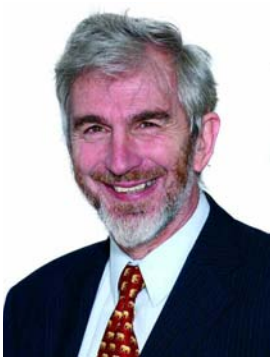
Department for Environment Food and Rural Affairs

Met Office Hadley Centre

Climate change and the greenhouse effect

A briefing from the Hadley Centre

December 2005

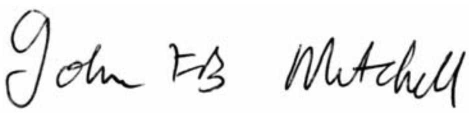


Foreword

The Hadley Centre for Climate Prediction and Research has been a vital department of the Met Office since it was established in Bracknell in 1990, and continues to be so after its move (with the rest of the Met Office headquarters) to Exeter in 2003. Most of its 120 staff give presentations and lectures on all aspects of the research. Many of these are to conferences and workshops on the detailed specialisms of climate change, such as the modelling of clouds or the interpretation of satellite measurements of atmospheric temperatures. But others are to less specialised audiences, including those from Government — ministers and senior policymakers — industry and commerce, pressure groups and the media, in each case from the UK and overseas.

In 1999 we collected some of the slides that had been drawn up to give these talks — mostly based on results from the Hadley Centre — into a general presentation, and made this freely available, recognising that this would reach a wider audience. Although our basic understanding of the science of the greenhouse effect was well founded in 1999, the vast amount of new research carried out over the past six years has produced many interesting and exciting results, and strengthened some earlier, more tentative conclusions (such as the attribution of recent climate change to human activities) which we decided to reflect in this second edition of the presentation; in fact, only seven out of the 61 slides remain from the first edition. This presentation can be used simply as a self briefing or, better still, as a tool to brief others, perhaps by selecting a subset of the slides and notes. We encourage their further dissemination and use, asking only that the Met Office Hadley Centre (or another originating institute where shown) is fully acknowledged as the source.

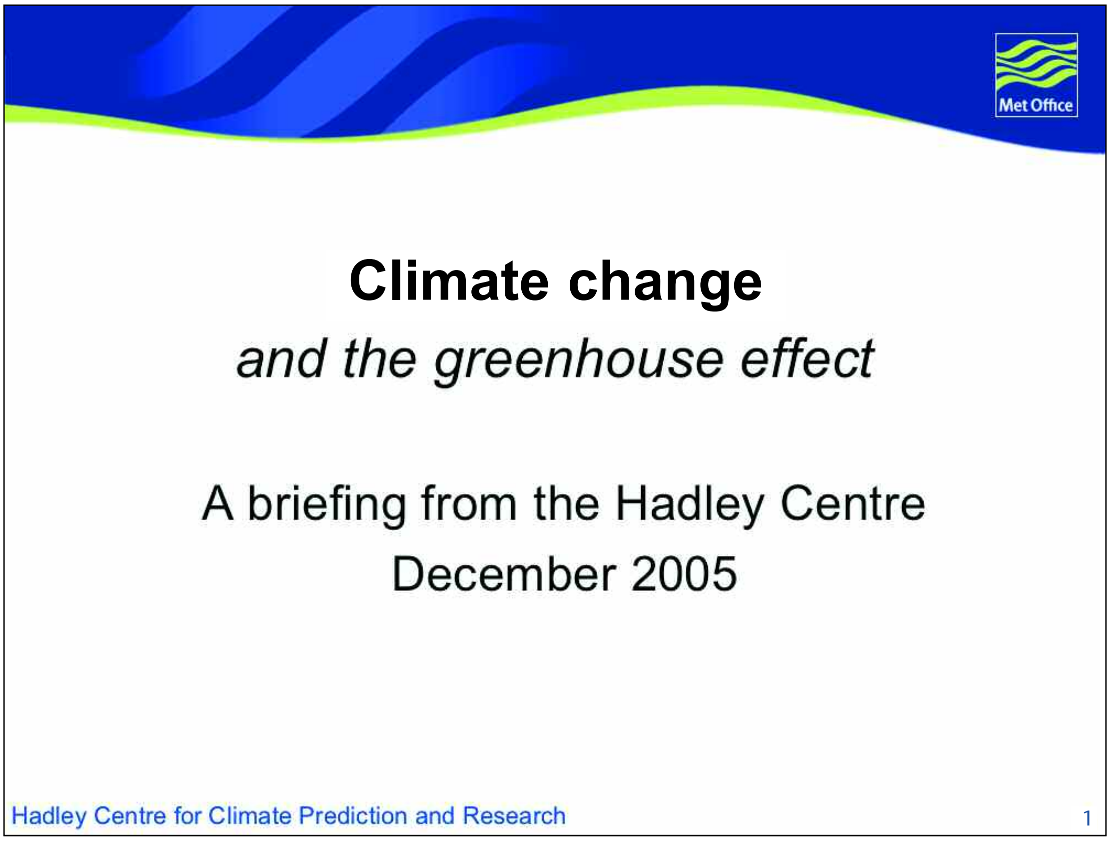
I would like to thank Geoff Jenkins for putting together this presentation and the text on the notes pages, and Chris Durman, Chris Folland, Jonathan Gregory, Jim Haywood, Lisa Horrocks (Defra), Tim Johns, Cathy Johnson (Defra), Andy Jones, Chris Jones, Gareth Jones, Richard Jones, Jason Lowe, James Murphy, Peter Stott, Simon Tett, Ian Totterdell, Peter Thorne and David Warrilow (Defra), for their comments, which have greatly improved it. Fiona Smith and the Met Office Design Studio handled the layout and production. Consistent funding from the Global Atmosphere Division of the UK Department of the Environment, Food and Rural Affairs, and the Government Meteorological Research programme over the last 15 years, has enabled us to plan a sensible long-term research strategy. Finally, I would thank all members of the Hadley Centre, and those from other institutes, for letting us use their results here.



Professor John Mitchell, FRS, OBE

Chief Scientist

Met Office



The Hadley Centre for Climate Prediction and Research, a division of the Met Office based at Exeter, is the UK Government's research centre into climate change. It was opened by the then Prime Minister, Margaret Thatcher, in 1990, although work on climate change had been taking place at the Met Office for a decade or more before that. The aims of the Centre, relevant to climate change, are to:

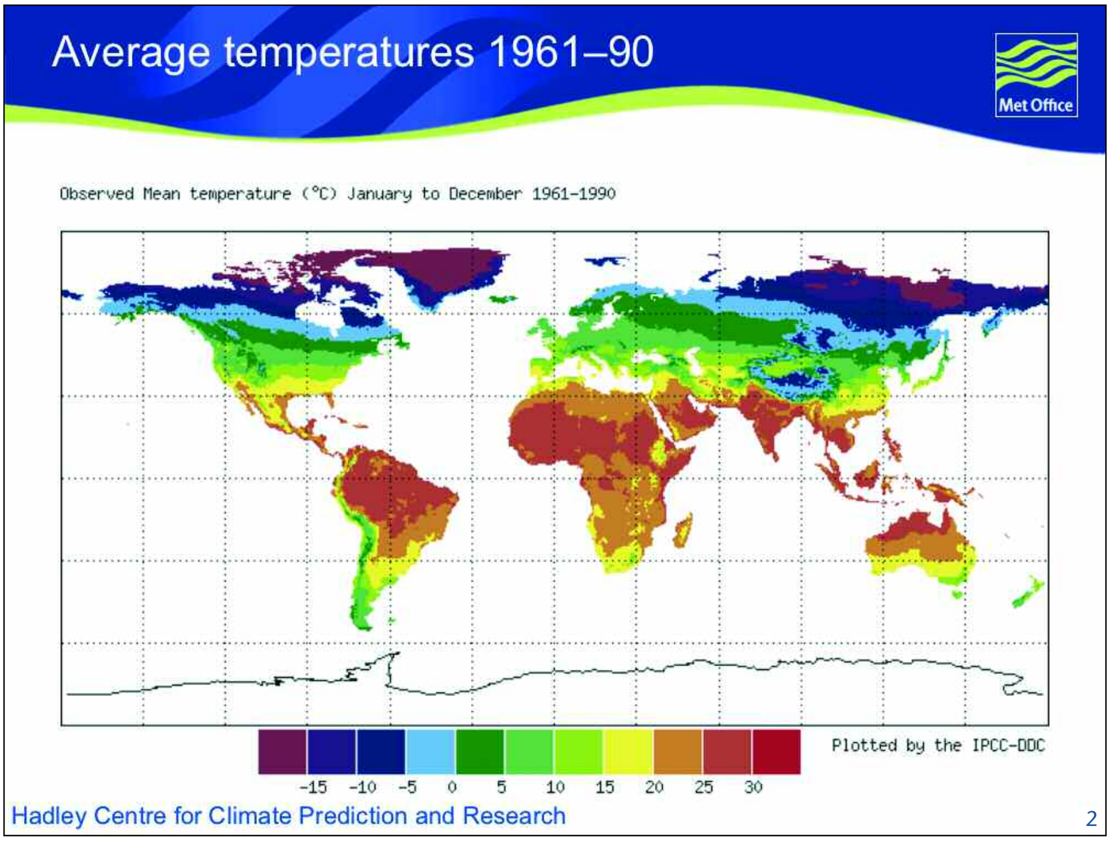
- understand processes within the climate system and develop models which represent them;
- monitor climate variability and change on global and national scales;
- simulate climate change over the past 100 years and predict change over the next 100 years and beyond;
- attribute recent changes in climate to specific natural and man-made factors;
- predict the impacts of climate change, such as those on water availability and the capacity for food production.

The programmes of research are funded mainly by contracts from the Department of the Environment, Food and Rural Affairs (Defra); the Government Meteorological Research and the European Union DGXII Climate and Environment Programme, together with smaller contracts from the Foreign and Commonwealth Office.

Many of the slides in this booklet give references in abbreviated form to one of the following reports:

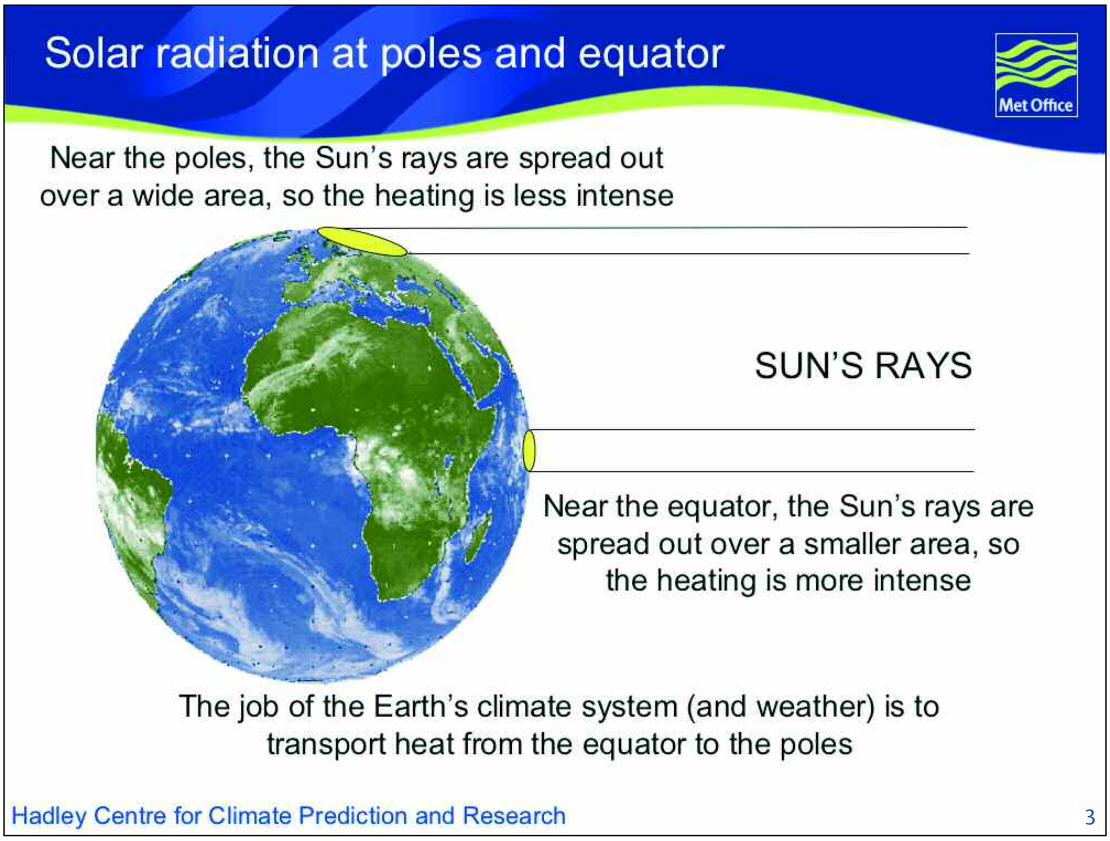
TAR	IPCC 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds). Cambridge University Press, Cambridge, UK, 2001.
4AR	Fourth Assessment Report from the IPCC, due to appear in 2007.
SRES	Special Report on Emissions Scenarios. A Special Report of Working Group III of the IPCC. Nakicenovic et al (eds). Cambridge University Press, Cambridge, UK, 2000.
UKCIP02	Hulme, M., G.J. Jenkins et al. Climate Change Scenarios for the United Kingdom. April 2002.

see: www.ukcip.org.uk/resources/publications/pub_dets.asp?ID=14



Before looking at how the climate has changed recently, and the effects of man's activities, it is worth looking at the natural climate of the Earth and how this can be explained. The map above* shows the long-term average distribution of annual temperature at the land surface of the Earth, collected from weather and climate observing stations. Because there are so few measurements in Antarctica, it is not possible to colour the map in with confidence over this continent, although the Antarctic is in fact colder than the Arctic. As we recall from school geography lessons, temperatures near the equator are generally high, whereas temperatures near the poles are low, with a gradient in between the two. The reason for this is given in the next slide. Other factors also affect surface temperatures, notably altitude, which explains why mountainous regions, such as the Himalayas, are colder than other land at the same latitude.

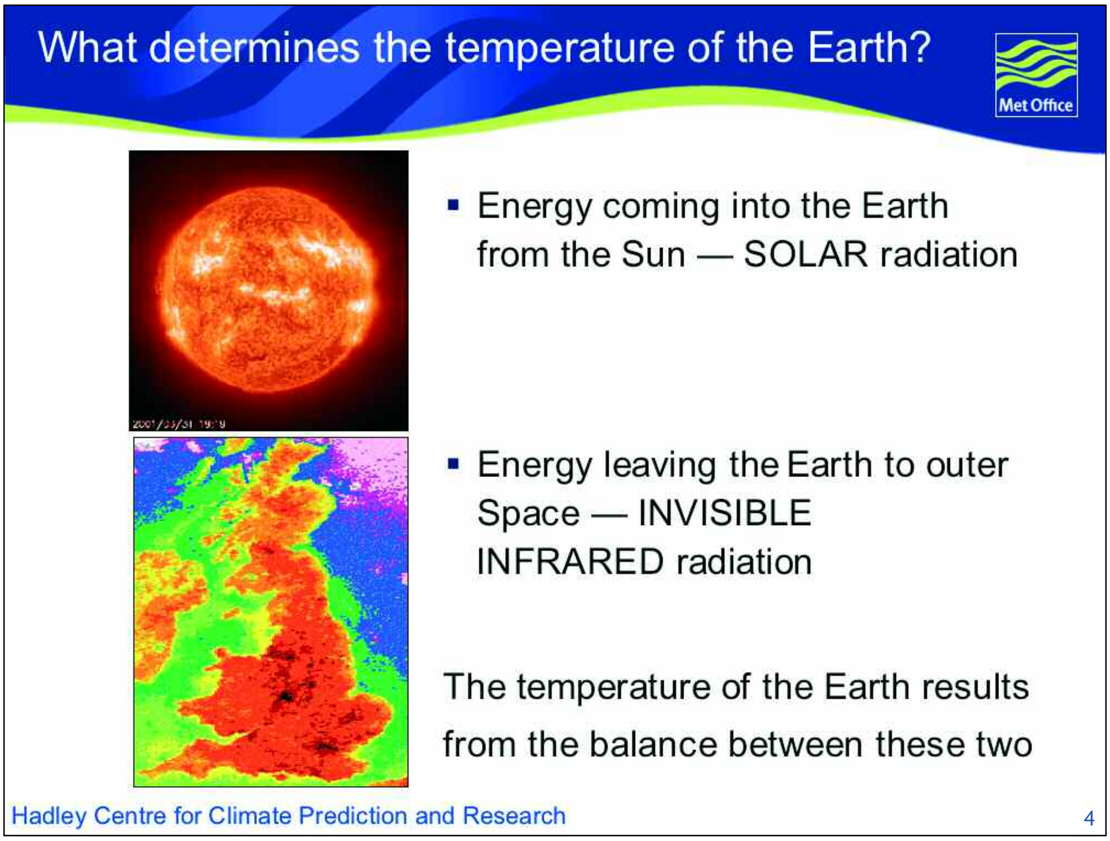
Taken from the IPCC Data Distribution Centre at the Climatic Research Unit, University of East Anglia: http://ipcc-ddc.cru.uea.ac.uk/java/visualisation.html



Because the Earth is a sphere, solar radiation (sunlight) striking it near the equator will be spread out over a relatively small area, and will have a large heating effect per square metre. At higher latitudes, sunlight will strike the Earth's surface more obliquely, be spread out over a larger area, and hence have a smaller heating effect per square metre. This is why equatorial regions are hot and polar regions are cold. This temperature difference drives weather, which seeks to minimise this temperature gradient through the general circulation of the atmosphere. One major circulation system is that in which air rises near the equator, moves polewards in the higher atmosphere, sinking in higher latitudes, and blowing equatorwards near the surface as the trade winds. This system is known as the Hadley Cell after its discoverer George Hadley (1685–1768) — after whom the Hadley Centre is also named.

The diagram shows the situation at the equinoxes (21 March and 21 September) when the Sun is directly over the equator at noon. During the northern summer, the northern hemisphere is tilted towards the Sun, making the Sun higher overhead (hence solar heating more intense) and the day longer. During the northern winter, the northern hemisphere is tilted away from the Sun, so the Sun appears lower in the sky and the day is shorter. This gives the seasonal cycle of temperature through the year.

Climate is the description of the long-term averages of weather, usually taken over a 30-year period. It describes not only the long period averages of temperature, rainfall and other climate quantities in different months or seasons, but also the variability from one year to the next.



Previous slides discussed the distribution of temperatures across the Earth, but the Earth also has a global average temperature, averaged across its entire surface and over a long period such as a decade, of about 14 °C. Two streams of energy determine what the average surface temperature of the Earth is.

Firstly, energy coming in from the Sun as sunlight, which we can see with our eyes. This acts to warm the surface of the Earth and the atmosphere.

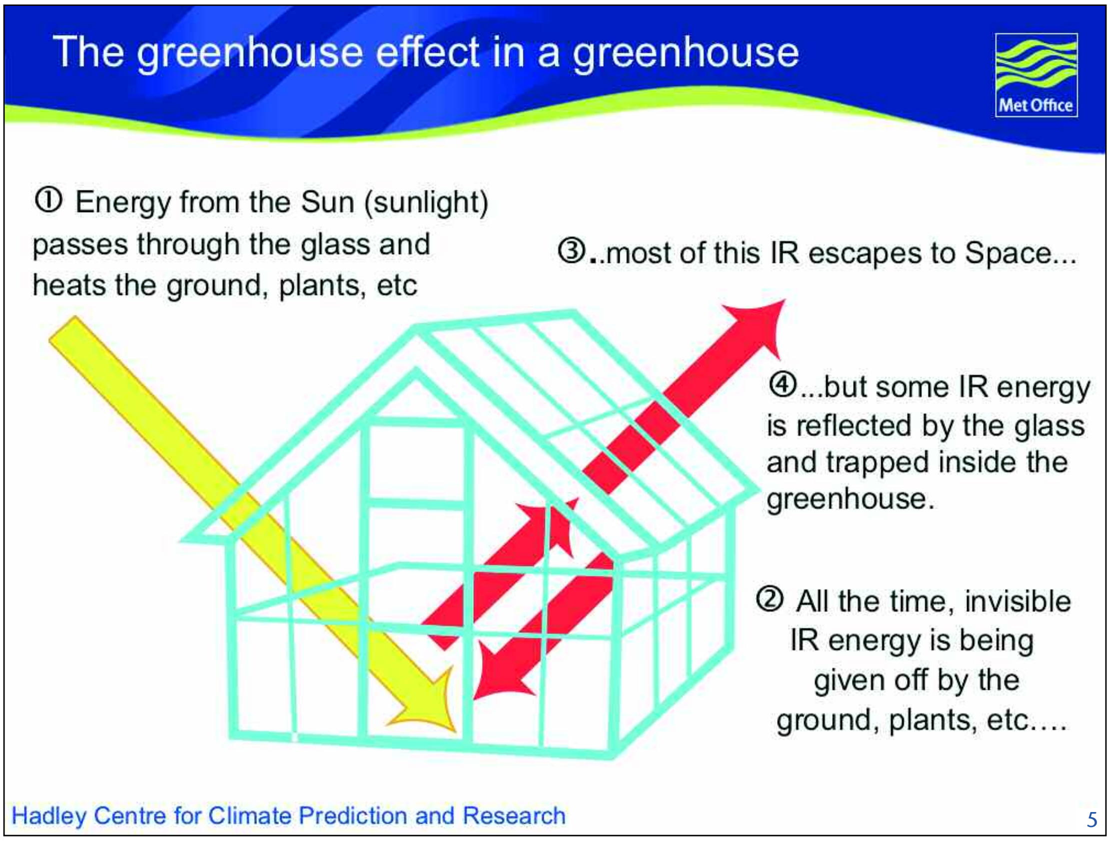
Secondly, because the surface of the Earth (even on the coldest night in Antarctica) is warmer than outer Space, infrared radiation is everywhere being emitted from the surface of the Earth. This acts to cool the Earth's surface.

