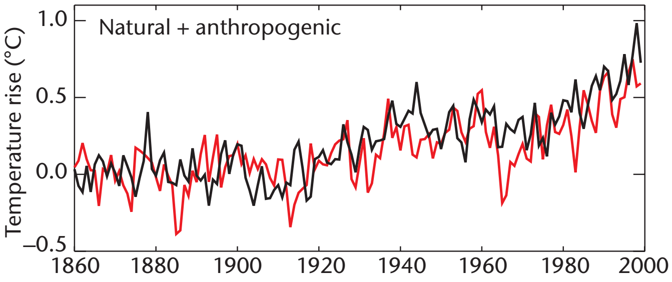


Observed change in heat storage in the ocean. Data provided by Sidney Levitus, National Ocean Data Center, Silver Spring, USA.

Can the observations of deep ocean heat storage help us to identify the cause of global warming?

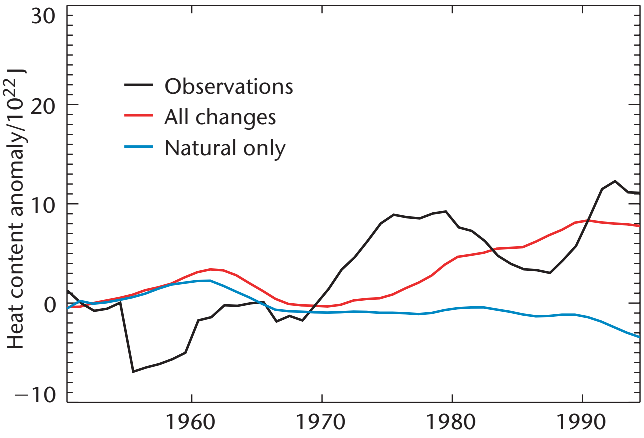
Most previous attempts to demonstrate a link between increases in atmospheric greenhouse gases concentrations and warming over the past century have compared the observed surface temperature record or the vertical temperature structure of the atmosphere with climate model simulations. The diagram at top right shows the ability of the Hadley Centre climate model (which includes natural forcing, anthropogenic greenhouse gases and sulphate aerosols) to reproduce the global mean surface temperature over the last 140 years.

Because only a small amount of the extra heat trapped in the climate system is stored in the atmosphere, land surface or upper ocean, we can only be confident that our climate model is providing a good representation of the climate system if it can also simulate the expected behaviour of the deep ocean. Consequently, we have used our coupled climate model (see box on page 6) to simulate the expected change in ocean heat content.



Comparison of observed (black) and simulated (red) global mean temperatures.

If our climate model is run with just natural changes (changes in solar output, volcanic activity, natural variability) over the past 50 years then we calculate from model that the heat content of the ocean should have decreased slightly. But if we also include man-made emissions of greenhouse gases (and other pollutants), the model simulates a change in ocean heat content which is in reasonable agreement with observation over the whole period. The model does not reproduce the large variability from decade to decade seen in the observations, and we are investigating this.



Comparison of simulated and observed changes in ocean heat content.

This agreement can be viewed in two ways. First, it gives us greater confidence that our climate model is a reasonable representation of the real climate system. Second, because it is necessary to include both anthropogenic greenhouse gases and sulphate aerosol particles in order to achieve the good agreement between the observations and simulations, the result gives extra weight to the belief that anthropogenic emissions have played a substantial role in the ocean climate change observed over the last 50 years.

4 Predictions of future climate change

Making predictions

Predictions of climate change are made in several stages. First, the effects of emissions of greenhouse gases and sulphur on atmospheric concentrations are calculated using carbon cycle and chemistry models. The concentrations are then used to calculate the resulting changes in the heat trapped by the atmosphere (the radiative forcing). In turn, changes in temperature, precipitation and atmospheric circulation (winds) are calculated from the radiative forcing. The calculations of radiative forcing and climate change are performed in a global climate model (GCM).

The Special Report on Emissions Scenarios (SRES), which was published by the IPCC in 2000, contains a large number of projections of future emissions. These are divided into four groups, each with its own 'storyline' describing the way in which the world (population, economies, etc.) may develop over the next 100 years. The SRES predictions are based on recent estimates of population growth; they include a greater range of economic futures, and some scenarios with a significant closing of the gap between developing and developed countries.