We cannot see infrared with our eyes, but it is straightforward to measure with instruments.
In the image of the UK shown above, a satellite infrared imager shows cold areas (such as the open sea and cloud tops) as green, blue and purple; warm areas (such as coasts and inland countryside) as yellow and red; and very warm areas (mainly urban) in black.

The balance between these two streams of energy — that emitted by the Sun and that emitted by the Earth — determines the global average surface temperature of the Earth.

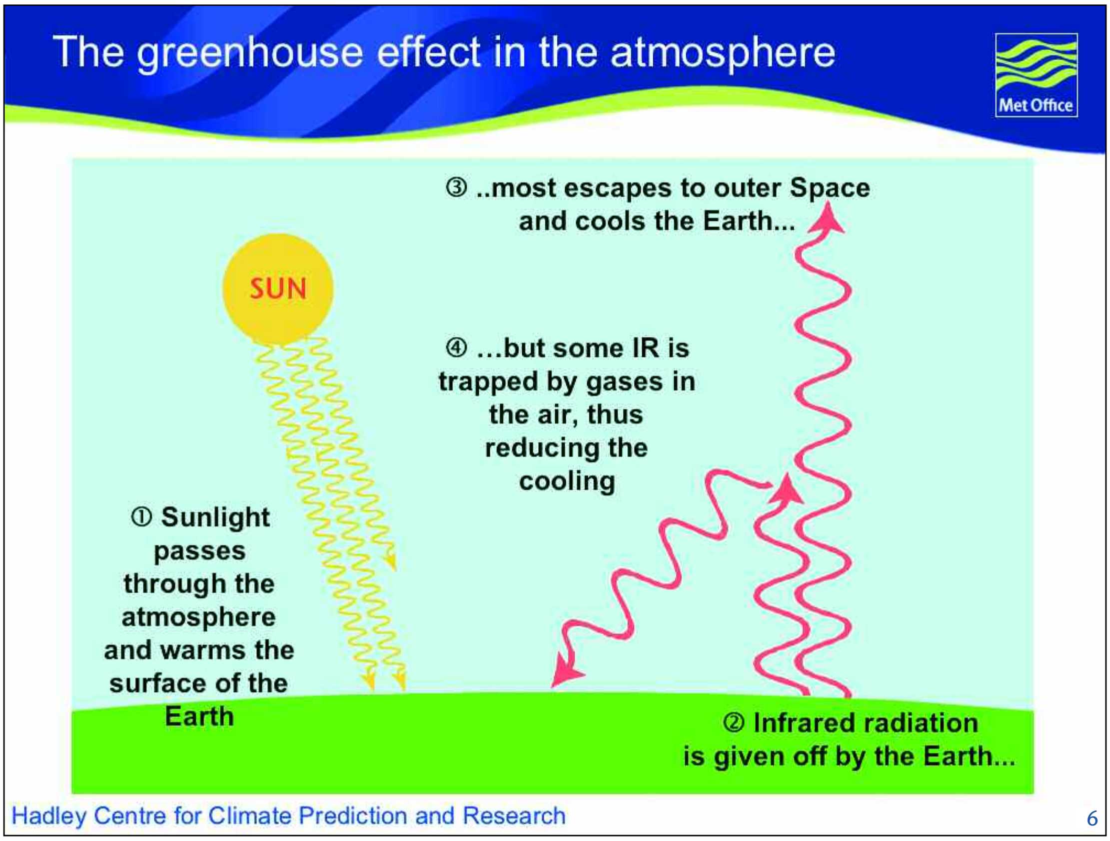
If the amount of solar radiation reaching the Earth, or the amount of infrared radiation leaving the ground, changes, then the Earth's temperature will change. Any change will be very slow because the Earth's climate system has a large thermal inertia, mainly due to the ocean.

Photo credits, top: Space Environment Center, NOAA, USA.



In order to understand the greenhouse effect on Earth, a good place to start is in a greenhouse. A greenhouse is kept warm because energy coming in from the Sun (in the form of visible sunlight) is able to pass easily through the glass of the greenhouse and heat the soil and plants inside. But energy which is emitted from the soil and plants is in the form of invisible infrared (IR) radiation; this is not able to pass as easily through the glass of the greenhouse. Some of the infrared heat energy is trapped inside; the main reason why a greenhouse is warmer than the garden outside. However, this is a rather crude analogy to the way the greenhouse effect works on Earth, as will be seen next.

The existence of the greenhouse effect has been known about for a long time. In a paper published in 1896 by the Swedish scientist Arrhenius, he discusses the mean temperature of the ground being influenced by the presence of heat-absorbing gases in the atmosphere. Indeed, the notion of heat absorption by gases was put forward even earlier than Arrhenius' time, by scientists such as Tyndall and Fourier. So the greenhouse effect may be relatively new to policy makers and the media, but in the scientific community it has been known about, and investigated, for well over 100 years.

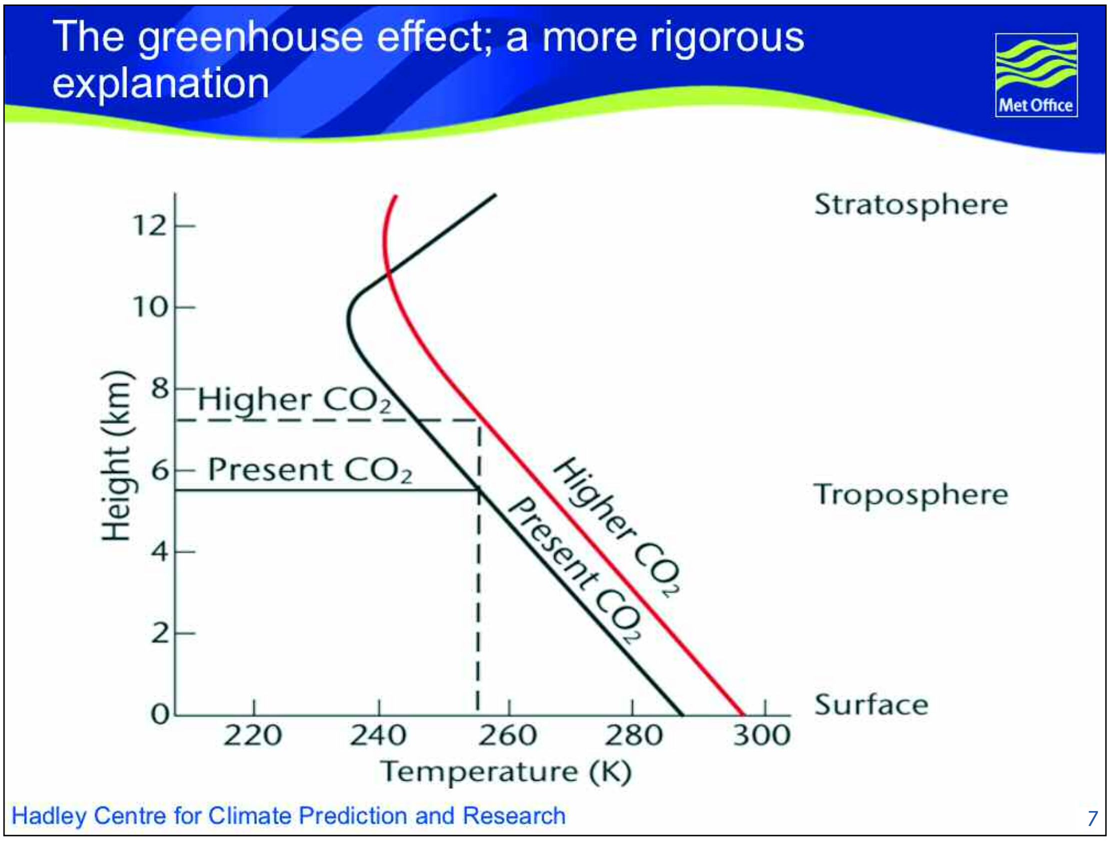


As explained earlier, the temperature of the Earth is determined by the balance between energy coming in from the Sun in the form of visible radiation, sunlight, and energy constantly being emitted from the surface of the Earth to outer Space in the form of invisible infrared radiation. The energy coming in from the Sun can pass through the clear atmosphere pretty much unchanged and therefore heat the surface of the Earth. But the infrared radiation emanating from the surface of the Earth is partly absorbed by some gases in the atmosphere, and some of it is re-emitted downwards. The effect of this is to warm the surface of the Earth and lower part of the atmosphere. The gases that do this work in the natural atmosphere are primarily water vapour (responsible for about two-thirds of the effect) and carbon dioxide.

A rather more rigorous explanation is given in the next slide.

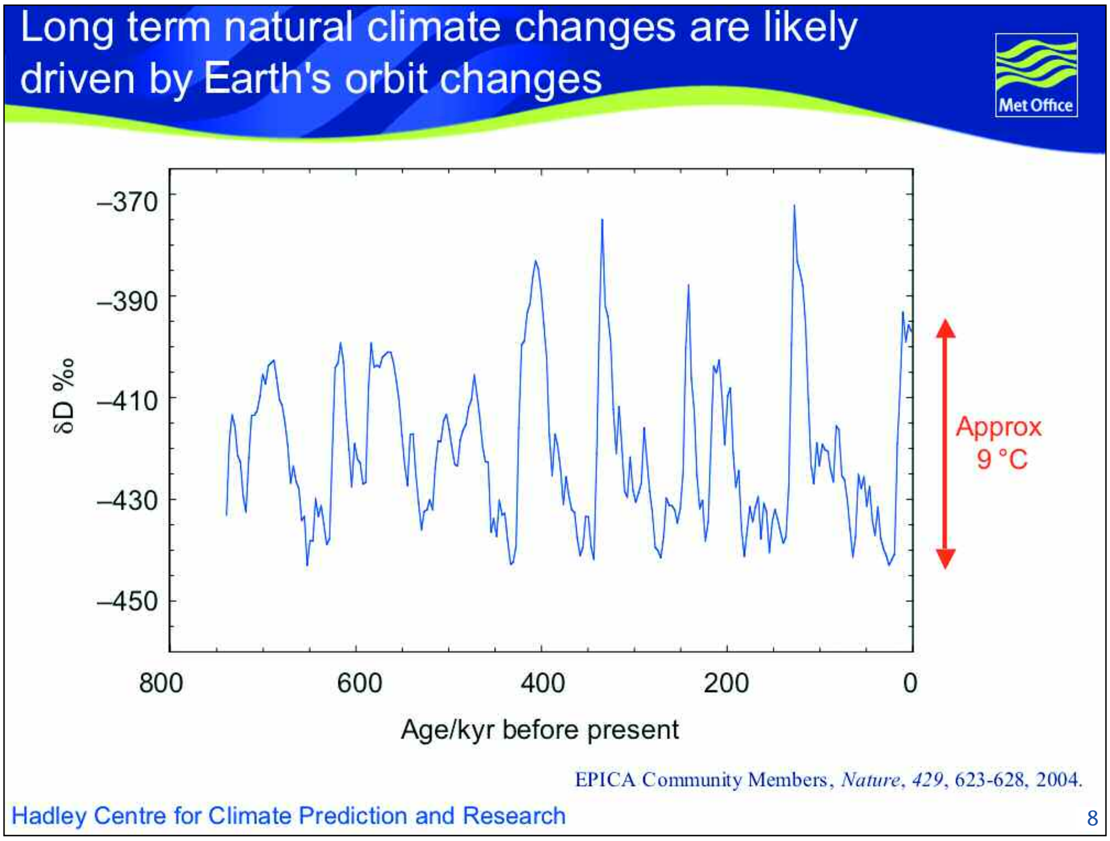
The natural greenhouse effect has operated for billions of years. Without the greenhouse effect due to natural water vapour, carbon dioxide, methane and other greenhouse gases in the atmosphere, the temperature of the Earth would be about 30 °C cooler than it is, and it would not be habitable. So the greenhouse effect due to naturally occurring greenhouse gases is good for us. The concern is that emissions from human activities (for example, CO_2 from fossil-fuel burning) cause these greenhouse gas concentrations to rise well above their natural levels and as new greenhouse gases (such as CFCs and the CFC replacements) are added, the further warming which will take place could threaten sustainability. This is discussed in later slides.

Further reading: Houghton, J.T., Global Warming. Rep. Prog. Phys. 68, 1343–1403 (2005).



A more rigorous explanation of the greenhouse effect is as follows. Temperature in the lower atmosphere (troposphere) decreases with height, on average. That for the present day climate is shown by the black line in the above diagram. (Temperature is shown in units of Kelvin (K); 0 °C is about 273 K). The infrared radiation that cools the Earth comes from an average height of about 5.5 km at present, due to absorption and re-emission of greenhouse gases. In a future world with higher greenhouse gas concentrations, emission of IR to space will be from a higher (and therefore cooler) layer (in the hypothetical example shown above, just over 7 km). Because the rate of emission of IR increases with temperature, emission from this cooler layer will be reduced, and the atmosphere then warms up (red line) until the rate of IR emission to space reaches the original rate. The surface temperature will then be warmer than that in the present day (by about 10 K, that is 10 °C, in the hypothetical figure above).

Further reading: Houghton, JT, Global Warming. Rep. Prog. Phys. 68, 1343-1403 (2005).

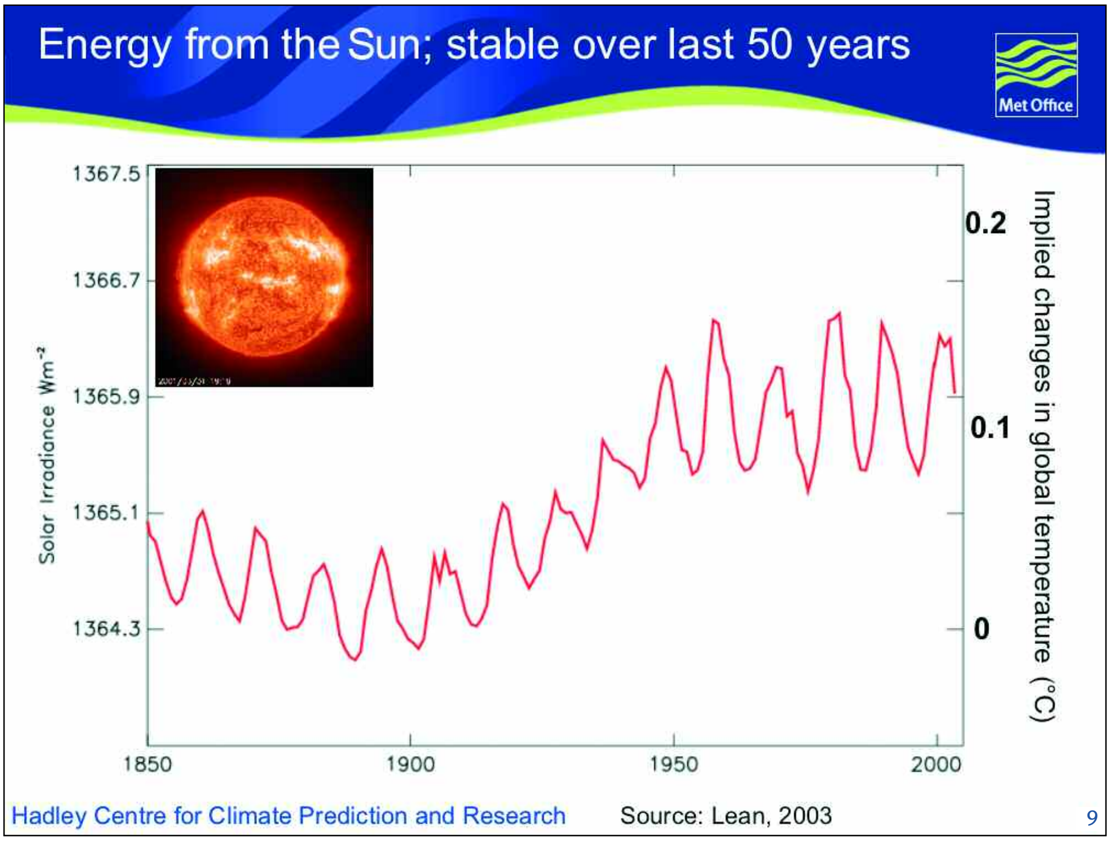


Before moving on to discuss recent changes and their causes, it is worthwhile setting the long-term context.

It is well known that global temperatures change substantially over timescales of a hundred thousand years, as climate moves from ice ages to interglacials. The figure above shows measurements* deduced from ice cores drilled from the Greenland ice sheet and analysed by the British Antarctic Survey and others as part of the European programme EPICA (Figure courtesy Eric Wolff, BAS). The actual measurement is of the concentration of deuterium in air bubbles, and this can be related to local temperatures. The figure shows that temperature rise between the depth of the last ice age 20,000 years ago and the current interglacial (Holocene) is about 9 °C. Swings between glacial and interglacial climate are likely to be initiated by subtle differences in the Earth's orbit and tilt of axis around the Sun, known as the Milankovic Effect after its proposer.

Although these orbital changes dictate that the Earth will enter another ice age, this is unlikely to be for many thousands of years – quite a different timescale to that of man-made warming. Some researchers believe that man-made warming may actually prevent the Earth from entering another ice age.

**Reference: Eight glacial cycles from an Antarctic ice core. EPICA Community Members, Nature, 429, 623–628, 2004.*



In addition to long-term changes due to the Earth's orbit, there are two main natural agents which can change global climate: changes in energy we receive from the Sun and the effect of volcanoes.

The estimated change in solar irradiance — the amount of energy received at the Earth from the Sun — is shown here. There are several estimates of this quantity; the one shown here is due to Lean, Beer and Bradley*, updated to 2003. The eleven-year solar cycle is clearly seen, and so too is a rise between about 1900 and 1960, with little if any change after that. Solar irradiance before 1978 is estimated from proxy data (sunspots, etc) and is less reliable than that measured since then by satellites. Based on the Hadley Centre HadCM3 climate model, we can estimate the global temperature increase which the changing solar radiation may have caused; this is shown on the right-hand scale and amounts to one or two tenths of a degree, so may explain at least some of the global temperature rise observed in the early part of the 20th century.

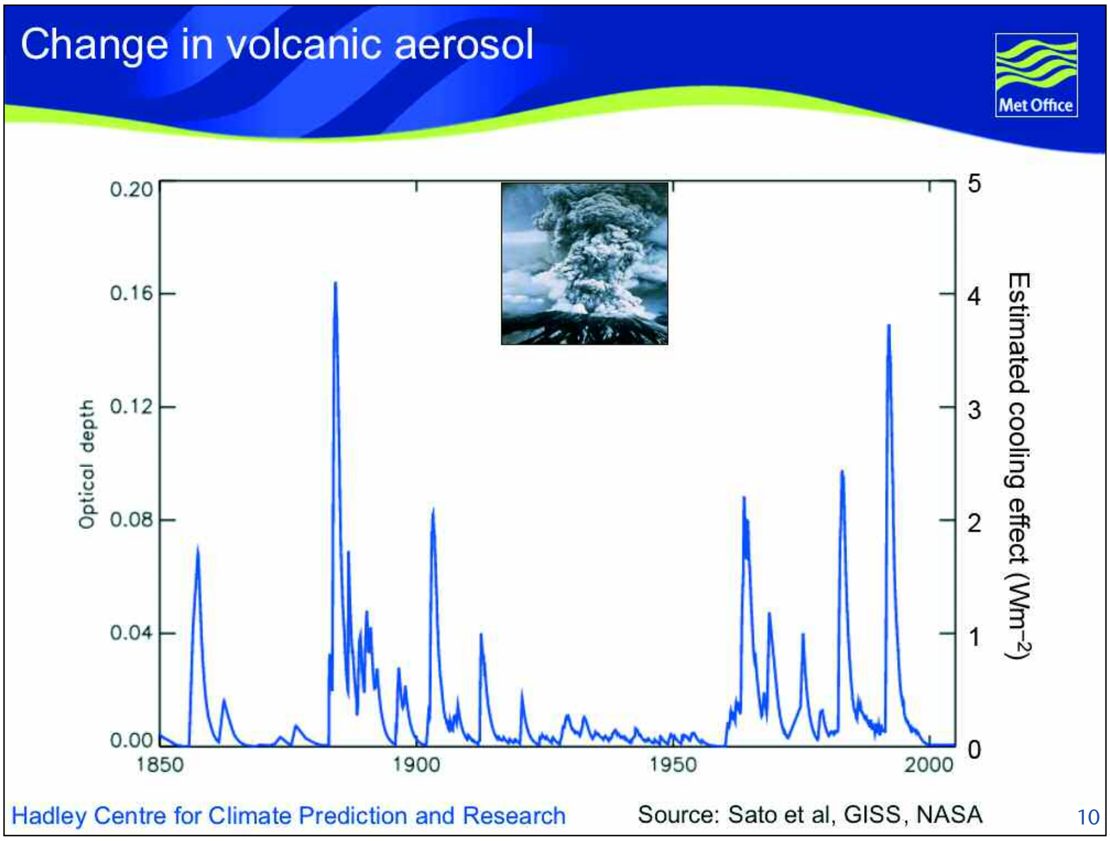
(Note that, because of the large inertia of the climate system, global temperature does not respond significantly to the 11-year solar cycle).

There are some theories that the solar influence on global climate could be amplified by an indirect route, for example involving stratospheric ozone or cosmic rays or clouds. A review** of current understanding was prepared for the Hadley Centre by the University of Reading and Imperial College, London. This concluded that there is some empirical evidence for relationships between solar changes and climate, and several mechanisms, such as cosmic rays influencing cloudiness, have been proposed, which could explain such correlations. These mechanisms are not sufficiently well understood and developed to be included in climate models at present.

However, current climate models do include changes in solar output, and attribution analyses that seek to understand the causes of past climate change by comparing model simulations with observed changes, do not find evidence for a large solar influence. Instead, these analyses show that recent global warming has been dominated by greenhouse gas-induced warming, even when such analyses take account of a possible underestimate of the climatic response to solar changes by models.

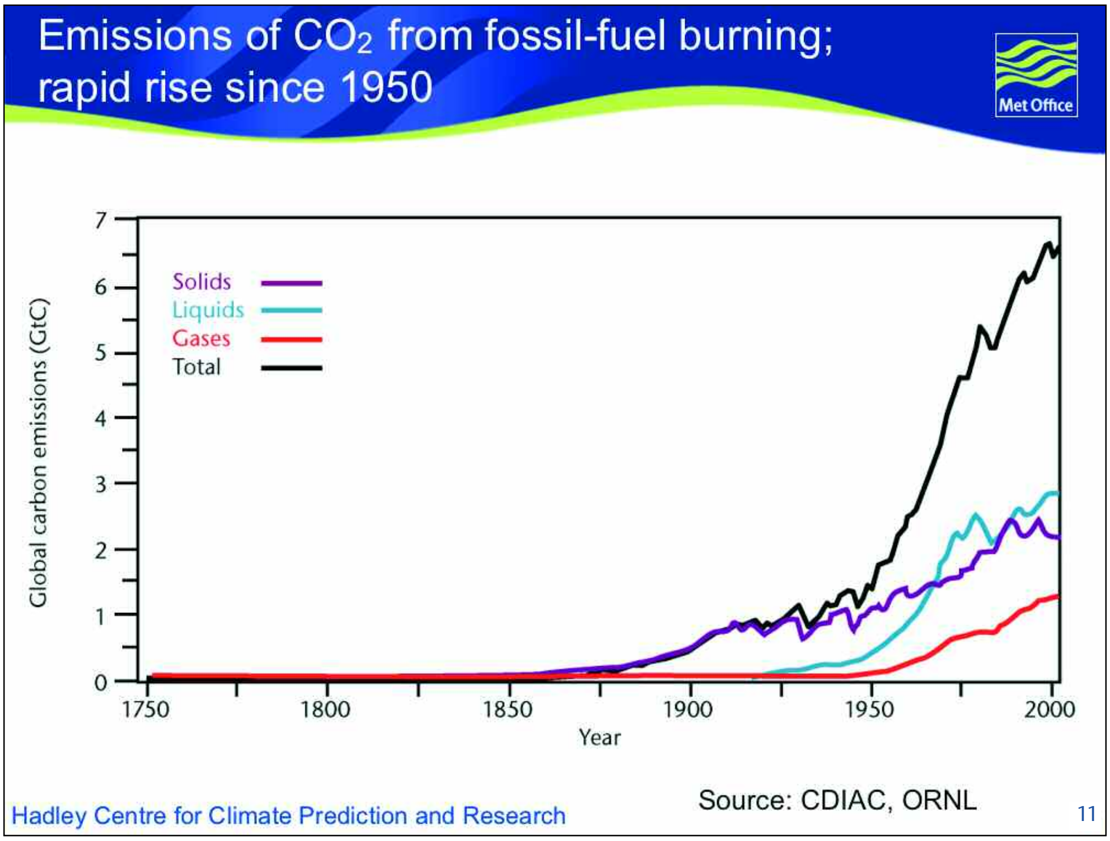
**Lean J., J. Beer and R. Bradley, Reconstruction of solar irradiance since 1610: Implications for climate change, Geophys. Res. Letts. 22, 3195–3198, 1995.*

*** The Influence of Solar Changes on the Earth's Climate. L.J. Gray, J.D. Haigh, R.G. Harrison. Hadley Centre Technical Note 62, January 2005. This can be downloaded from www.metoffice.gov.uk/research/hadleycentre/pubs/HCTN/index.html*



Volcanoes inject gas into the atmosphere. If they are energetic enough, this gas will reach the stratosphere and form small sulphate aerosol particles which can persist for a few years. They reflect back some of the solar radiation which otherwise would have heated the surface of the Earth, and hence act to cool the planet. The amount of volcanic aerosol in the atmosphere is very variable, indicated by this time series of its estimated optical depth*, and the cooling effect that this would have. Although energetic volcanoes were relatively common in the late 19th century (for example, Krakatoa in 1883) and early 20th century, and there have been substantial numbers of energetic volcanoes since the 1960s (most recently, Pinatubo in 1991), there was a period in the 1940s and 1950s when the atmosphere was relatively clear of volcanic aerosol. The amount of climate cooling due to volcanic aerosols would have been quite small in that period. This unusually low amount of volcanic cooling (together with the increase in solar radiation shown in the last slide) may have contributed to temperatures in the 1940s being relatively high compared to earlier decades. As with solar energy, optical depth due to volcanic aerosols has been estimated indirectly before about 1983, and hence is less certain.

**Source: Sato, M., J.E. Hansen, A. Lacis, L. Thomason: Stratospheric aerosol optical thickness. At: www.giss.nasa.gov/sata/strataer/*

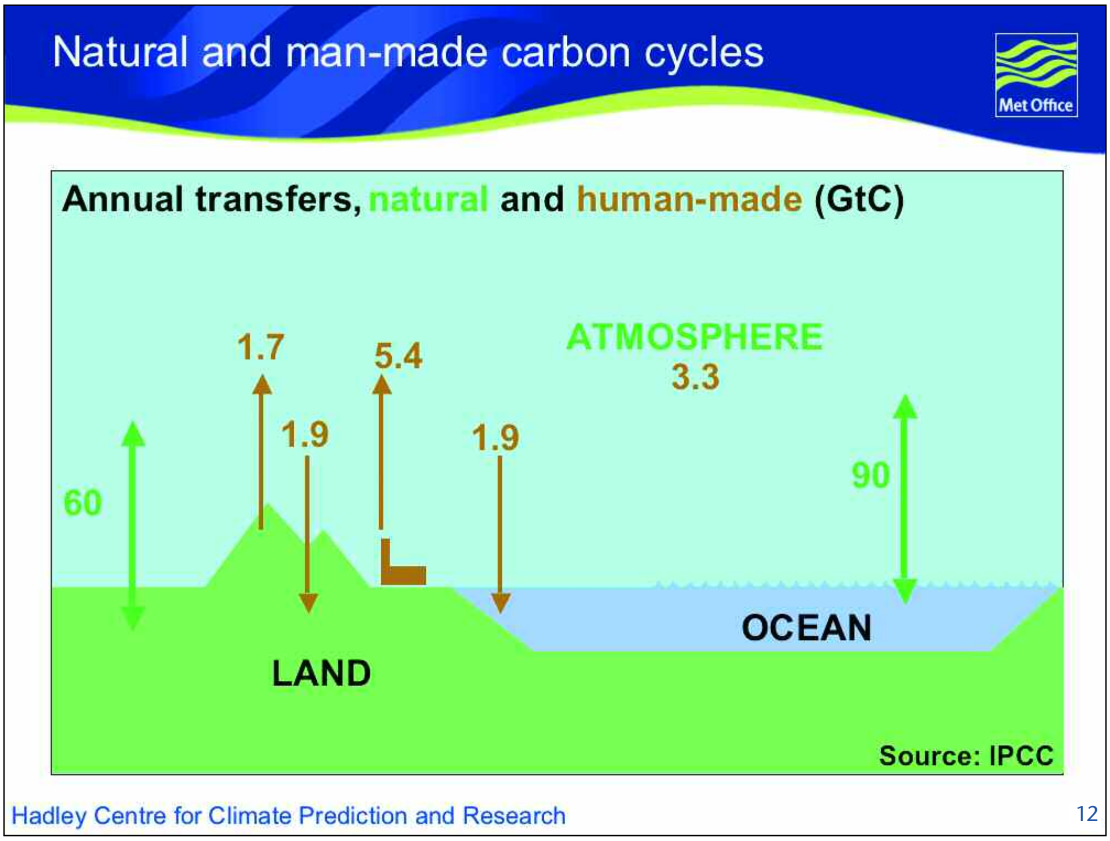


In an earlier slide, mention was made of emissions from human activities enhancing the natural greenhouse effect. The main gases involved in this are shown in the table below.

Gas	Main sources	Effective lifetime
carbon dioxide CO_2	fossil fuel combustion, land-use changes	approximately 100 years
methane CH_4	natural gas extraction, agriculture	12 years
nitrous oxide N_2O	fossil fuel combustion	114 years
ozone in lower atmosphere	reactions between emissions from transport and industry	3 months

Emissions of carbon dioxide into the atmosphere from human activities have increased since the Industrial Revolution, particularly since about 1950. The graph above shows changes in emissions from solid fuel (mainly coal), liquid (oil) and gas, and the total emissions from burning fossil fuels. Units are gigatons (billion tons) of carbon per year; to calculate the amount of CO_2, multiply by this by 3.7. Smaller sources such as cement production and gas flaring are omitted for clarity, but included in the total. (Source: Carbon Dioxide Information and Analysis Centre, Oak Ridge National Laboratory, USA. See: http://cdiac.esd.ornl.gov/trends/emis/glo.htm)

In addition to the fossil-fuels source, carbon dioxide is also emitted when forests are cleared and burnt. Figures for this source are less accurate, but the best estimate from IPCC is 1.7 GtC per year during the 1980s.



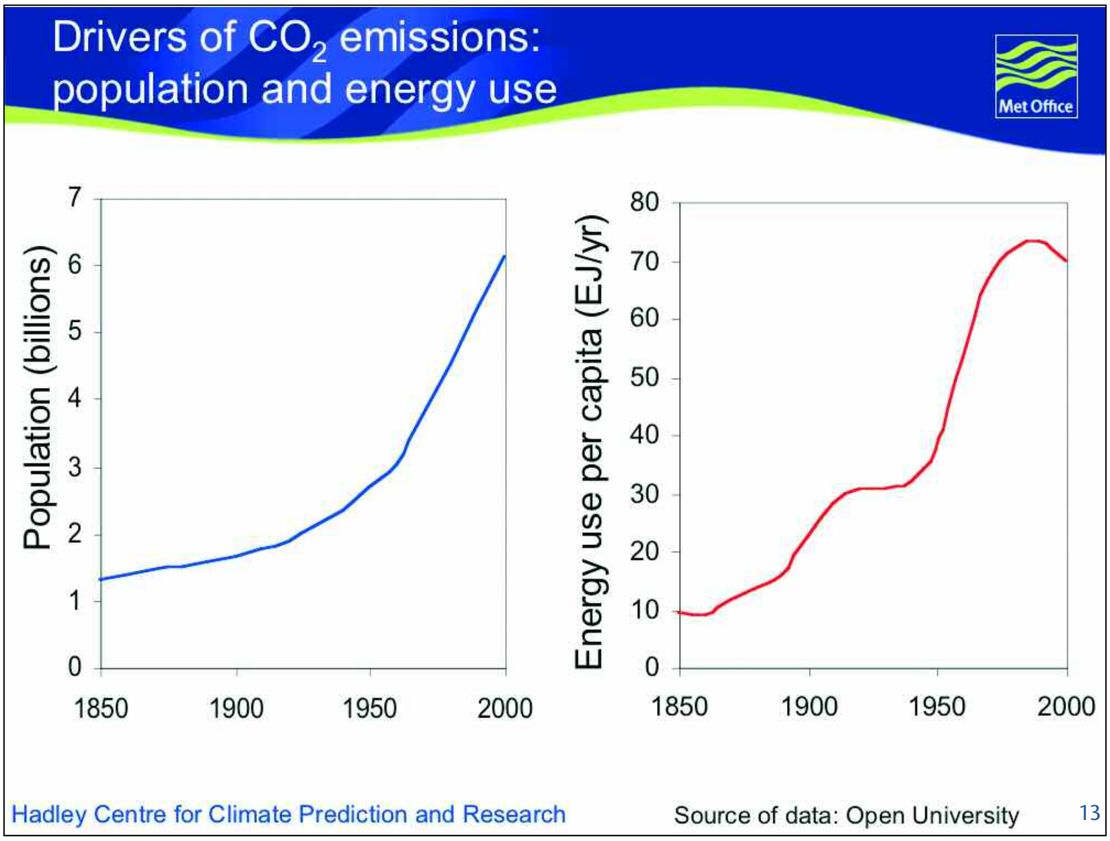
Emissions of CO_2 from human activities become involved in the natural carbon cycle, a system of fluxes of CO_2 between land (vegetation and soils), ocean (water and ecosystems) and the atmosphere. The IPCC TAR estimated that, averaged over the decade of the 1980s, fossil-fuel burning emitted 5.4 GtC/yr into the atmosphere and land use change (mainly deforestation) a further 1.7 GtC/yr, giving a total of about 7 GtC/yr. The atmosphere retained about 3.3 GtC of this per year, leading to the measured rise in CO_2 concentration, with about 1.9 GtC/yr going into each of the two main sinks, the ocean and the land (soils plus vegetation). Many of these estimates are very uncertain; a more detailed analysis with uncertainty estimates is given in Chapter 3, Sections 3.1 and 3.2 of the IPCC TAR.

As can be seen from the slide, these man-made fluxes are much smaller than the fluxes in the natural carbon cycle. However, the natural carbon cycle is in balance, and has led to concentrations of CO_2 in the atmosphere remaining relatively constant for the thousand years before the industrial revolution.

Similar cycles (known by the general term of biogeochemical cycles) exist for other greenhouse gases such as methane and nitrous oxide. In the case of methane, emissions from natural and human activities undergo complex chemical interactions in the atmosphere with species such as the hydroxyl radical (OH), concentrations of which are themselves affected by other man-made emissions, such as carbon monoxide.

Ozone in the lower atmosphere (troposphere) is also a greenhouse gas. It is formed by atmospheric chemical reactions between man-made emissions such as hydrocarbons, nitrogen oxides, carbon monoxide and methane.

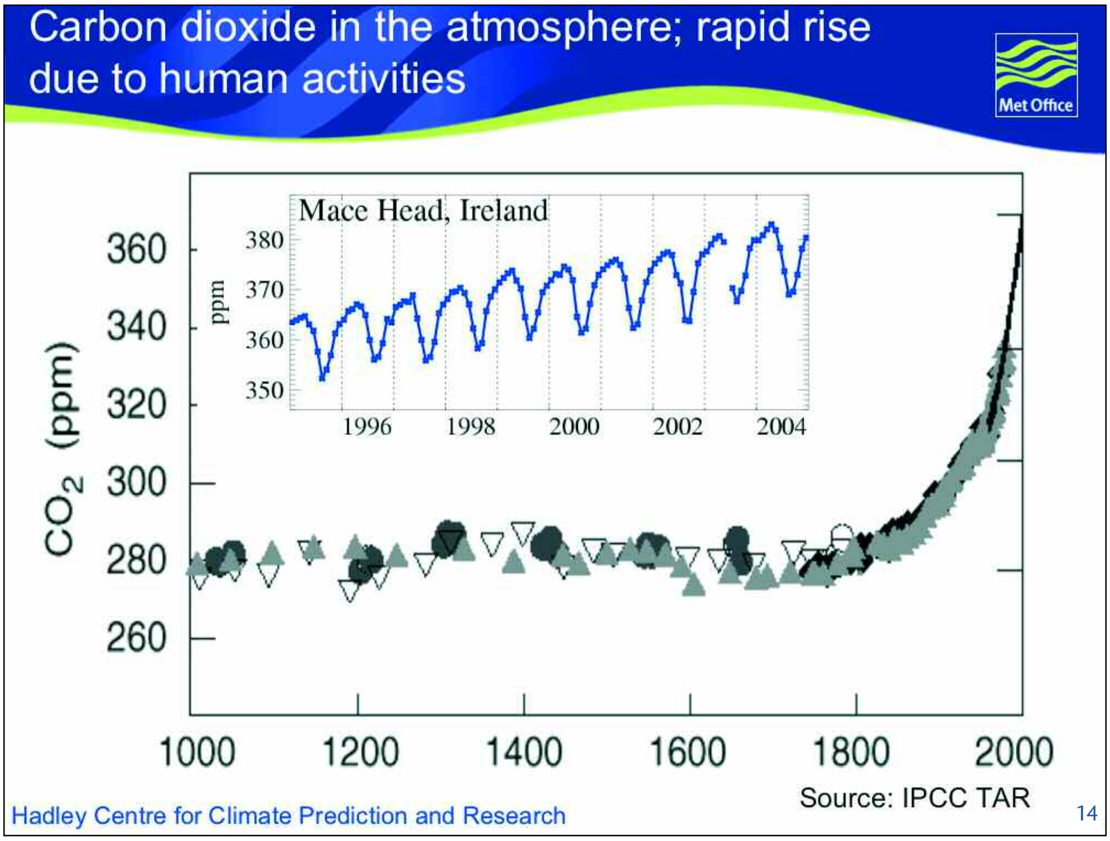
In the case of water vapour, which is the most important natural greenhouse gas, emissions from human activity have very little effect on its concentration in the atmosphere, which is mainly determined by temperature (and, hence, human activity does affect it indirectly, via global warming).



The main factors which have caused the rise in CO_2 emissions shown in the previous slide are twofold: (a) growth in population (shown in the left-hand panel) and (b) growth in energy use per person (shown in the right-hand panel), as more people enjoy a more energy-intensive standard of living, with increased ownership of goods, more services and greater travel.

Of course, energy use per person is very different from country to country.

The source of the data used to draw these diagrams was the Open University website: http://www.open.ac.uk/T206/3longtour.htm

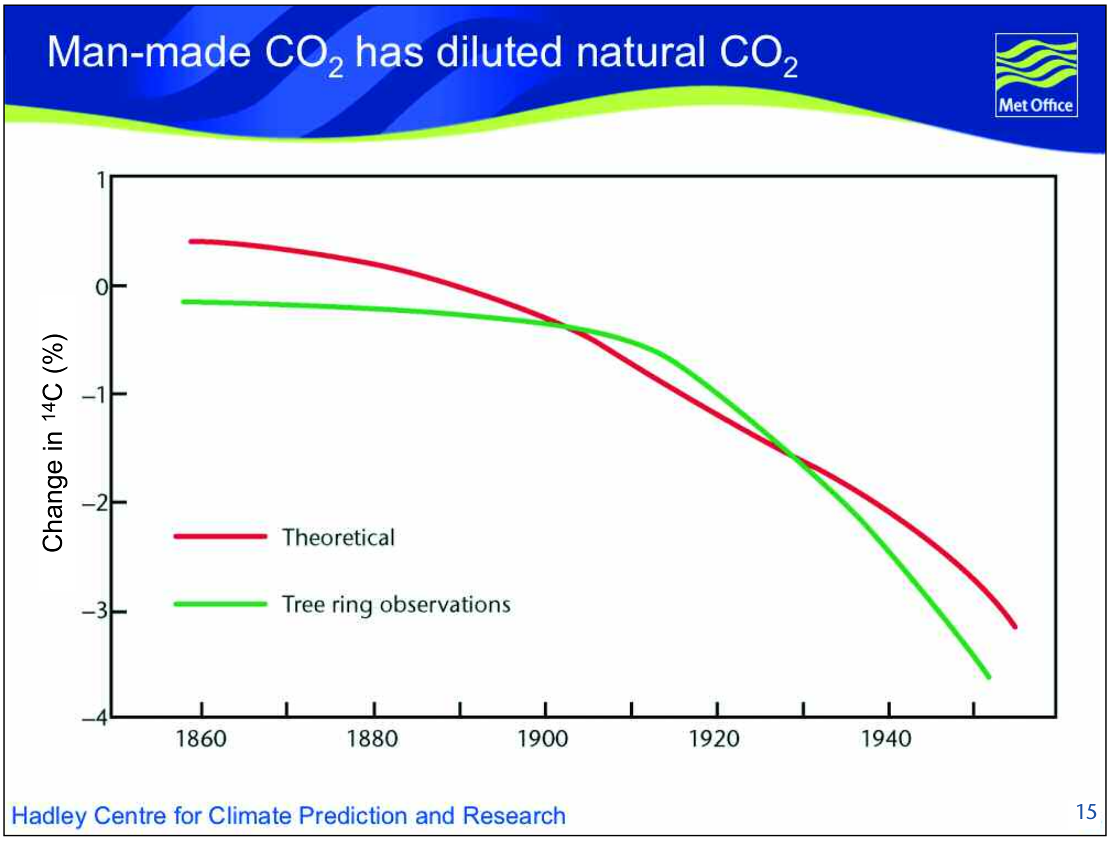


The concentration of carbon dioxide in the atmosphere was roughly constant at about 280 parts per million (ppm) for 800 years (and probably longer) before the start of the industrial revolution. We know this from analysis of air trapped in bubbles in ancient ice cores in Antarctica and Greenland. These ice-core samples then show a gradual rise from about 1800, accelerating with time. Direct measurements of CO_2 in the atmosphere have been made since the late 1950s, notably by Keeling on Mauna Loa in Hawaii. These measurements have shown a steady rise up to a current annual-average value (2004) of 378 ppm. The figure above comes from the IPCC TAR, Figure 3.2.