We have used the Hadley Centre third generation global climate model to make predictions of how climate would change under four SRES emissions scenarios (B1, B2, A2 and A1FI) which span most of the total SRES range.

Coupled global climate models (GCMs)

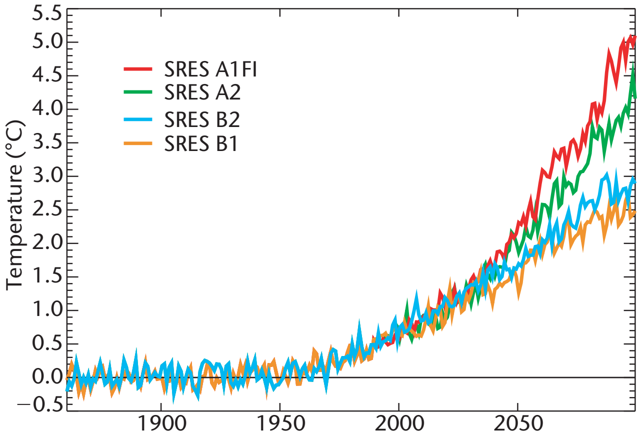
Global climate models (often called general circulation models) simulate processes in the atmosphere, ocean and on the land. The atmospheric component consists of a three-dimensional representation of the atmosphere coupled to those of the land surface and cryosphere. The atmosphere model is similar to those used for weather forecasting but, because it has to produce projections for decades or centuries rather than days, it uses a coarser level of detail. The ocean component of the models consists of a three-dimensional representations of the ocean and of sea-ice. Global climate models typically have a horizontal resolution of a few hundred kilometres. Processes operating on smaller scales are 'parametrised', that is, they are included through numerical relationships with the larger scales.

Many climate models now include the cooling effects of sulphate aerosol particles. The most recent models include aspects of the biosphere, carbon cycle and atmospheric chemistry as well.

Global climate models are used to simulate past climates and to predict future climates. They are also used to study natural variability and the physical processes of the coupled climate system.

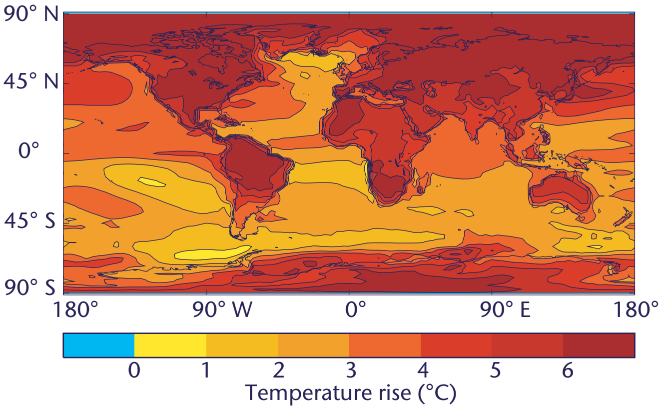
Temperature

The global mean temperature rise for the four SRES emissions scenarios is shown in the figure below for the period 1860 to 2100. Between present day and 2100, the range of warming is predicted to be 2 °C to 5 °C, with the largest warming in the fossil fuel intensive (A1FI) scenario. This predicted range is smaller than that presented by the IPCC in their third assessment report because here we are using just one climate model whereas the IPCC report used several. It is interesting to note that, until the 2040s, the predicted warming is similar for all four, quite different, SRES emissions scenarios. Later in the century, the warming rate becomes much more dependent on emissions.



Simulated global mean surface temperature changes.

Although the global average warming to the end of the century is dependent on future emissions, the major features of the spatial pattern of warming are similar for all of the scenarios and are shown below for A1FI. The temperature rise is greater over land than ocean (the land is warming approximately 1.7 times faster than the ocean) and is greatest around the Arctic. Over the northern North Atlantic, much of the southern ocean and over South East Asia the rise in temperature is less than the global average.