In the inset we show CO_2 concentrations over the last 10 years at the Mace Head station in Galway, Ireland*. In addition to the trend, the effects of seasonal cycle of vegetation growth and decay can be clearly seen.

Concentrations in the atmosphere of other greenhouse gases have also risen due to human activities. Methane was about 800 parts per billion (ppb) 200 years ago, and is now at more than 1750 parts per billion, although its rise has levelled off, possibly due to reduction in natural gas leakages. Nitrous oxide has risen from a pre-industrial concentration of about 270 ppb to a current level of over 310 ppb. Ozone in the lower atmosphere has a less robust observational long-term record but appears to have increased over the same period by about 30%.

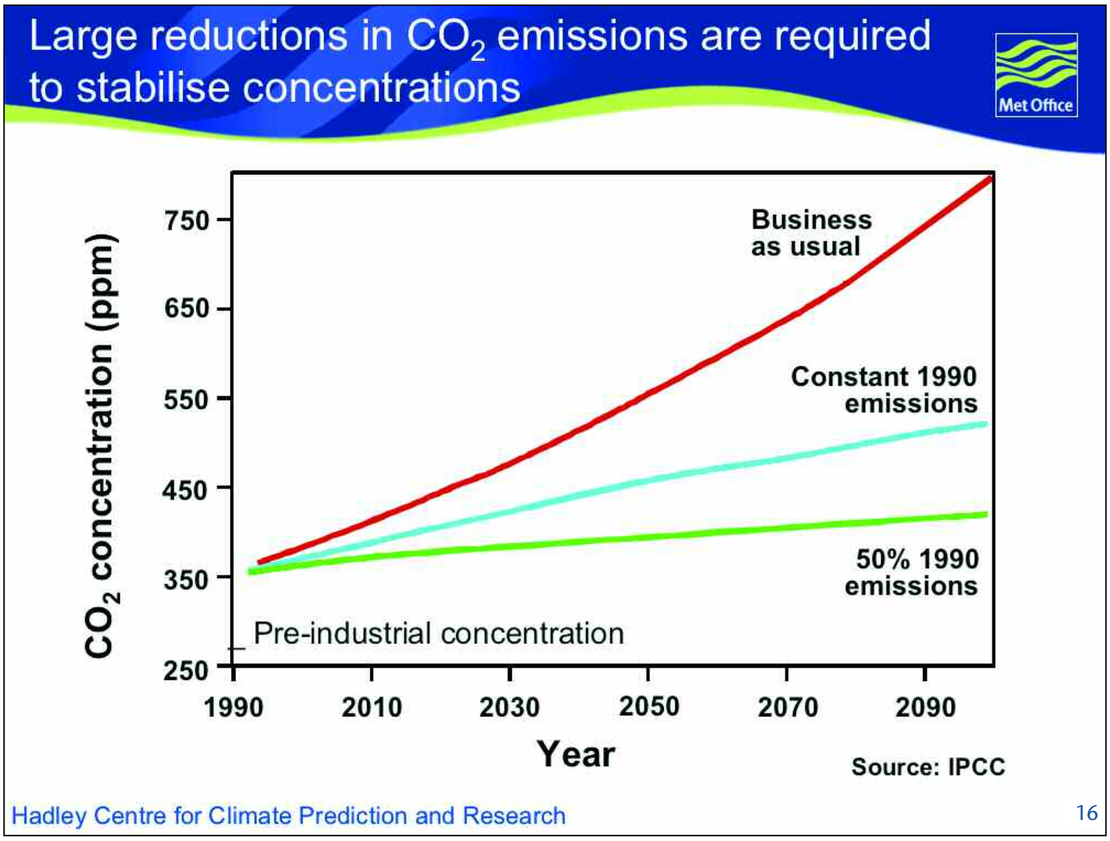
Reference: A burning question. Can recent growth rate anomalies in the greenhouse gases by attributed to large-scale biomass burning events? P.G. Simmonds, A.J. Manning, R.G. Derwent, P. Ciais, M. Ramonet, V. Kazan, and D. Ryall (2005) Atmospheric Environment, 39, Issue 14, pp. 2513–2517.
Further reading: IPCC TAR Chapter 3.
**Laboratoire des Sciences du Climat et de l'Environnement, France; National University of Ireland, Galway; UK Department for Environment, Food and Rural Affairs.*



How do we know that the rise in carbon dioxide concentrations since the Industrial Revolution is due to emissions from man's activities? The carbon in CO_2 has several different forms; the most common (about 99%) is called ^{12}C, but there is a very small fraction of ^{14}C, which is radioactive, with a half life of about 5,700 years. Because fossil fuels are so old, the ^{14}C in them has decayed, so the CO_2 given off when we burn them has very much less ^{14}C in it. So the amount of ^{14}C in the air is being diluted by CO_2 emissions from burning coal, oil and gas, known as the 'Suess effect'. We can estimate the change in ^{14}C in the air from 1850 to 1950 by measuring it in tree rings; this estimate is shown above in green. When we calculate what this should be, based on man-made CO_2 emissions, the calculation (red line) agrees well with the measurements. This is proof that the rise in CO_2 concentration is due to fossil-fuel burning. The technique fails to work after about 1950, because radioactivity from atomic bombs corrupts the technique.

There is other supporting evidence, such as the consistency between the rise in concentration (unprecedented over the last several hundred thousand years) and man-made emissions, and the north-south gradient of CO_2 concentration.

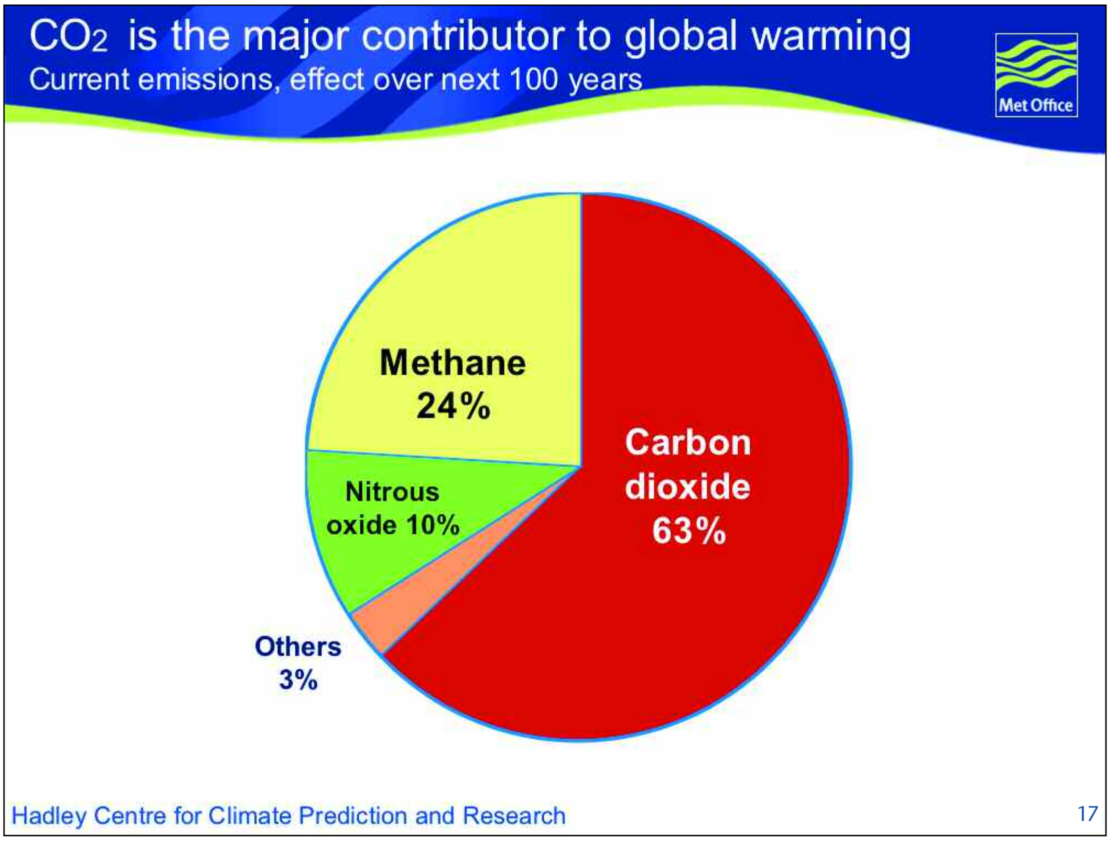
Source (tree ring observations): Damon, P.E., Long, A., and Wallick, E.I. (1973) On the magnitude of the 11-year radiocarbon cycle. Earth Planet. Sci. Lett. 20, 300–306.
Source (theoretical calculations): Baxter, M.S. and Walton, A. (1970) A theoretical approach to the Suess effect. Proc. Roy. Soc. London A318, 213–230.
See SCOPE 13: The global carbon cycle. Chapter 2: Variations in atmospheric CO2 content, by H.-D.Freyer. http://www.icsu-scope.org/downloadpubs/scope13/chapter03.html#abs



The long, effective lifetime of carbon dioxide means that its concentration in the atmosphere would be very slow to respond to a reduction in emissions. This figure shows the concentration of carbon dioxide in parts per million from 1990 to the end of the next century. The red line shows that if future carbon dioxide emissions follows one 'business as usual' projection, then its concentration in the atmosphere will roughly double over the next 100 years.

If we were able to stabilise global emissions at constant 1990 levels, carbon dioxide concentration in the atmosphere would still go on rising substantially (blue line). And even if emissions were cut in half overnight and continued at that level for 100 years, then carbon dioxide concentrations would still actually creep up (green line). Only by a reduction of about 70% in carbon dioxide emissions would we be able to stabilise its concentration in the atmosphere. That is not the same thing as calling for a cut of 70%; it is simply pointing out that the science of the carbon cycle leads to that conclusion.

However, the carbon cycle model used in the calculations above assume no feedback between the climate and the carbon cycle. Slide 60 shows that the two are actually closely coupled, and the resulting feedback may mean that the reduction in emissions required to stabilise carbon dioxide concentrations in the atmosphere would be even larger than 70%.

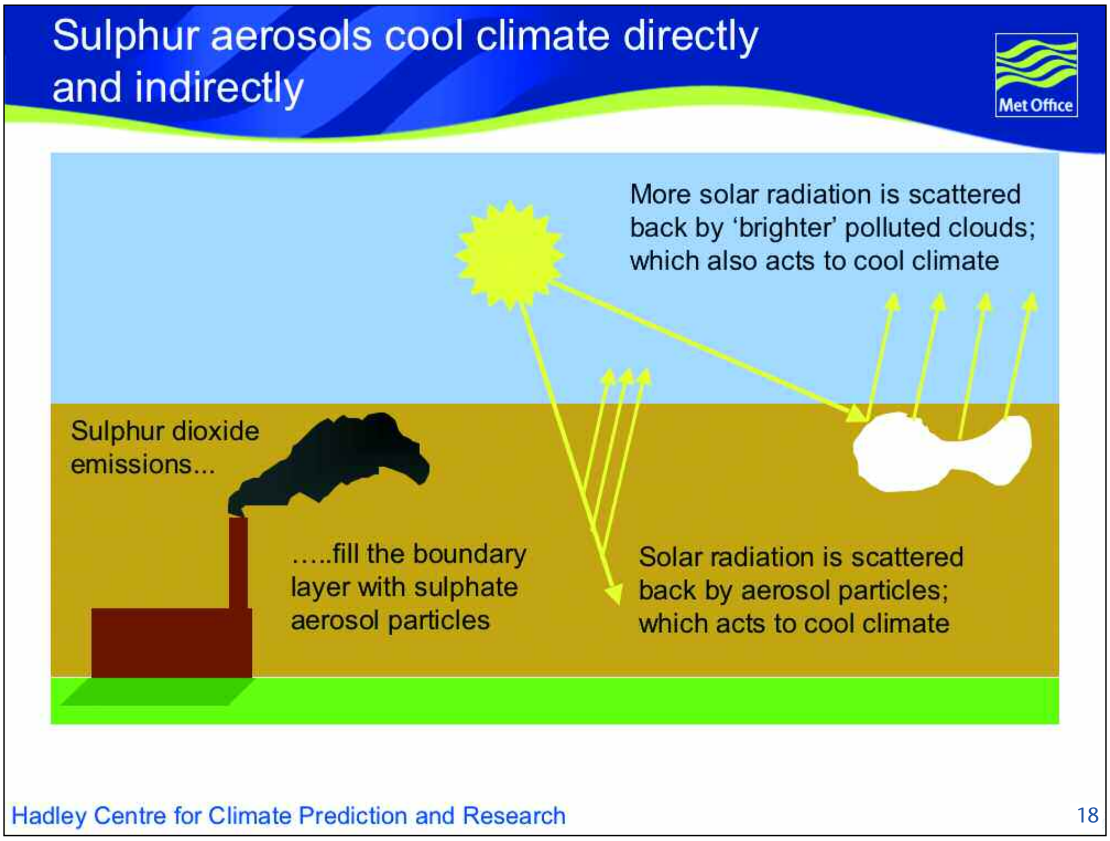


We have already discussed CO_2, methane, nitrous oxide and ozone as greenhouse gases. Other greenhouses gases such as chlorofluorocarbons (CFC) damage the ozone layer and emissions have, hence, been virtually eliminated as a result of the Montreal Protocol. However, because they have lifetimes of around 100 years, their concentrations in the atmosphere are only now slowly starting to decrease.

Equal amounts emitted of each greenhouse gas has a different capacity to cause global warming. This depends upon its lifetime (the longer the emission remains in the atmosphere, the more time it has to exert a warming influence), the amount of extra outgoing infrared radiation it will absorb in the atmosphere, and its density. The future warming effect, usually taken over the next 100 years, of an extra 1 kg of a greenhouse gas emitted today, relative to 1 kg of CO_2, is known as its Global Warming Potential (GWP). Current estimates are: methane: 23; nitrous oxide: 296; CFC12: 7300; SF6: 22200. CO_2 = 1, by definition.

The warming effect over the next 100 years of current emissions of the greenhouse gases will depend upon the amount of each gas being emitted globally and its GWP. When this calculation is done, it is seen in this slide that carbon dioxide will be responsible for about two-thirds of the expected future warming. About a quarter of the warming is expected to be due to methane, with other greenhouse gases making up the rest. Carbon dioxide is certainly the most important man-made greenhouse gas, presently and in the future. Note that tropospheric ozone is not included in this calculation.

Further reading: IPCC TAR Chapter 6, Section 12.



Very small particles, known as aerosol, have a substantial effect on climate. Sulphate aerosol in the lowest part of the atmosphere (the boundary layer) is created when sulphur dioxide, emitted by human activities such as power generation and transport, is oxidised. Sulphate aerosol particles scatter some sunlight, which would otherwise reach the surface of the Earth and heat it, back out to Space. They therefore have a cooling influence on climate. The amount of sulphate aerosol in the atmosphere has increased by three or four times over the past 100 years or more.

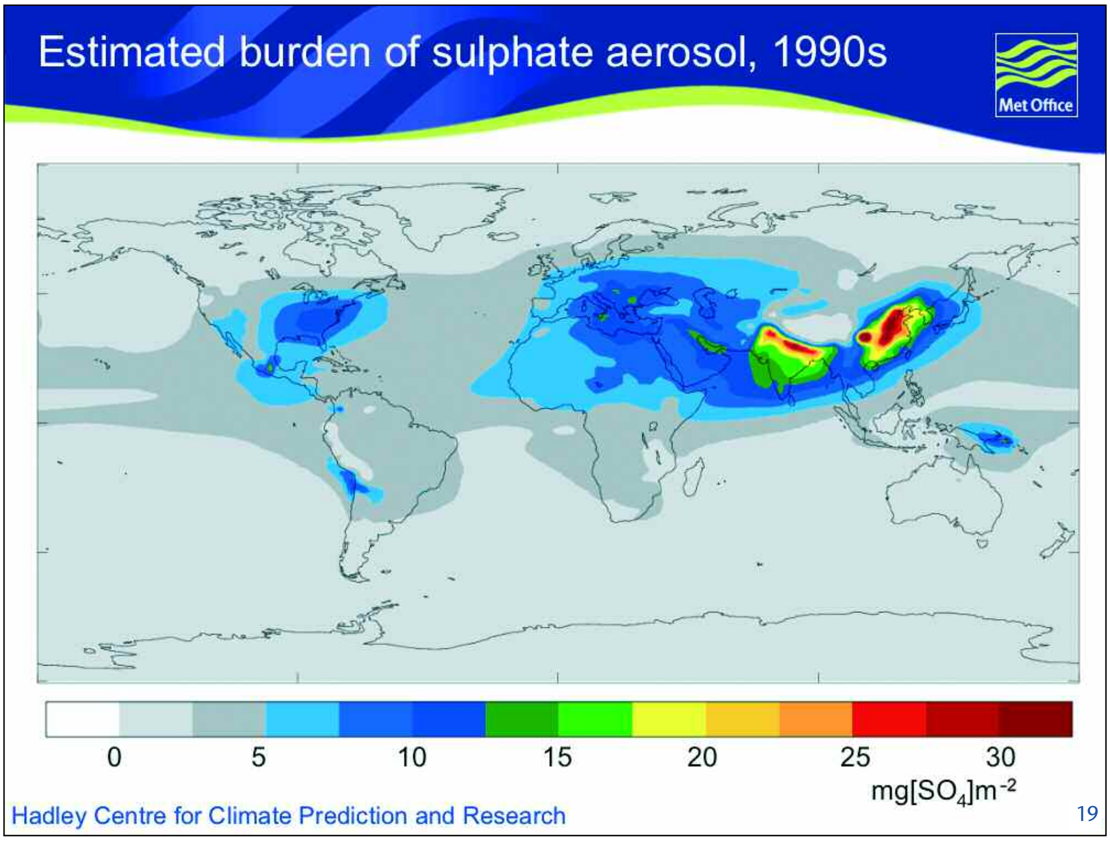
Sulphate aerosol particles also have a further, indirect, effect on climate, shown on the right of the diagram. Clouds are generated when air becomes saturated with water vapour and water condenses onto small particles (cloud condensation nuclei) to form cloud droplets which reflect some sunlight. In a polluted lower atmosphere, because there are more cloud condensation nuclei, then for the same amount of water we get clouds which have a larger number of smaller droplets. These have a greater surface area and, hence, will reflect back more sunlight than clouds in clean air. This gives an additional, indirect, cooling effect of aerosols.

The story is further complicated by the ability of aerosols to change the lifetime of the cloud. Smaller droplets are less likely to coalesce to form drizzle drops. So clouds in a polluted atmosphere will persist longer than their clean-atmosphere equivalents, and the consequent greater cloud cover will also exert a cooling influence.

Other types of aerosol particles can have different effects on climate. Black carbon (soot) emitted from (incomplete) burning of fossil fuels, such as in diesel smoke, will absorb solar radiation and cause the atmosphere to heat up. IPCC estimates that this may have caused about 7% of the man-made heating effect since pre-industrial times. Windblown dust, inorganic carbon and sea-salt aerosols are also important.

Aerosols in the boundary layer have a lifetime of only a few days, since they can easily be washed out by rain or incorporated into clouds which subsequently rain.

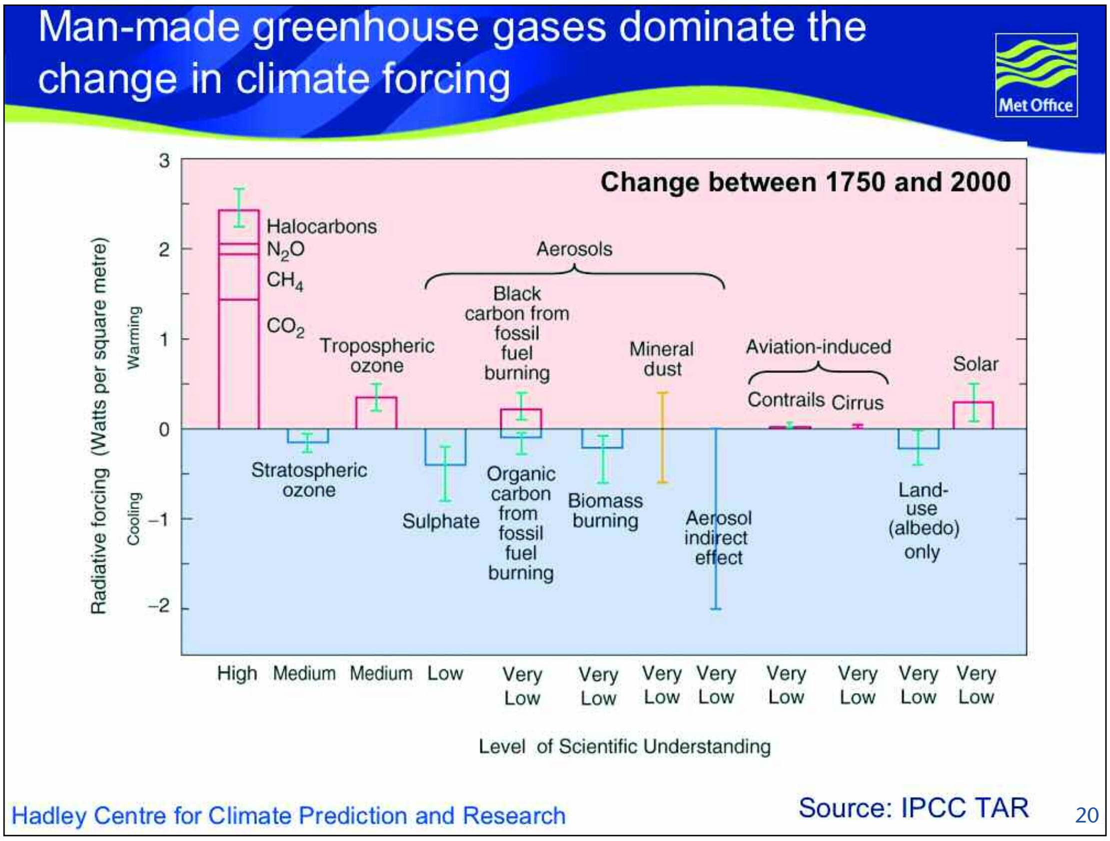
Further reading: IPCC TAR Chapter 5.