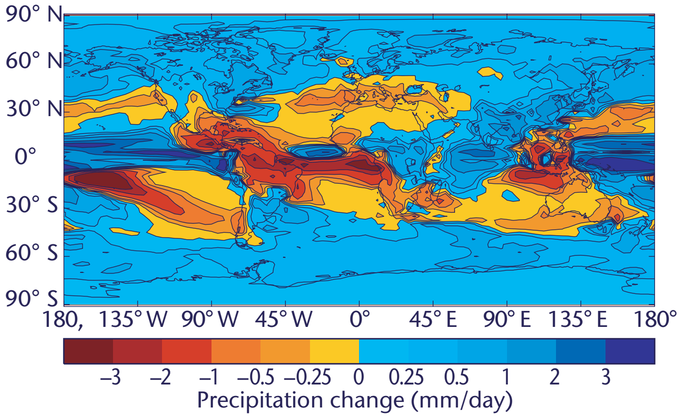


Pattern of annual mean surface temperature rise for the A1FI scenario at the end of the 21st century, relative to present day.

Precipitation

The warmer future climate will very likely be accompanied by an intensification of the hydrological cycle, with increases in both the evaporation of water from the surface and precipitation. The increase in global mean precipitation predicted by the Hadley Centre model is approximately 1% per °C of warming.

Like temperature, the major features of the spatial patterns of precipitation change are similar in all four SRES emission scenarios, but, again, the magnitude of the pattern is greatest in the A1FI scenario and least in the B1 scenario. The major features of the spatial patterns are increases of precipitation in the extratropics, associated with a greater poleward movement of moisture, and decreases over much of the subtropics. Along the intertropical convergence zone (the 'thermal equator') precipitation generally increases, although some regions do experience a reduction. Over the Amazon Basin, precipitation is predicted to decrease throughout the year.

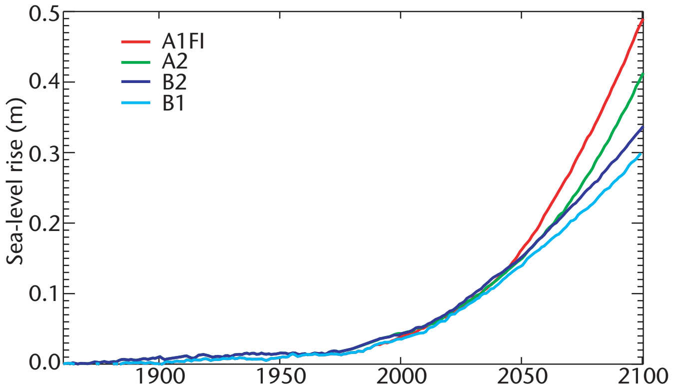


Pattern of annual mean precipitation change for the A1FI scenario at the end of the 21st century, relative to present day.

The changes in both evaporation and rainfall lead to changes in the amount of moisture stored in the soil, which can have important impacts, for example, on agriculture. In the northern hemisphere the changes closely follow those in precipitation with the continents outside the tropics becoming wetter in winter while North America and Europe become drier in summer. Northern Canada and Siberia become wetter all year round. Soils also become wetter in most of the regions that are affected by tropical monsoons, except the northern part of South America.

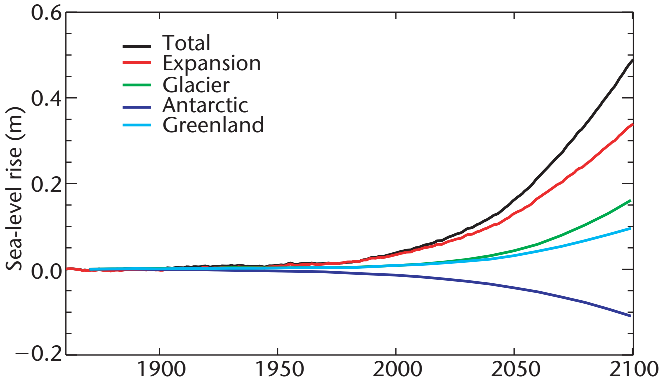
Sea level

Sea-level rise is an important consequence of climate change, leading to both the relatively slow inundation of low-lying coastal areas and an increase in the frequency of short-lived extreme high-water levels. The rise in mean sea level predicted by the Hadley Centre is shown below.



Simulated global mean sea-level changes.

For all four scenarios the global mean sea-level rise is dominated by thermal expansion of the ocean as it warms (shown below for the A1FI scenario). Additional contributions come from the melting of land ice contained in small glaciers and in the Greenland ice sheet. This rise in mean sea level is partially offset by the increased precipitation over Antarctica, which traps additional water on the land.



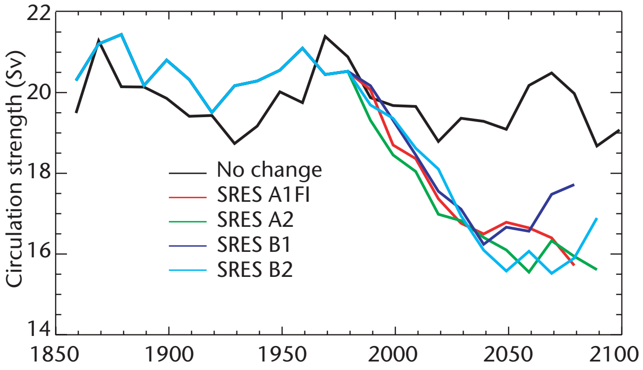
Components of global mean sea-level rise for the A1FI scenario.

We do not expect the changes in sea level to occur uniformly over the entire ocean. The Hadley Centre model shows that some regions may experience almost no rise, while in others the rise could be twice the global mean. However, while we have confidence in the predictions of future global mean sea-level rise, the spatial patterns of sea level change vary considerably from model to model for reasons we do not yet fully understand. Consequently, our confidence in regional sea-level rise predictions is currently limited.

Ocean circulation

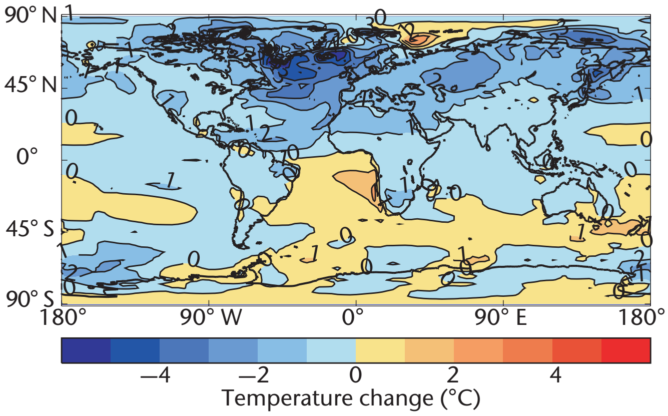
The ocean (thermohaline) circulation transports large amounts of heat from the tropics to high northern latitudes. At high latitudes, cooling causes the water to sink and move southward to tropical latitudes as a deep ocean current. This slowly upwells over large regions of the tropical ocean. The surface current that completes the cycle in the Atlantic, by taking water and heat from the tropics to the high-latitude, is the Gulf Stream. Early climate model simulations suggested that climate changes over the coming 100 years might completely shut down the thermohaline circulation leading to a cooling of mid and high latitudes.

Recent simulations using the Hadley Centre model with the SRES emission scenarios suggest that the thermohaline circulation will not completely shut down during this century, but it might decrease in strength by up to 25% (see diagram below). Despite the reduced heat transport by the weaker Gulf Stream circulation, the atmospheric heat transport and the local greenhouse effect still lead to a net warming of the mid and high latitude regions.



Strength of the thermohaline circulation, in the North Atlantic.

We have investigated the importance of the thermohaline circulation on global temperatures using a hypothetical experiment in which the circulation is completely shutdown (diagram below). The large reductions in surface temperature illustrate the importance of the thermohaline circulation to climate.



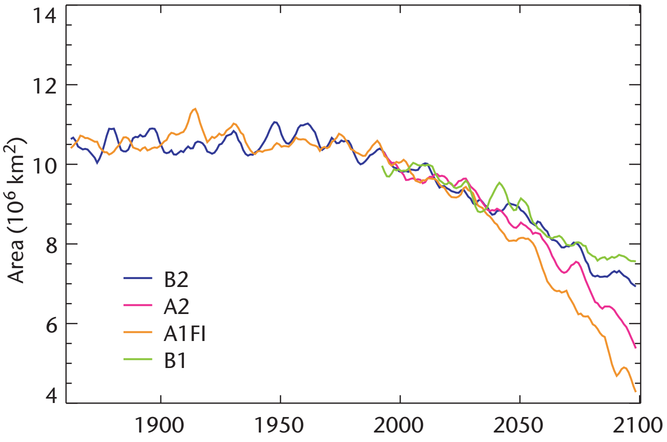
Changes in surface air temperature, relative to present day, 20 years after the hypothetical collapse of the thermohaline circulation.