The amount of sulphate (SO_4) aerosol in the atmosphere, averaged over the decade of the 1990s and calculated by the latest Hadley Centre climate model (HadGEM1), is shown in this slide. Sources considered are sulphur dioxide from human activities, 'background' non-explosive volcanoes, and natural di-methyl sulphate (DMS) from ocean plankton. The model takes these, considers the effect of chemical processes in the atmosphere and physical processes such as dry and wet deposition, and deduces the resulting concentration of sulphate aerosol, expressed here as a column burden in milligrams per square metre.

Because aerosols only remain in the atmosphere for a few days, the highest atmospheric concentrations are estimated to be downwind of the greatest emissions areas in Asia. DMS is an important contributor only to oceanic areas away from human activities. This uneven geographic distribution means that sulphate aerosols have a complex effect on climate, both locally and globally.

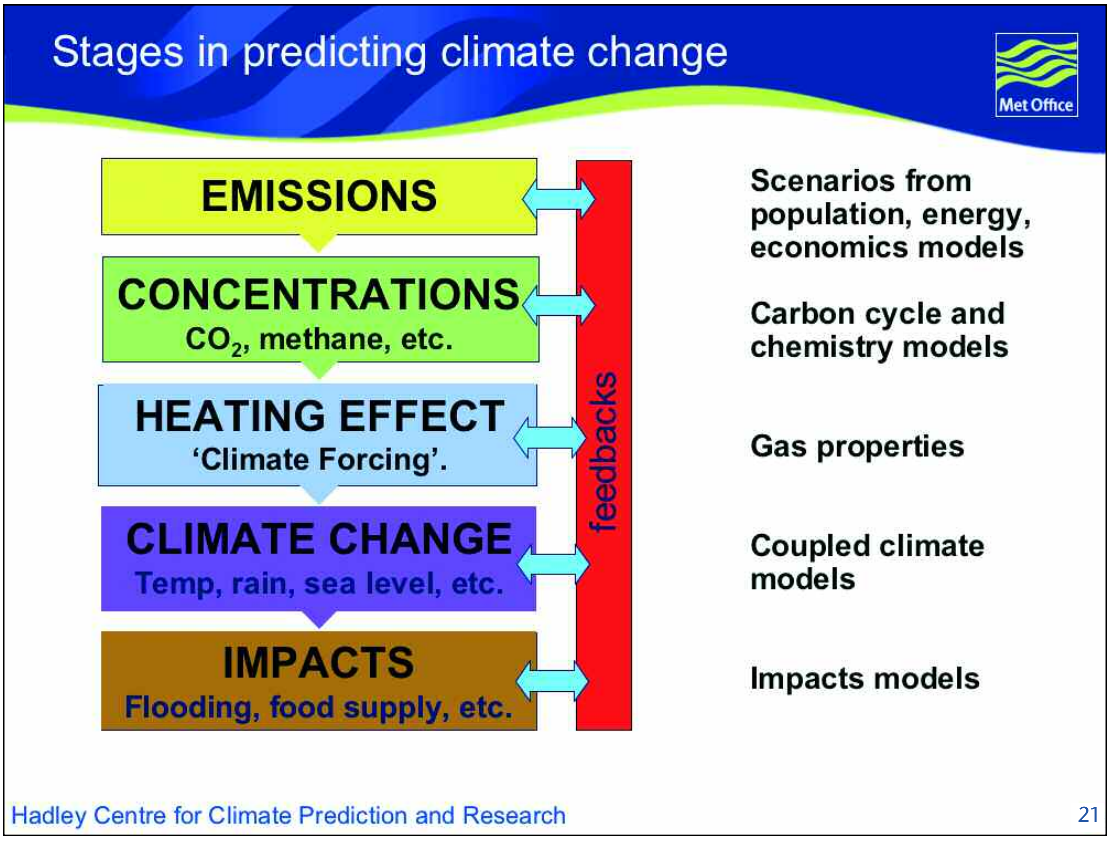
Sulphur dioxide gas and sulphate aerosols in the atmosphere can have impacts on human health, and also lead to acid rain which can fall at considerable distances from the emissions, acidifying waters such as lakes and endangering ecosystems. For these reasons, sulphur emissions have been greatly reduced in the US and Europe since the 1980s. It is expected that similar considerations will, in due course, lead to reductions of sulphur emissions in Asia and other rapidly developing parts of the world. When this happens, the current cooling effect of sulphate aerosols will be reduced, producing a warming effect which would add to that from greenhouse gases.



The external agents which act to change the climate of the Earth, such as greenhouse gases and solar radiation discussed in earlier slides, are known as forcing agents. The change in the energy available to the global Earth-atmosphere system due to changes in these forcing agents is termed the radiative forcing of the climate system and has units of watts per square metre (Wm^{-2}). Thus, the radiative forcing is an index of the relative global mean effect of various agents on the climate of the Earth's surface and lower atmosphere.

This slide, taken from the IPCC TAR, shows the change in radiative forcing over the period 1750 to 2000, due to a number of forcing agents, each of which is linked to human activity (except for solar radiation). In some cases (for example, tropospheric ozone) a best estimate is shown, together with a vertical error bar showing the range of estimates. In other cases, such as mineral dust, only a range of uncertainty can be given. The level of scientific understanding of each of the factors is shown along the bottom of the diagram. Man-made changes in greenhouse gas concentrations represent the biggest and best-understood effect on climate over the period, as shown on the far left of the diagram, and carbon dioxide is the biggest contributor to this.

Further reading: IPCC TAR Chapter 6, Section 13.

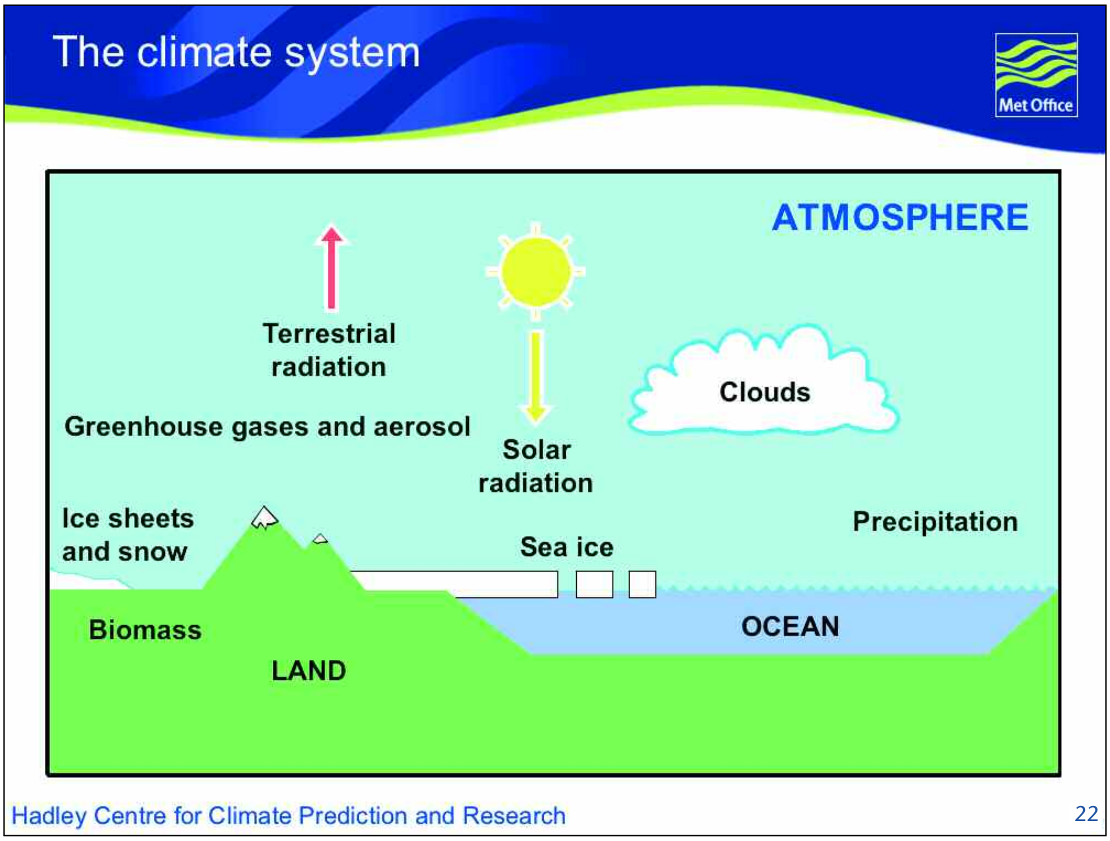


How quickly the climate will change in the future depends upon two factors: how much greenhouse gas emissions grow, and how sensitive the climate system is to these emissions. We predict future climate change in a number of stages, shown in this figure. The first thing we need to estimate is the future emissions of greenhouse gases and other gases which affect climate change. These projections are deduced from separate models which take into account population growth, energy use, economics, technological developments, and so forth. We do not carry out this stage at the Hadley Centre, but we take future scenarios of these emissions from others, particularly the IPCC in its Special Report on Emissions Scenarios (SRES).

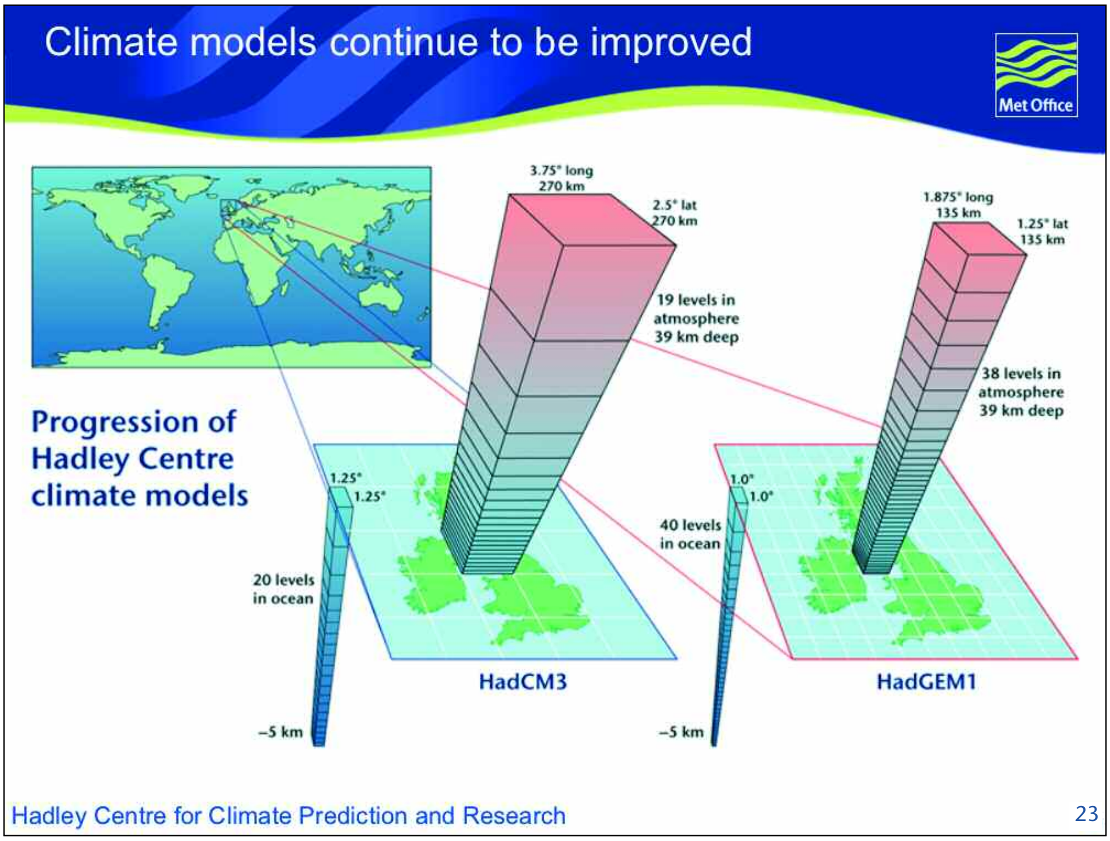
Having obtained projections of how emissions will change, we then calculate how much remains in the atmosphere, i.e. what future concentrations will be. For CO_2, this is done using a model of the carbon cycle, which simulates the transfer of carbon between sources (emissions) and sinks in the atmosphere, ocean and land (vegetation). For gases such as methane, we use models which simulate chemical reactions in the atmosphere. Next we have to calculate the heating effect of the increased concentrations of greenhouse gases and aerosol particles, known as radiative forcing. This is relatively straightforward because we know their behaviour quite well from laboratory studies. Finally, the effect of the changed heating on climate has to be calculated. This complete pathway, from emissions to concentrations to heating effect to climate change, can be done within the climate model, described shortly, which can predict changes in spatial patterns of climate quantities such as temperature at the Earth's surface and through the depth of the atmosphere and oceans.

The additional heating of the climate system which would occur if the concentration of CO_2 in the atmosphere was doubled, is about 3.8 Wm^{-2}. In a simple world this would ultimately warm the surface by about 1 °C. The prediction of climate change is complicated by the fact that, once climate change starts, there will be consequences (feedbacks) in the climate system which can act to either enhance or reduce the warming. For example, as the atmosphere warms it will be able to 'hold' more water vapour. Water vapour itself is a very powerful greenhouse gas, so this will act as a positive feedback and roughly double the amount of warming. Similarly, when sea ice begins to melt, some of the solar radiation which would otherwise be reflected from the sea ice is absorbed by the ocean, and heats it further; another positive feedback. On the other hand, when carbon dioxide concentrations increase in the atmosphere then it acts to speed up the growth of plants and trees (the fertilisation effect) which in turn absorb more of the carbon dioxide; this acts as a negative feedback. There are many of these feedbacks, both positive and negative, many of which we do not fully understand. This lack of understanding is the main cause of the uncertainty in climate predictions; this applies in particular to changes in clouds which we will return to later.

Following on from the climate change prediction, the impacts of climate change, on socio-economic sectors such as water resources, food supply and flooding, can be calculated. These is usually done by supplying climate change predictions to other, off-line, impacts models, and Hadley Centre data have been used by hundreds of impacts researchers in this way. At the Hadley Centre we are also incorporating some impacts models into the climate model itself, as this has many advantages.



In order to estimate climate change, we have to build a mathematical model of the complete climate system. Firstly, the atmosphere; the way it circulates, the processes that go on in it, such as the formation of clouds and the passage of terrestrial and solar radiation through it. Secondly, the ocean, because there is a constant exchange of heat, momentum and water vapour between the ocean and atmosphere and because in the ocean there are very large currents which act to transport heat and salt. In fact, the ocean does about half the work of the climate system in transporting heat between the equator and the poles. Thirdly, the land, because it affects the flow of air over it, and is important in the hydrological (water) cycle. In addition, we model the cryosphere; ice on land and sea. All of these components of the climate system interact to produce the feedbacks which determine how climate will change in the future.

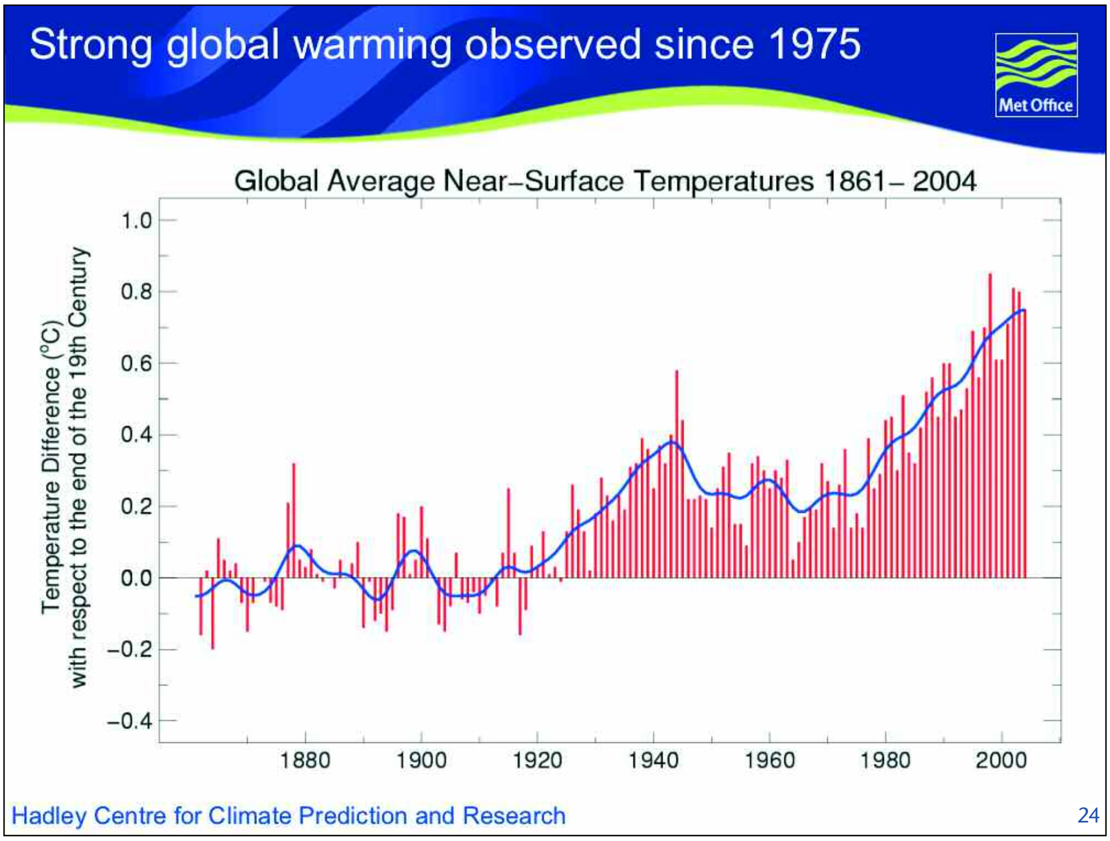


The climate model is a mathematical description of the Earth's climate system, broken into a number of grid boxes and levels in the atmosphere, ocean and land, as shown above. At each of these grid points in the atmosphere (for example) equations are solved which describe the large-scale balances of momentum, heat and moisture. Similar equations are solved for the ocean. The atmospheric part of the third Hadley Centre coupled ocean-atmosphere climate model, HadCM3 — many results from which are shown in this presentation — has a grid of 2.5° latitude x 3.75° longitude, and has 19 vertical levels. The ocean model has 20 vertical levels and a grid size of 1.25° latitude x 1.25° longitude. In all, there are about a million grid points in the model. At each of these grid points equations are solved every half hour of model time throughout a model experiment which may last 250 or, in some cases, 1,000 years.

The Met Office currently uses a NEC SX-6/SX-8 supercomputer. The HadCM3 model is run typically for 250 years of simulation (1850–2100) taking about three months' clock time on one SX-6 node. Several simulations can be run at the same time. Currently, some 300 terabytes (million million bytes) of data are stored for future analysis. This is expected to double each year.

The Hadley Centre has just completed development of its new climate model, known as the Hadley Global Environment Model (HadGEM1). As can be seen above, this has a higher resolution horizontally and vertically, on land and over the oceans. It also incorporates improvements to the representation of the dynamics of the atmosphere, and of many processes in the atmosphere and oceans. Because of this, it is about 15 times more expensive to run than HadCM3. Results from this will be included in the IPCC Fourth Assessment Report (4AR).

Further reading: Gordon C. et al. The simulation of SST, sea-ice extents and ocean heat transports in a version of the Hadley Centre model without flux adjustments. Clim. Dyn., 16, 147–168, 2000.
Pope V.D. et al, The impact of new physical parametrisations in the Hadley Centre climate model, HadAM3. Clim. Dyn., 16, 123–146, 2000.
Johns, T.C. et al, The new Hadley Centre climate model, HadGEM1: Evaluation of coupled simulations in comparison to previous models. J. Clim. (submitted).