Sea ice

Sea ice has an important effect on climate because it reflects a large proportion of incoming sunlight straight back into space. In addition, sea ice can trap heat in the ocean by insulating the relatively warm water from the very cold polar atmosphere. Sea ice is also important from the perspective of socio-economic impacts. In the northern hemisphere, removing the coastal protection provided by sea ice can leave many arctic coastlines much more susceptible to erosion from storm surges and waves. A reduction in sea ice coverage may open up many additional shipping and trade routes.

Observations of Arctic sea ice area show a decline over recent decades. Hadley Centre climate model simulations are able to reasonably reproduce these changes.

The annual average coverage of Arctic sea ice is predicted to decline during the 21st century (see below). For A1FI emissions, the annual average area of coverage in 2100 is only around 40% of the pre-industrial value. For B1 the decline is less pronounced, but still falls to 70% of the pre-industrial value by the end of the 21st century. The reductions are greatest in September when Arctic sea ice is usually at its minimum extent, which is consistent with a slightly later onset of cold autumn conditions. In all four SRES scenarios the thickness of sea ice is also predicted to decline during the 21st century.



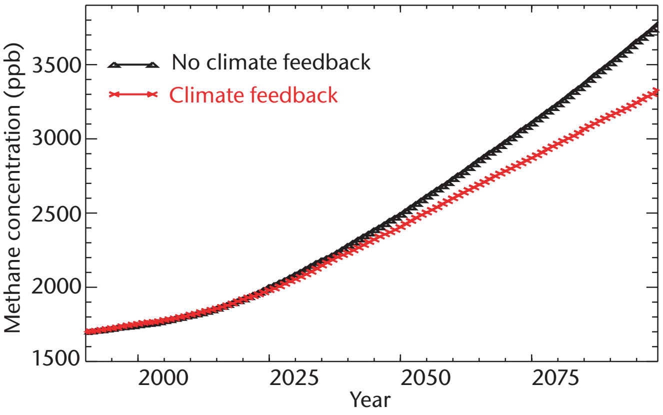
Simulated annual average area covered by Arctic sea ice.

5 How chemical reactions in the atmosphere could affect predictions of climate change

Man-made emissions of some greenhouse gases, particularly methane, take part in many chemical reactions in the atmosphere, so that their concentration (which determines their warming effect) is complex to calculate. In other cases, greenhouse gases are created from non-greenhouse precursor emissions by chemical reactions in the atmosphere; ozone at the surface is the best example of this. Hence, comprehensive models of atmospheric chemistry have been developed over many years, which calculate future concentrations of greenhouse gases from scenarios of emissions. These concentrations are then passed to climate models to calculate their warming effect. The Hadley Centre atmospheric chemistry model (known as STOCHEM) simulates the transport of, and reactions between, about 80 chemical species, following emissions of methane, nitrogen oxides, carbon monoxide, hydrocarbons, sulphur, ammonia and many others (carbon dioxide is not included as it undergoes very few chemical reactions).

However, the chemistry of the atmosphere will change as climate changes. For example, as the temperature of the air rises it will contain more water vapour, and this will produce more hydroxyl radicals, a chemical which strongly reduces the concentrations of many gases in the atmosphere, including methane. In addition, many reactions in the atmosphere will speed up or slow down as temperature increases. Thus, the concentrations of some greenhouse gases calculated by separate models will be incorrect. Hence, we have coupled the atmospheric chemistry model and the climate model together, so that interactions between the two can be taken into account to give a better prediction of both the chemistry and climate change.

The coupled chemistry–climate model was used to calculate concentrations in the troposphere (the lowest 10–15 km of the atmosphere) of methane and ozone, following the A2 scenario of future emissions. The same calculation was done, but without any feedback from the climate system. The two are compared below. It is seen that the predicted increase in methane over the next 100 years is substantially reduced (by 25–30%) when the climate feedback is included.