This graph shows the change in global average surface temperature from 1861 (when sufficient observations were made to form a meaningful global average) to 2004. The individual annual averages are shown by red bars, and the blue line shows a smoothed trend*, with changes shown relative to temperatures over the last decades of the 19th century. The observations combine those of near-surface air temperatures with those of sea-surface temperatures. Updates to this graph can be seen at the Met Office Hadley Centre website:

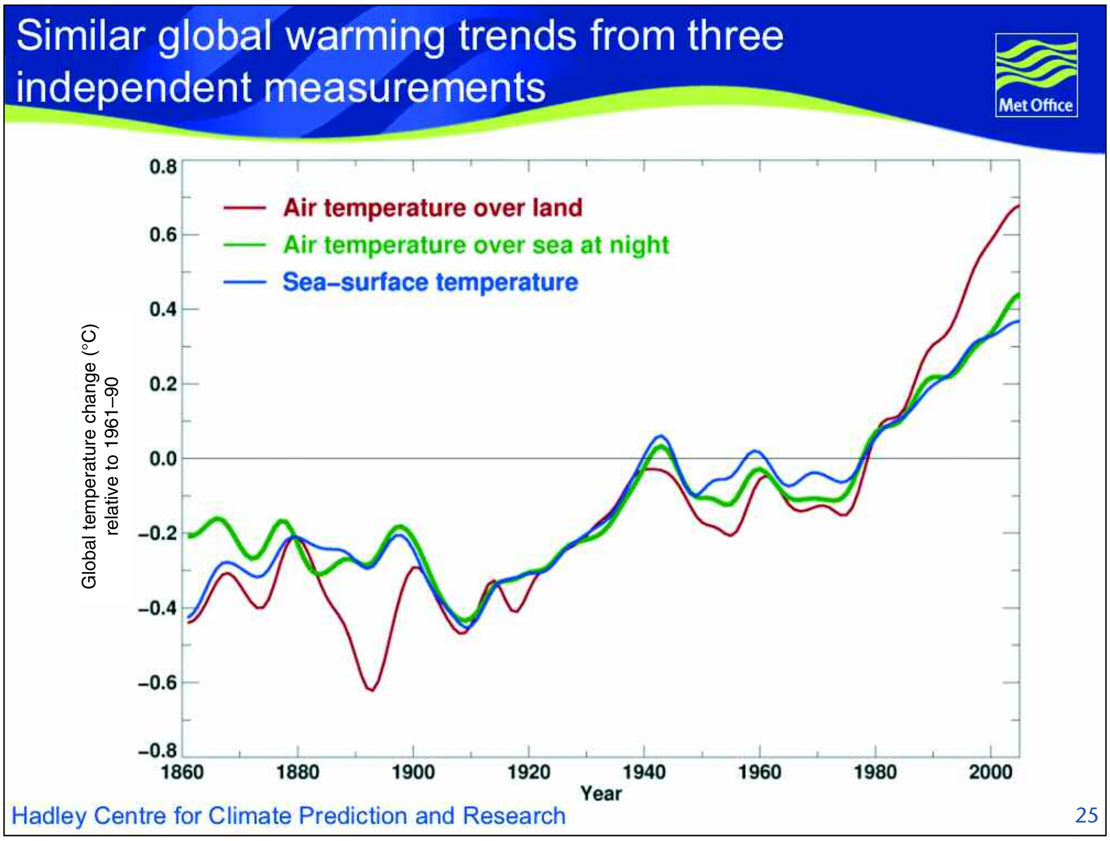
http://www.metoffice.gov.uk/research/hadleycentre/obsdata/globaltemperature.html

This time series has been used in all the reports of the Intergovernmental Panel on Climate Change (IPCC); it is a joint effort between the Met Office's Hadley Centre and the University of East Anglia's Climate Research Unit.

Although there is a considerable year-to-year variability in annual-mean global temperature, an upward trend can be clearly seen; firstly over the period from about 1920–1940, with little change or a small cooling from 1940–1975, followed by a sustained rise over the last three decades since then.

1998 was the warmest year in this time series, followed by 2002, 2003 and 2004. All of the 'top-ten' years have been since 1990, and all the 'top-twenty' warmest years have been since 1981, with the exception of one (1944).

** The smoothing is done with a 21-year binomial filter, to suppress variations on timescales less than about a decade.*
Reference: Jones, P.D. et al, Adjusting for sampling density in grid box land and ocean surface temperature time series. J. Geophys. Res. 106, 3371–3380, 2001.



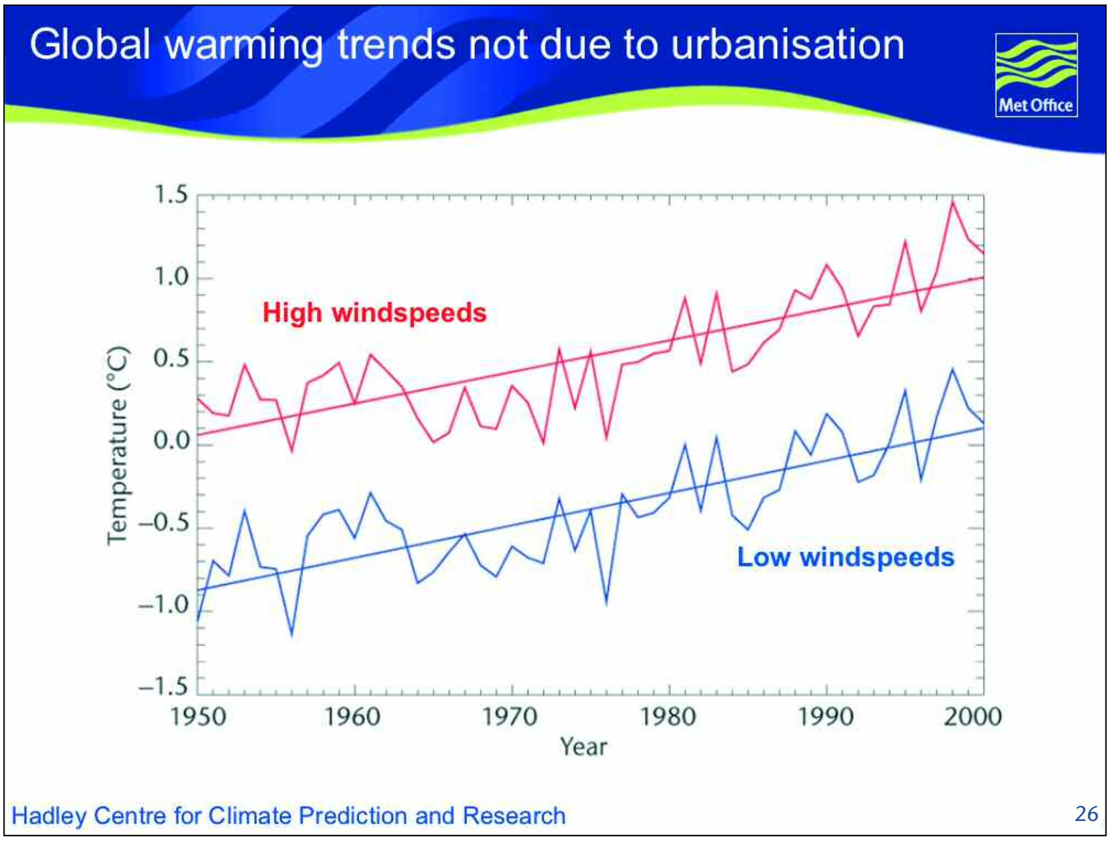
The global average temperature measurements shown in the previous diagram are taken from thousands of weather stations all across the globe on land, from ships at sea, buoys and, more recently, satellites. They represent a substantial effort on the part of national meteorological services worldwide. They are corrected to minimise any errors due to changes in measurement practices, and for artefacts which may result from changes in the nature of observing stations (urbanisation, for example).

Shown in this slide are three independent measurements of global mean temperature; sea-surface temperature, the air temperature over the land surface and the air temperature over the sea. For most of the time, they agree with each other reasonably well, which shows that this temperature rise is real. As can also be seen, warming since the 1970s has been more rapid over land than over the oceans, as would be expected from an increasing man-made greenhouse effect.

The amount of warming observed varies considerably from place to place, because natural variability of climate can add to man-made warming in some places, or subtract from it in others. Local factors (such as aerosol cooling) may also come into play.

That the Earth's surface has experienced a recent warming is also supported by the widespread recession of mountain glaciers over the last few decades, and by measurements made at different depths in boreholes, which can be used to estimate the historical rise in temperature.

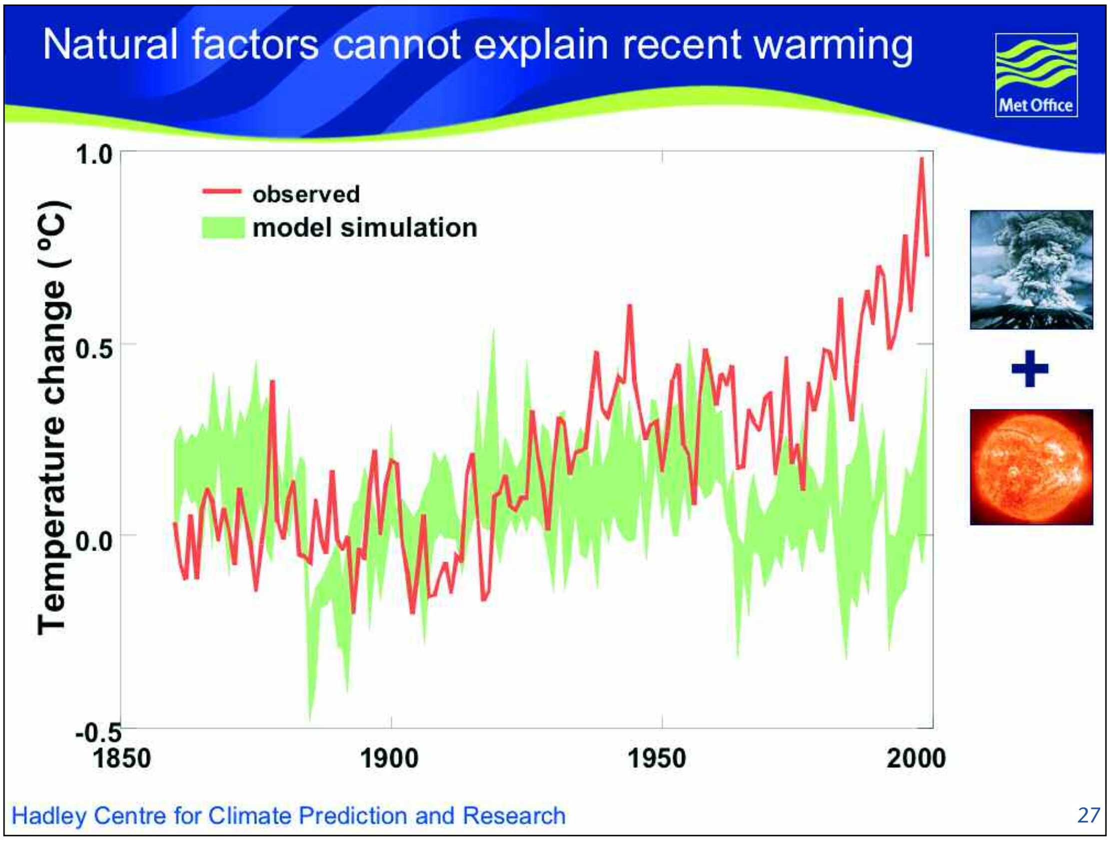
References: Jones, P.D. and Moberg, A. Hemispheric and large-scale surface air temperature variations: an extensive revision and update to 2001. J.Clim., 16, 206–223, 2003.
Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent and A. Kaplan, Global analyses of sea surface temperature, sea ice, and night marine temperature since the late nineteenth century. J. Geophys. Res. 108 (D14), 4407, 2003.



Despite the careful corrections that are made to temperature observations to account for urbanisation, concerns still remain that part of the rise in land temperatures seen over past decades is due to changes in or around observing sites; for example, where a town is creeping out towards a previously rural area where the climate observation is made. We know that the climate of an urban station differs greatly from the surrounding countryside; the so-called urban heat island (UHI) effect. In the night, temperatures do not fall as quickly in cites, as the mass of concrete helps to retain heat, and city surfaces cannot radiate heat away as fast as in the country.

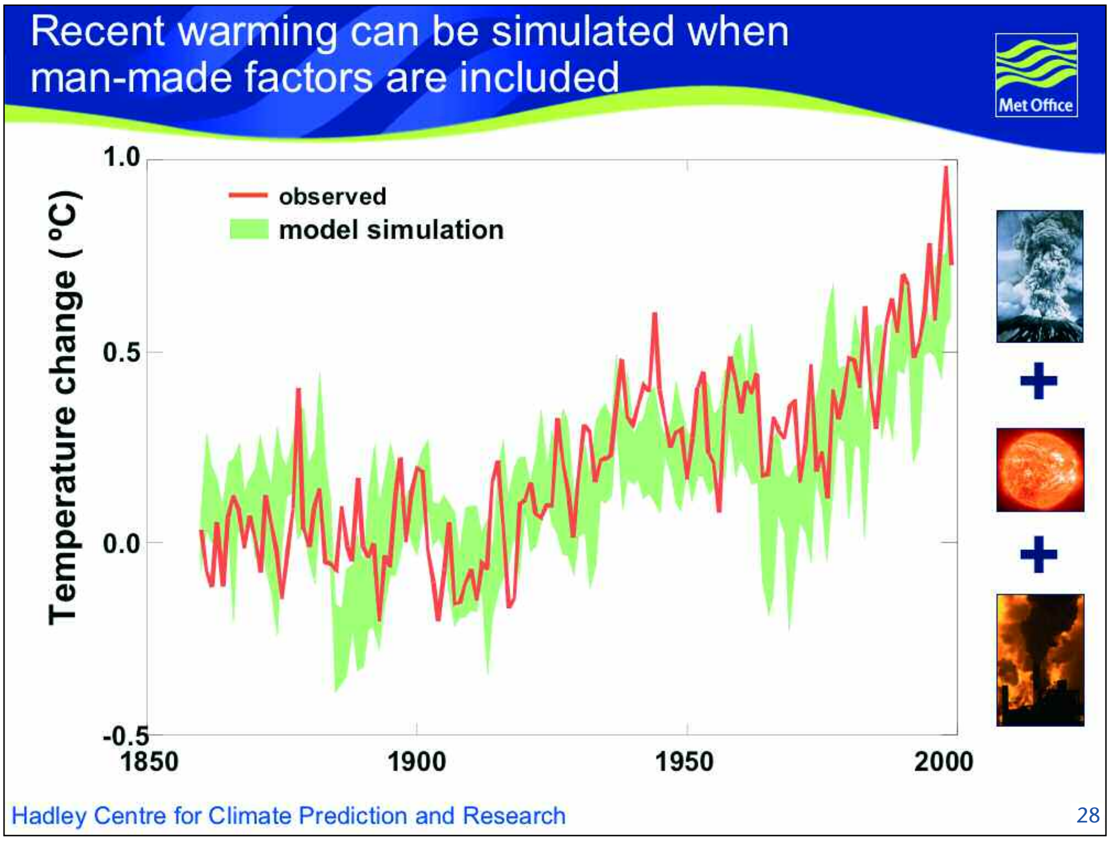
The UHI effect is weakened or destroyed when there is a strong wind. So if the recently observed warming is an artefact of urbanisation, then one might expect the temperature rise on calm nights to show this increasing urbanisation and, hence, to be more rapid than that on windy nights. Recent Hadley Centre work* has used daily night-time minimum temperature measurements at more than 250 land stations over most of the world, during the period 1950–2000. Data were taken for the top third most windy nights and the bottom third least windy nights (that is, the most calm conditions). Trends for these two subsets are plotted in the slide. Although, as expected, minimum temperatures in windy conditions are somewhat higher, the trend is the same in windy and calmer conditions. This clearly demonstrates that warming over the past 50 years has not been due to urbanisation.

Parker, D.E., Large scale warming is not urban. Nature, 432, 290, 2004.



What are the causes of changes in global mean temperature observed since the early 1900s, shown in red on this slide? As we have already outlined, natural factors include a chaotic variability of climate due largely to interactions between atmosphere and ocean; changes in the output of the Sun and changes in the optical depth of the atmosphere from volcanic emissions.

The Hadley Centre climate model has been driven by changes in all these natural factors, and it simulates changes in global temperature shown by the green band in the slide above. This clearly does not agree with observations, particularly in the period since about 1970 when observed temperatures have risen by about 0.5 °C, but those simulated from natural factors have hardly changed at all.

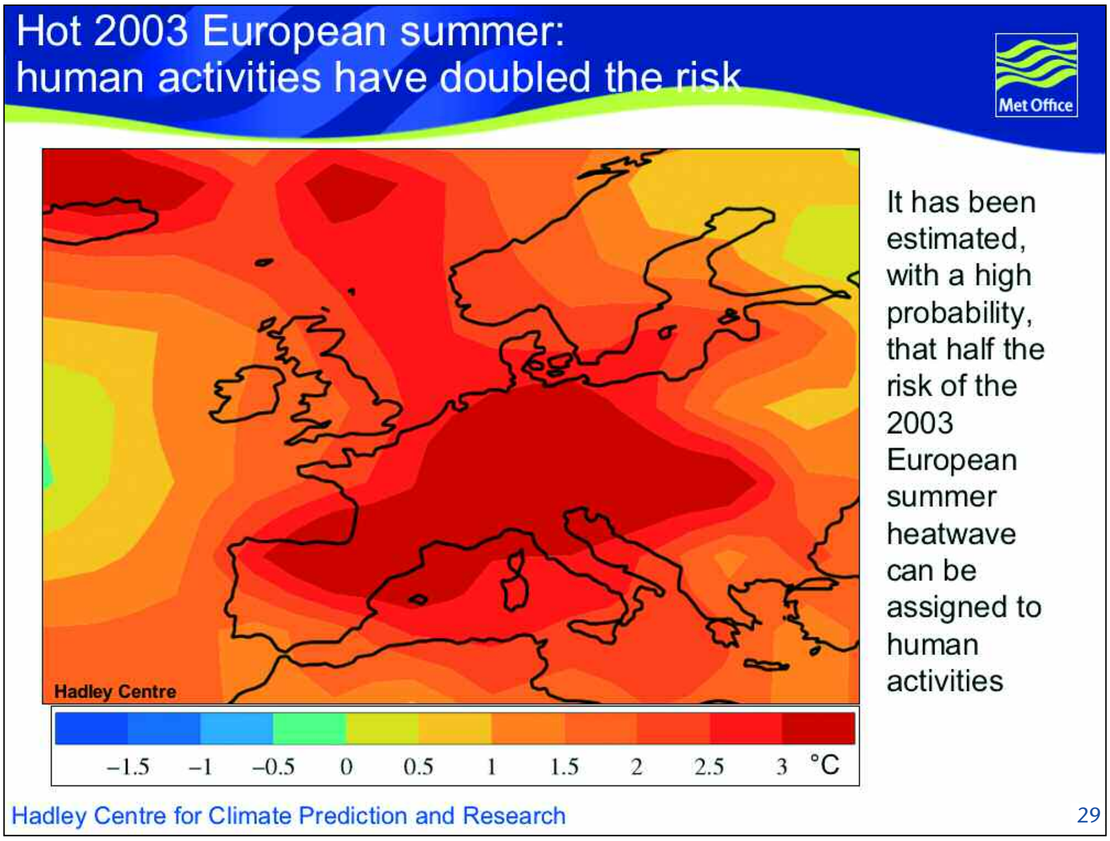


If the climate model is now driven by changes in human-made factors — changes in greenhouse gas concentrations and sulphate particles — in addition to natural factors, observations (red) and model simulation (green) are in much better agreement. In particular, the warming since about 1970 is clearly simulated. Of course, this agreement may, to some extent, be fortuitous, for example, if the heating effect of man-made greenhouse gases and the cooling effect of man-made aerosols have been overestimated. Nevertheless, the ability to simulate recent warming only when human activities are taken into account is a powerful argument for the influence of man on climate. Since this initial Hadley Centre experiment*, other modelling centres have been able to reproduce the same broad conclusion.

In addition to simulating the global mean temperature, the model also simulates the pattern of changes in temperature, across the surface of the Earth and through the depth of the atmosphere. These 'fingerprints of man-made warming' have been compared to observations, providing even stronger evidence for the majority of the long-term trend over the last 50 years having been due to human activity.

Further work at the Hadley Centre** and elsewhere*** has recently demonstrated that warming over individual continental areas in the last few decades can only be explained if human activities are included.

** Stott, P.A., S.F.B. Tett, G.S. Jones, M.R. Allen, J.F.B. Mitchell and G.J. Jenkins. External control of twentieth century temperature variations by natural and anthropogenic forcings. Science, 15, 2133–2137, 2000.*
*** Stott P.A., Attribution of regional scale temperature changes to anthropogenic and natural causes. Geophys. Res. Lett., 30 (14), CLM 2.1 to 2.4. 2003.*
**** Karoly, D.J., K. Braganza, P.A. Stott, J. Arblaster, G. Meehl, A. Broccoli and K.W. Dixon. Detection of a human influence on North American climate. Science, 302, 1200–1203, 2003.*

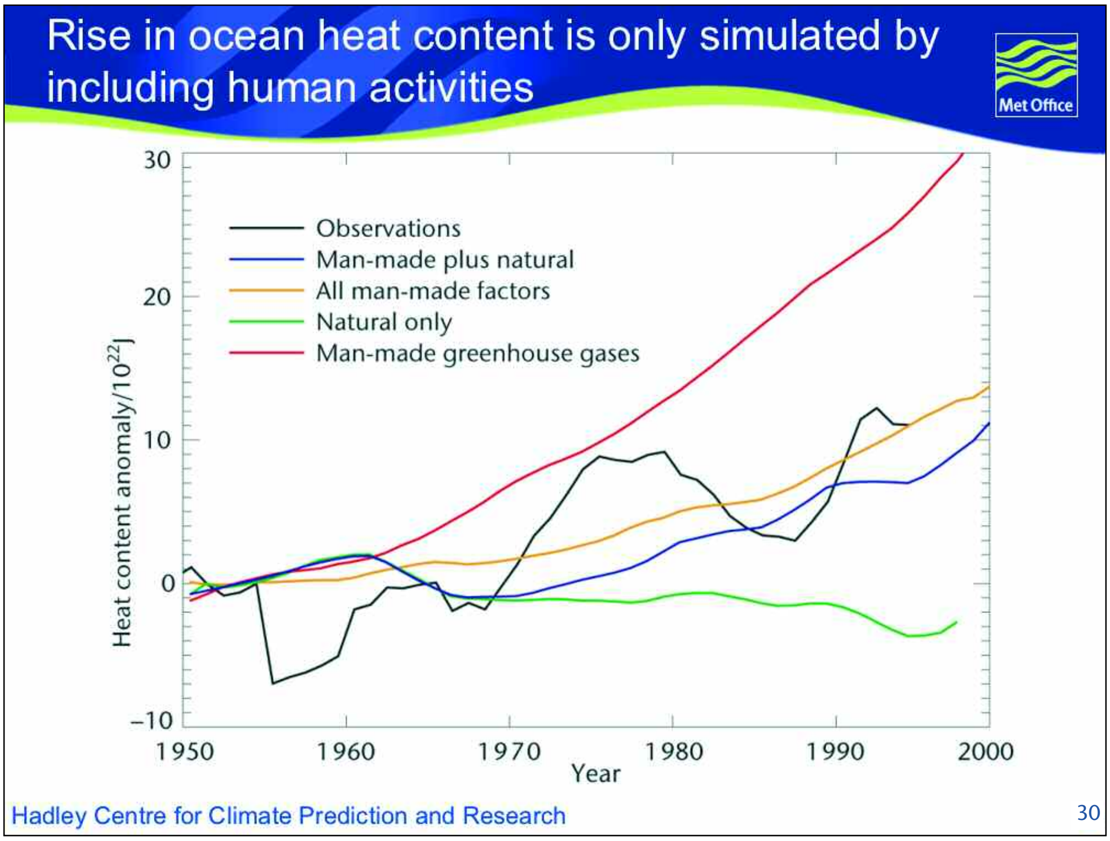


In addition to the attribution of changes on a global and continental scale, we can also examine the influence of man on specific weather events.