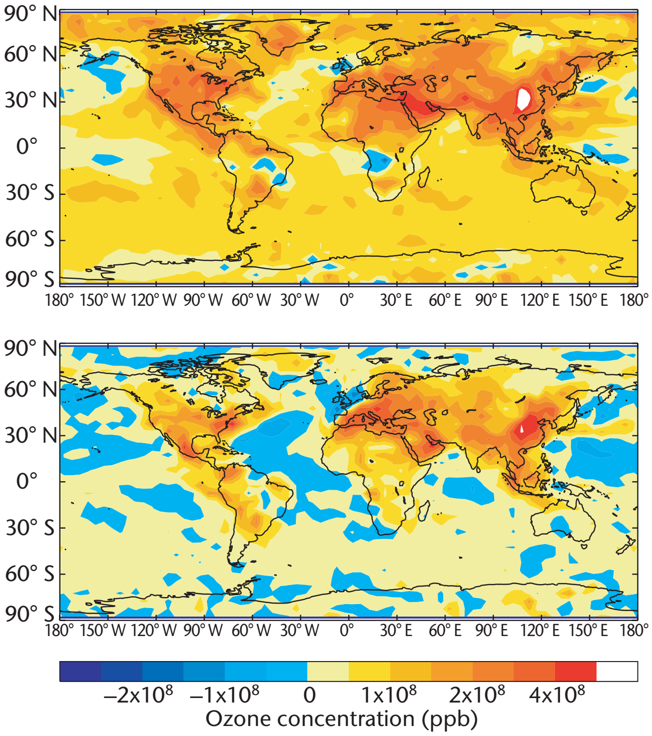


Predicted changes in tropospheric methane concentrations.

Presently, ozone at the surface has a global average concentration of about 30 ppb (parts per billion). The prediction that ozone will increase globally by about 10 ppb due to man-made emissions by the end of the century, is halved when the climate feedback is accounted for. This is mainly due to its increased rate of destruction at higher water vapour concentrations.

These slower increases predicted in methane and ozone will reduce the rate of climate change. However, mainly because carbon dioxide is the dominant greenhouse gas, the difference in temperature by the end of the century in the ‘chemistry-feedback’ and ‘no-feedback’ cases is so small that it cannot be distinguished in the ‘noise’ of natural climate variability. These results have been contributed to, and have appeared in, the IPCC Third Assessment Report.

The smaller increases in global ozone will have an important effect on regional and local pollution because it implies a slower increase in the number of days with high ozone levels.



The change in lower atmospheric ozone concentration (ppb) between present day and the end of the 21st century with no climate feedback (top) and climate feedback (bottom).

Hadley Centre staff: October 2001

Lisa Alexander, Richard Allan, Robert Allan, Jim Arnott, David Baker, Helene Banks, David Barnett, Steve Bass, Martin Best, Richard Betts, Daniel Bleaken, Penny Boorman, Cyndy Bunton, Andy Bushell, Mick Carter, Claire Cooper, Peter Cox, Paul Davison, Chris Durman, Ian Edmond, Jonathan Gregory, John Edwards, Richard Essery, Chris Folland, Nicola Gedney, Pip Gilbert, Margaret Gordon, Alan Grant, Dave Griggs, Mike Harrison, David Hassell, Rosalyn Hatcher, Diane Hatcher, Chris Hewitt, Emma Hibling, Steven Hill, Briony Horton, Debbie Hudson, William Ingram, Sarah Irons, Sue Jackson, Geoff Jenkins, Tim Johns, Cathy Johnson, Colin Johnson, Richard Jones, Andy Jones, Chris Jones, Gareth Jones, Kumar Kaushal, Roy Kershaw, John King, Jeff Knight, Joe Lavery, Evelyn Leung, Linda Livingston, Jason Lowe, Gordon Lupton, Ian Macadam, Gill Martin, Kathy Maskell, Mark McCarthy, Ruth McDonald, John Mitchell, Steve Mullerworth, James Murphy, Maria Noguer, Elisabeth Öström, Alison Pamment, Anne Pardaens, David Parker, Vicky Pope, Nick Rayner, Graham Rickard, Jeff Ridley, Mark Ringer, David Roberts, Malcolm Roberts, Jose Rodriguez, Mark Rodwell, William Roseblade, Dave Rowell, Cath Senior, Dave Sexton, Tony Slingo, Doug Smith, Steven Spall, Peter Stott, Rachel Stratton, David Tan, Simon Tett, Robert Thorpe, Thomas Toniazzo, Paul Van Der Linden, Michael Vellinga, Mark Webb, Jean Weber, Stuart Webster, Paul Whitfield, Alastair Williams, Keith Williams, Damian Wilson, Simon Wilson, Richard Wood, Margaret Woodage, Stephanie Woodward, Peili Wu.

This report is also available at:

www.metoffice.com/research/hadleycentre/pubs/B2001/global.pdf

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