The summer of 2003 was an unusually warm one over large parts of the continent of Europe. The map shows a temperature anomaly of three degrees or more compared to the late 19th century over large parts of Europe in August 2003. The warm summer caused great losses in agricultural productivity in southern Europe, and during the hottest days there were some 20,000 excess deaths in urban areas such as Paris. Some of the main impacts are discussed in Ciais et al (2005).

Using a combination of observations and modelling, recent Hadley Centre/Oxford University research* estimates with high probability that the risk of such anomalously high European temperatures has already doubled due to the effects of human activities such as CO_2 from fossil-fuel burning.

** Stott, P.A., D.A. Stone and M.R. Allen, Human contribution to the European heatwave of 2003. Nature, 432, 610–614, 2004.*
Ref. Ciais, P.H. et al, Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533 (2005).

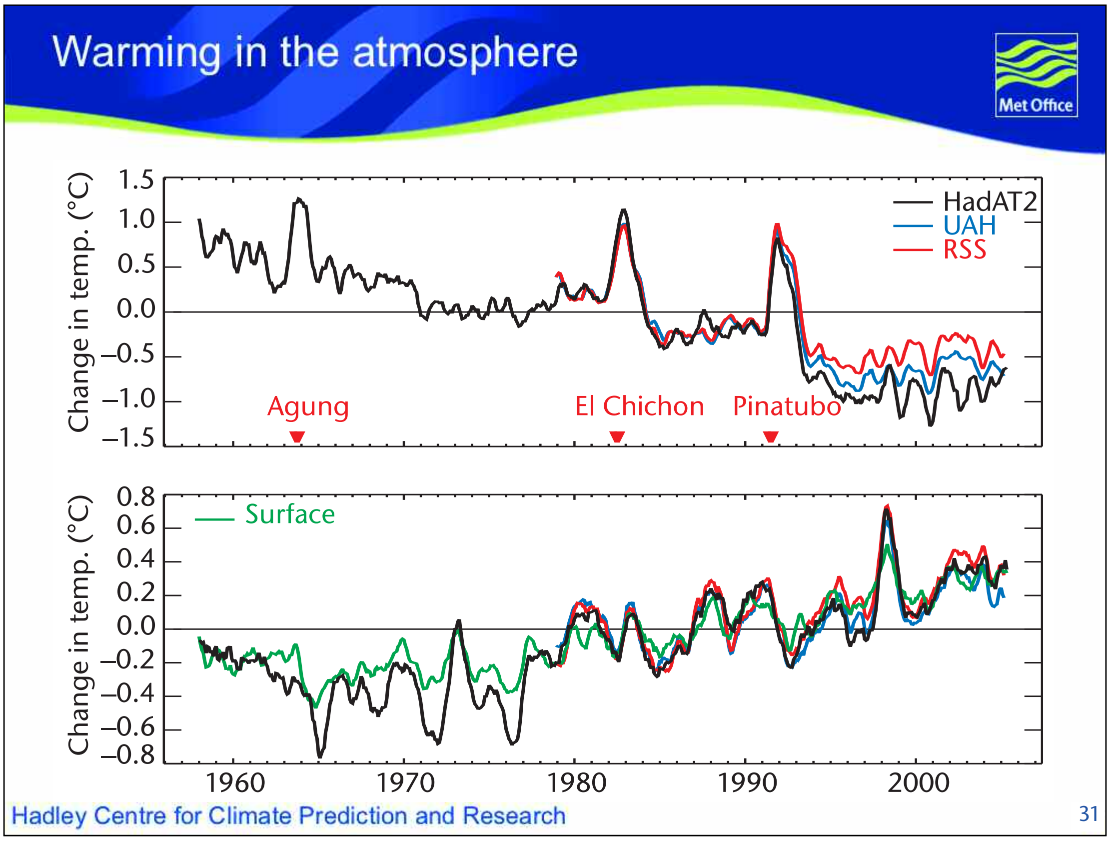


In Slide 25 we showed how sea-surface temperatures have risen, but at a slower rate than temperatures over land areas, in the last 50 years. When the atmosphere is warmed by the greenhouse effect due to man's activities, this warmth is then transferred to the sea surface by interaction between the sea and the air above, and thus sea-surface temperatures also rise. But the constant vertical mixing of the ocean waters transfers this heat deeper and deeper into the ocean, and dilutes the warming at the surface. To understand fully changes to the ocean we need to look at how the amount of heat contained in the whole ocean has changed. This was first estimated by the US National Oceanographic and Atmospheric Administration*, and is shown in the black line above.

The Hadley Centre model has been used to try to simulate these observations, and the results** are also shown in the same figure. Estimates of how the heat content of the ocean would have changed if only natural factors were responsible results in the green line above; this is obviously unable to mimic the observations. The estimate of heat content trends using only man-made greenhouse gases (red line) gives a trend in heat content which is too great. However, estimates from man-made gas plus aerosol emissions (yellow), or all factors (man-made and natural, blue) give a much better agreement with observations, implying that human activities must be largely to blame. The large decadal variability shown in the observations cannot be simulated by the models; it may have something to do with the limited number of observations of ocean heat content.

More recent research, undertaken jointly by the Hadley Centre and US scientists, has shown that models reproduce the penetration of heat into the various ocean basins over the last 50 years remarkably well. Again, this agreement with observations can only be achieved when model simulations include emissions from man's activities. This work shows that the observed warming of the world's oceans, which has a complex structure which varies from ocean to ocean, is largely of human origin.

** Levitus, S., J.I. Antonov, T.P. Boyer and C. Stephens. Warming of the world ocean, Science, 287, 2225–2229 (2000).*
*** Gregory, J.M., H.T. Banks, P.A. Stott, J.A. Lowe and M.D. Palmer. Simulated and observed decadal variability in ocean heat content. Geophys. Res. Lett. 31, L15312, 2004.*

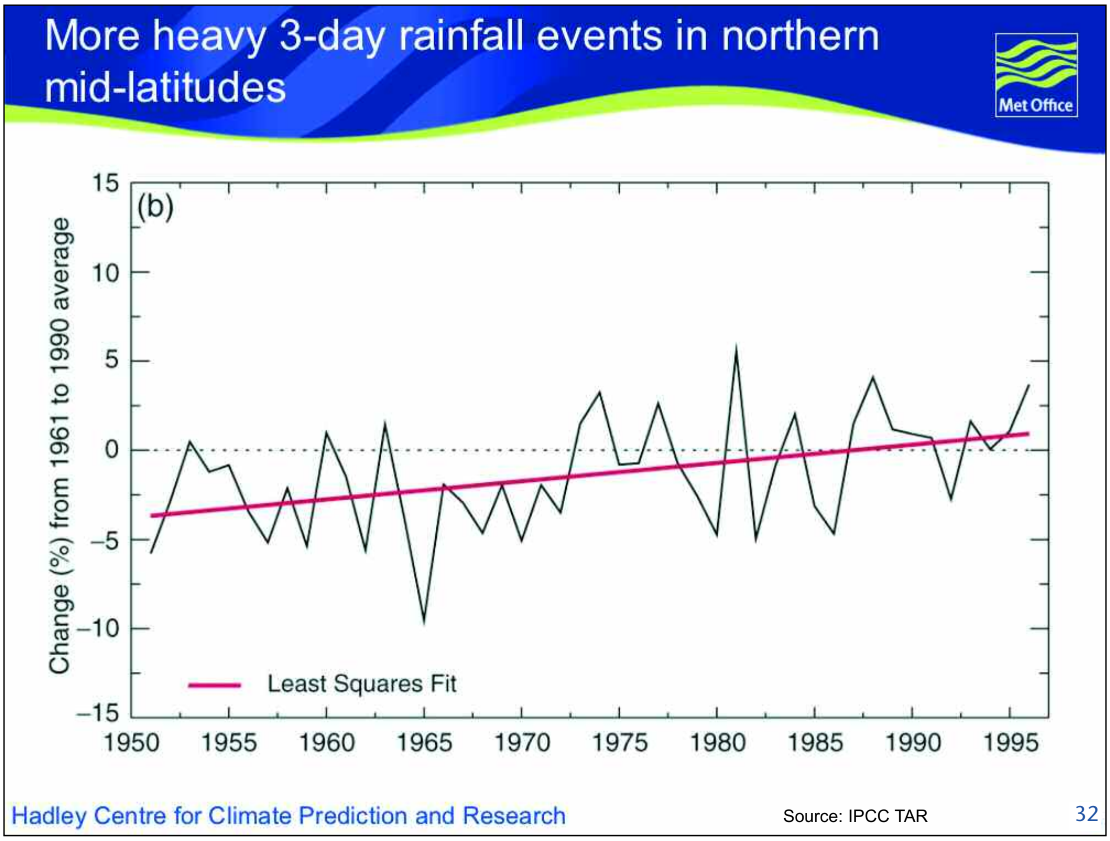


Temperatures are routinely measured not only at the Earth's surface and in the oceans, but in the atmosphere too. The two panels above show changes in temperatures in the lower stratosphere (roughly 12 km–18 km) and the lower troposphere (from the surface to roughly 7 km), relative to the period 1981–1990. Atmospheric temperatures are measured using two very different techniques: firstly using thermometers carried aloft on routine weather balloons (radiosondes) and, secondly, since 1978, by remote sensing from a Microwave Sounding Unit (MSU) carried on a series of satellites. Measurements from both techniques are subject to corrections and different methods of analysis The radiosonde data above (black) is from the Hadley Centre analysis known as HadAT2. Two different analyses of the MSU satellite data are shown, one (blue) from the University of Alabama at Huntsville (UAH, shown courtesy of John Christy, available at www.nsstc.uah.edu/public/msu) and one (red) from Remote Sensing Systems (RSS, shown courtesy Carl Mears, available at www.remss.com).

The stratosphere (top panel) has cooled on average by about 1.5 °C since the late 1950s. This arises from several causes. Firstly, CO_2 does not warm the stratosphere as it does the troposphere; instead it radiates away heat to outer Space and cools it. Thus, increases in CO_2 will have led to a greater cooling influence. Secondly, ozone in the stratosphere is heated by solar radiation and raises the temperature there; because stratospheric ozone has decreased (due to man-made CFCs) this will also act to cool the stratosphere. Lastly, some cooling is suspected to be due to increased concentrations of water vapour in the lower stratosphere, which radiates away heat in the same way as CO_2. The long-term cooling trend has been punctuated by spikes where aerosol from volcanoes Agung, El Chichon and Pinatubo absorbed solar radiation and thus produced strong stratospheric warming for two or three years.

The lower panel shows the change in global-average lower tropospheric temperature measured by radiosondes and satellite. Also shown in green is the change in global surface temperature. It can be seen that, since 1978, the longer term trend and the variability of two of the three measurements of tropospheric temperature agree well, and also agree with the surface observations. The alternative (UAH) analysis of satellite data shows substantially less warming than at the surface. Climate models predict that we should have seen a relatively greater warming in the troposphere than at the surface; this potential discrepancy between models and observations is not well understood, although uncertainty in observations is the more likely explanation. The topic of stratospheric and tropospheric temperature measurements is currently undergoing a thorough review* in the US, with the involvement of Hadley Centre staff. The conclusions are due out in early 2006.

** Karl, T.R., S. Hassol, C.D. Miller and W.L. Murray (eds), Temperature trends in the lower atmosphere: steps for understanding and reconciling differences. A report by the Climate Change Science Programme and the Subcommittee on Global Change Research, Washington, DC. (in draft).*



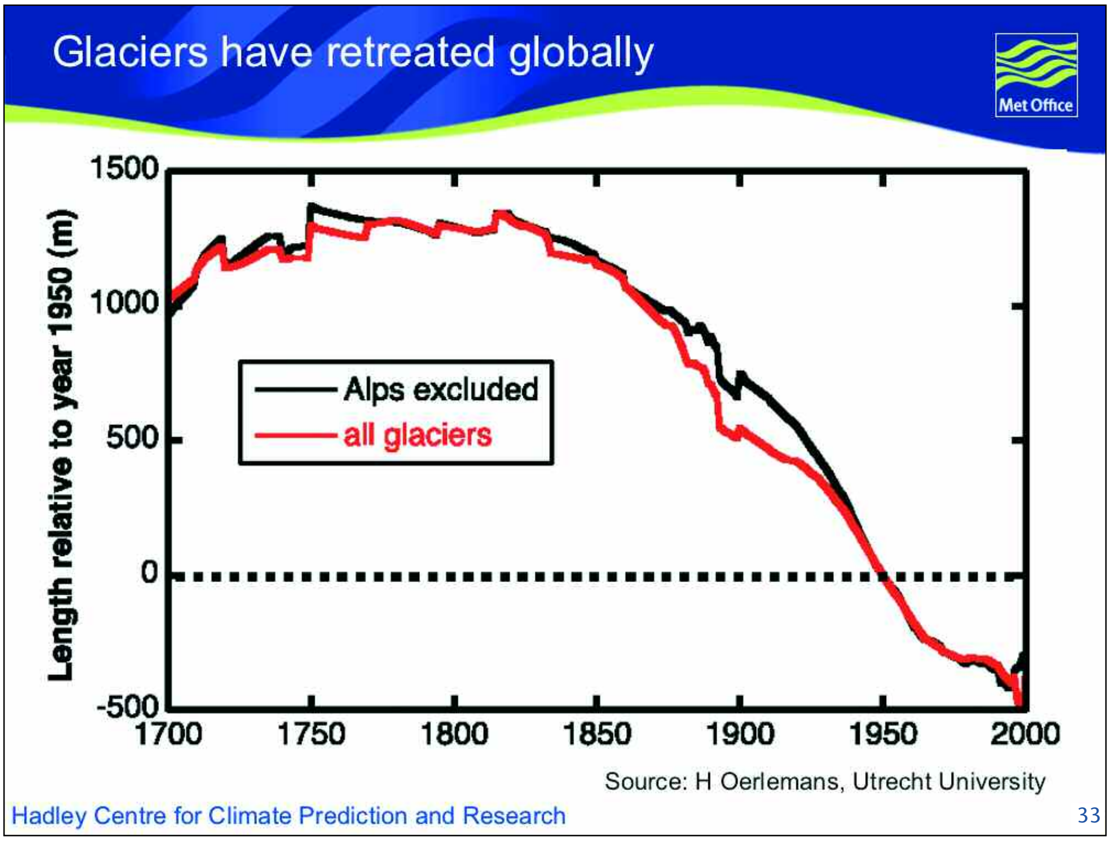
Global temperature is not the only climate indicator to have changed substantially over the last few decades. Here we show the change in maximum annual 5-day rainfall events, an important driver of flooding. The red line shows the least squares fit, which is statistically significant to 5%.

There have also been changes to the distribution of atmospheric surface pressure (as measured by barometers), with reductions in the high latitudes of both hemispheres, and increases at middle latitudes. This has affected weather patterns, and regional rainfall and temperature in both hemispheres in middle and higher latitudes.

Man-made climate change is expected to intensify the water cycle, with consequent increased rainfall at higher latitudes. This is observed in the northern hemisphere winter half year, and supporting indications come from the increasing amount of outflow from Eurasian rivers into the Arctic Seas. Recent Hadley Centre work* shows that this trend in outflow cannot be simulated with a climate model if only natural factors are included, but can be simulated well when human activities are taken into account.

* Wu P., R. Wood and P. Stott. Human influence on increasing Arctic river discharges, Geophys. Res. Lett., L02703, 2005.

Further reading: IPCC TAR Chapter 2, Section 7.

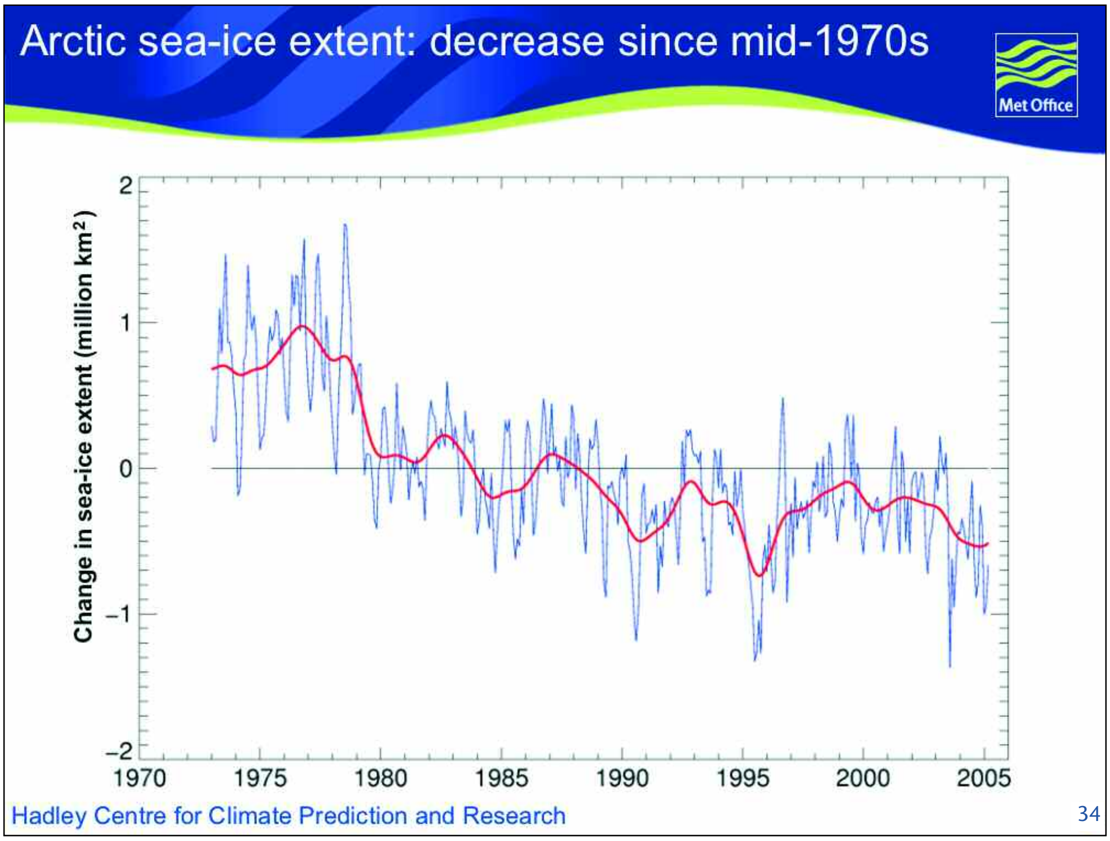


The IPCC Third Assessment Report commented that there is now ample evidence to support a major retreat of alpine and continental glaciers in response to 20th century warming. In a few maritime regions, increases in precipitation due to regional atmospheric circulation changes have overshadowed the effect of increases in temperature in the past two decades, and glaciers have re-advanced.

Other changes to snow and land ice have been observed. IPCC reports that there are very likely to have been decreases of 10% or so in the extent of snow cover since the 1960s, and there is very likely to have been a reduction of about two weeks in annual duration of lake and river ice in mid-to-high latitudes of the northern hemisphere over the past 100–150 years.

The figure above shows the cumulative change in length of a number of glaciers, estimated by the University of Utrecht*. For the period from 1900 to 1980, 142 of the 144 glaciers for which adequate information was available decreased in length. For the earlier period 1860–1900, 35 out of 36 glaciers retreated, although the total rate of retreat was not as fast as during the 20th century. Because glaciers take time to react to change in temperature, and because there are fewer accessible measurements after 1980, glacier retreat due to warming observed in the past 15 years is not yet reflected in the curve above.

** Oerlemans, H. Extracting a climate signal from 169 glacier records. Science 308 675–677 (2005).*



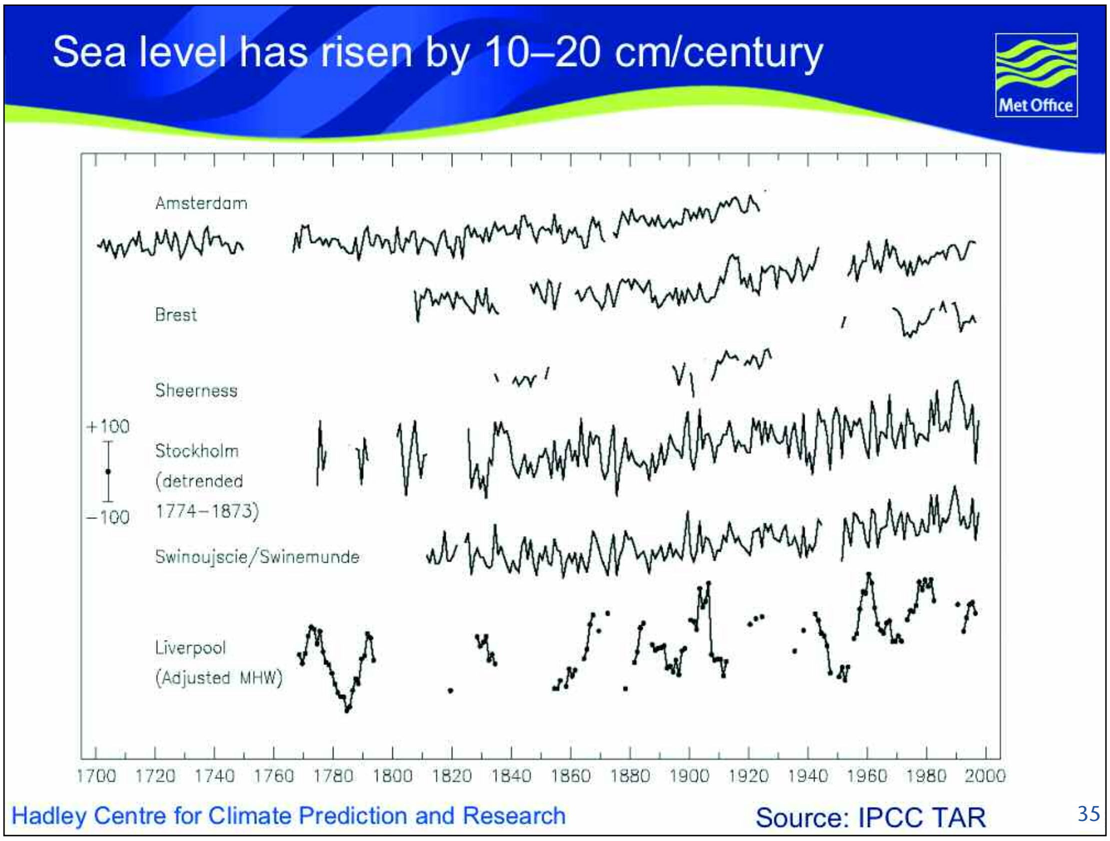
As the oceans warm, it might be expected that sea ice will melt. In the Arctic, after a period of stability from the beginning of the 20th century, there has been a decrease in the sea-ice extent by about 1 million km^2, as shown above*. The blue line is the monthly difference relative to the average for that month for the whole period (1972–2005); the red line is filtered to show longer period changes.**The extent of sea ice is defined as the area within which the concentration of sea ice is greater than 15%.

The decrease of about 2.5% per decade since 1970 is very similar to that simulated by the Hadley Centre climate model. Internal variability of the climate system, and external natural factors (solar and volcanic) are very unlikely to have caused a trend of this size, suggesting that human activities are at least in part responsible. Climate models are able to simulate this decrease well, when they include man-made greenhouse gas emissions as a factor, suggesting that human activities are contributing significantly to this decrease.

There are indications that the thickness of sea ice in the Arctic has also decreased, though trends are more difficult to measure.

In the case of Antarctica, there appears to have been no significant long-term trend in sea-ice extent.

**using a 128 term (128 month) binomial filter.*
***This graph is based on methodology described in: Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent and A. Kaplan, Global analyses of sea surface temperature, sea ice, and night marine temperature since the late nineteenth century. J. Geophys. Res. 108 (D14), 4407, 2003.*



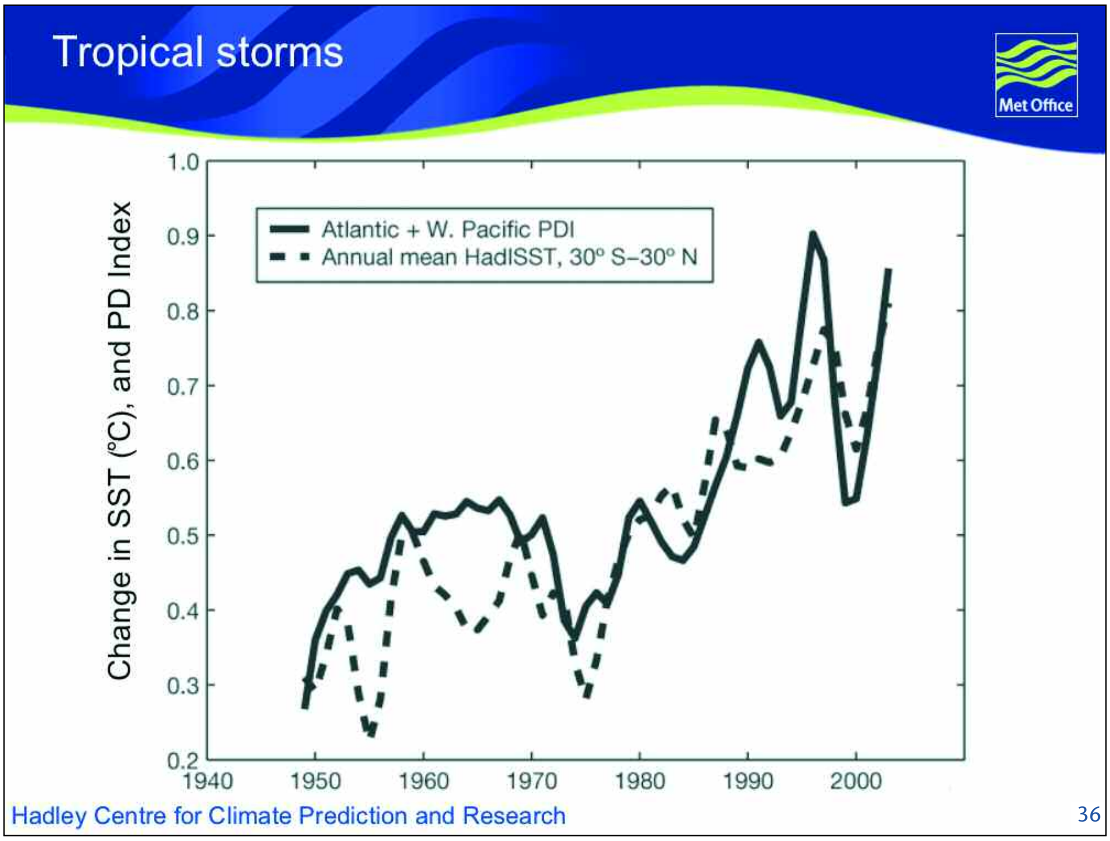
The longest direct measurements of sea level come from tide gauges and, based on their observations, the IPCC TAR estimated that the rate of global mean sea-level rise during the 20th century is in the range 10–20 cm, with a central value (not necessarily the best estimate) of 15 cm. Based on longer period records, the average rate of sea-level rise has been greater during the 20th century than during the 19th century. However, no significant acceleration in this rise has been detected during the 20th century.

Over the last ice age cycle, sea level has ranged from 5 m higher than today's, at the time of the last interglacial about 120 thousand years ago, to 120 m below today's, at the depth of the last ice 21,000 years ago when glaciers were at their maximum extent.

Models best simulate the rise over the last century when they take into account natural and man-made forcing. Even then, the simulated rate is significantly less than that observed, suggesting that predictions in the future may also be underestimated.

The figure above shows relative sea level for the past 2–300 years from stations in Northern Europe. The scale bar on the left indicates a relative change of ±100 mm (10 cm). Satellite measurements over the past decade indicate a rise of 2.5 mm/year in the global mean, but with large regional variations. For example, the East Pacific shows a fall in sea level over that period, with other areas showing a rise of twice the global mean.

Further reading: IPCC TAR Chapter 11, Section 3.2.



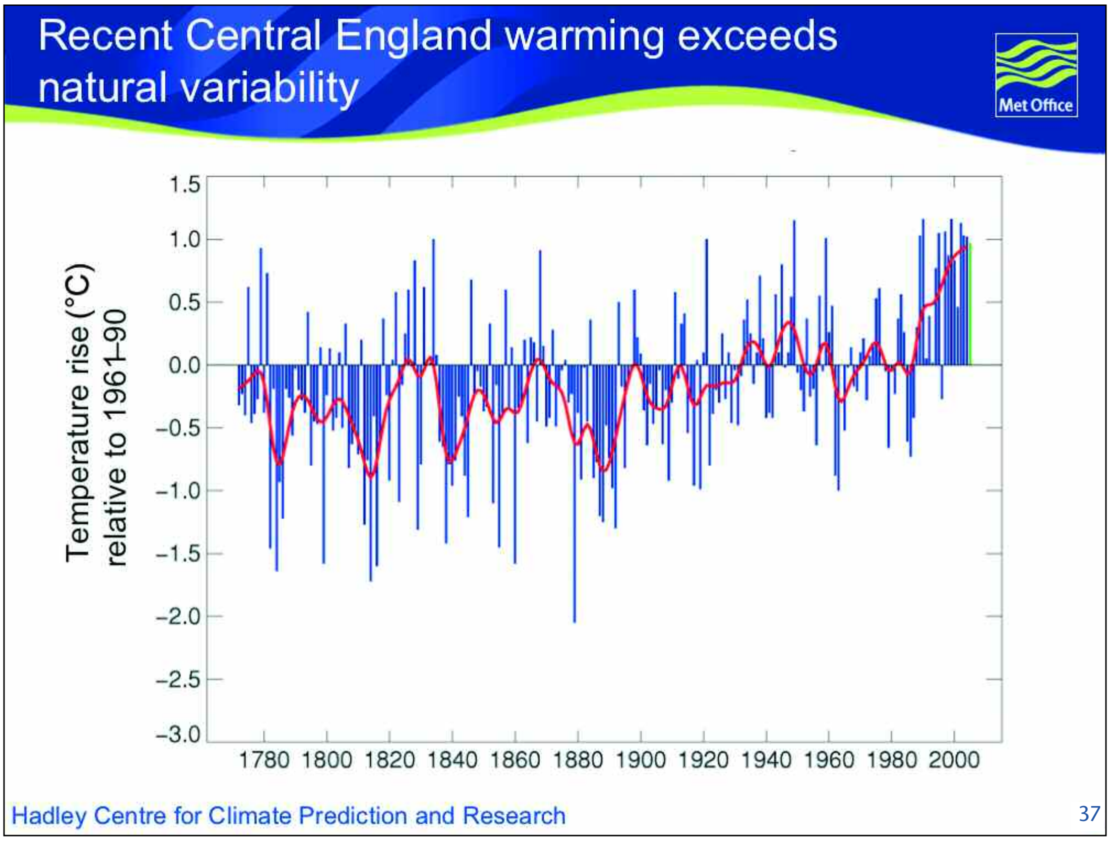
There appears to be no clear trend in the global frequency of tropical cyclones, also known as hurricanes in the North Atlantic and typhoons in the Pacific. However, research at MIT* has shown that the total power dissipated by tropical storms in both these regions, integrated over their lifetimes, has increased markedly since the mid-1970s. This trend is due to both longer storm lifetimes and greater storm intensities, and is highly correlated with change in tropical sea-surface temperatures (SSTs). The figure above* shows smoothed changes in the power dissipated by hurricanes (Power Dissipation Index, PDI) in the western North Pacific and North Atlantic areas, integrated over the lifetime of the storm and over its area, compared to changes in the annual mean sea-surface temperature in the Hadley Centre Sea-Ice and Sea Surface Temperature (HadISST) data set, averaged between 30° S and 30° N. The units of PDI are those of energy, with units multiplied by an arbitrary factor to match the same units as the change in SST, to facilitate the comparison between the two quantities. The power dissipation appears to have nearly doubled over the past 30 years. Based on theoretical considerations, only part of the observed increase in power dissipation is likely to be directly due to changes in SSTs. Other factors which are known to influence development are windshear and the depth of the warm water layer.

A recent survey** has shown that over the last 35 years there had been roughly a doubling of the number of hurricanes in the two most intense categories (known as Saffir-Simpson 4 and 5, having wind speeds over 56 m/s), with the largest increases in the North Pacific, Indian and Southwest Pacific Oceans, and the smallest in the North Atlantic.

In both these papers, relatively short periods of observational records are used. The role of natural cycles of hurricane activity, and the balance between natural and man-made influences in the recent record, are still a matter of debate. In order to attribute recent observed changes to human activity, in the context of substantial natural variability, further research, ideally involving a longer observational record would be required.

There is mounting theoretical and modelling evidence that tropical cyclones will become more intense, although not necessarily more numerous, in a warmer world.

** Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688, 2005.*
*** Webster, P.J., G.J. Holland, J.A. Curry, H-R. Chang. Changes in tropical cyclone number, duration and intensity in a warming environment. Science, 309, 1844–1846, 2005.*



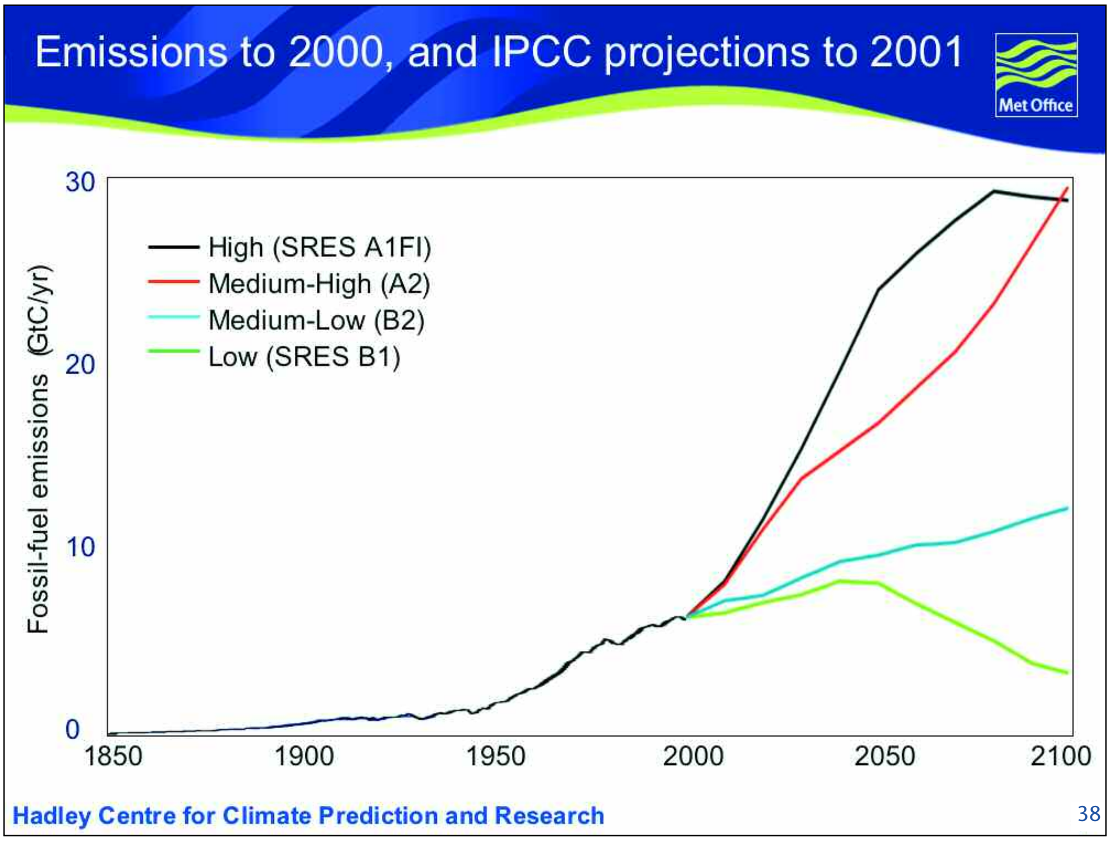
Global temperature rise is the average of individual changes at large numbers of observation stations, so it is not surprising that most of these also exhibit a warming trend. In the UK, the longest running series of temperature observations is from three stations in central England, where daily instrumental data have been recorded continuously since 1772. Yearly averages of Central England Temperature (CET) are shown in the slide in blue, together with a filtered trend in red. The data for 2005 to April are shown in green and the Met Office Hadley Centre website shows an up-to-date graph at:

http://www.metoffice.gov.uk/research/hadleycentre/obsdata/cet.html

The sustained rise of about one degree Celsius in CET since about 1980 is noticeable; due more to an increase in maximum temperatures (about 1.2 °C over the same period) than night minimum temperatures (about 0.7 °C). 1990, 1999, 1949 and 2002 were joint warmest years on record. Temperature averaged over such a small scale as Central England has much more variability than that averaged over the entire globe, as can be seen in the slide, and hence it is not surprising that years further back, such as 1949, were very warm.

Changes in UK rainfall climate have also been evident. The England and Wales Precipitation (EWP) record, reaching back to 1766, shows an increase in winter rainfall and a decrease in summer rainfall. The character of rainfall has also changed, with a trend over the past few decades to a greater proportion of winter rainfall falling in heavy events. Updated graphs of EWP can also be seen at the Met Office Hadley Centre website:

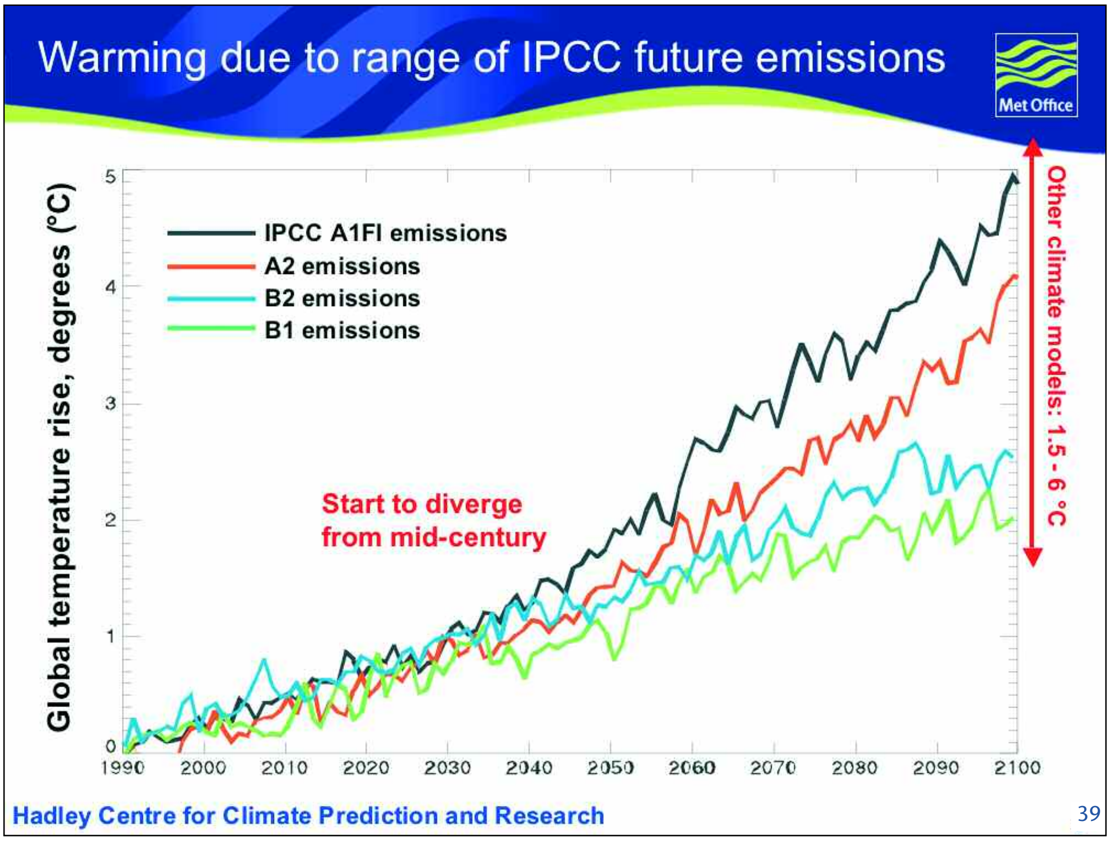
http://www.metoffice.com/research/hadleycentre/obsdata/climateindicators.html#EWPannual



Projections of emissions from human activity of carbon dioxide, other greenhouse gases, and other gases which can affect climate, have been made by the IPCC Special Report on Emissions Scenarios (SRES). There are four main 'marker' scenarios, labelled B1, B2, A2 and A1FI, which can be described (as in the UKCIP02 report) as Low Emissions, Medium-Low Emissions, Medium High Emissions and High Emissions, respectively. Each scenario is based on a 'storyline' of how the world might develop, in terms of population growth, economic growth, energy use, etc. A short summary of the storylines is given in Appendix 5 of the UKCIP02 report.

In this slide, projected emissions of carbon dioxide from fossil fuel burning are shown for the four future emissions scenarios, together with estimated emissions from 1850–2000. Similar data are available for methane, nitrous oxide and other greenhouse gases and their precursors (for example NOx which is a precursor of ozone) and sulphur dioxide, from which sulphate aerosols are formed.

IPCC stress that it is not possible to attach probabilities to each of the scenarios, and neither can they be considered all equiprobable. Work is in hand, however, for example at the US Environment Protection Agency, to develop probabilistic forecasts of emissions.



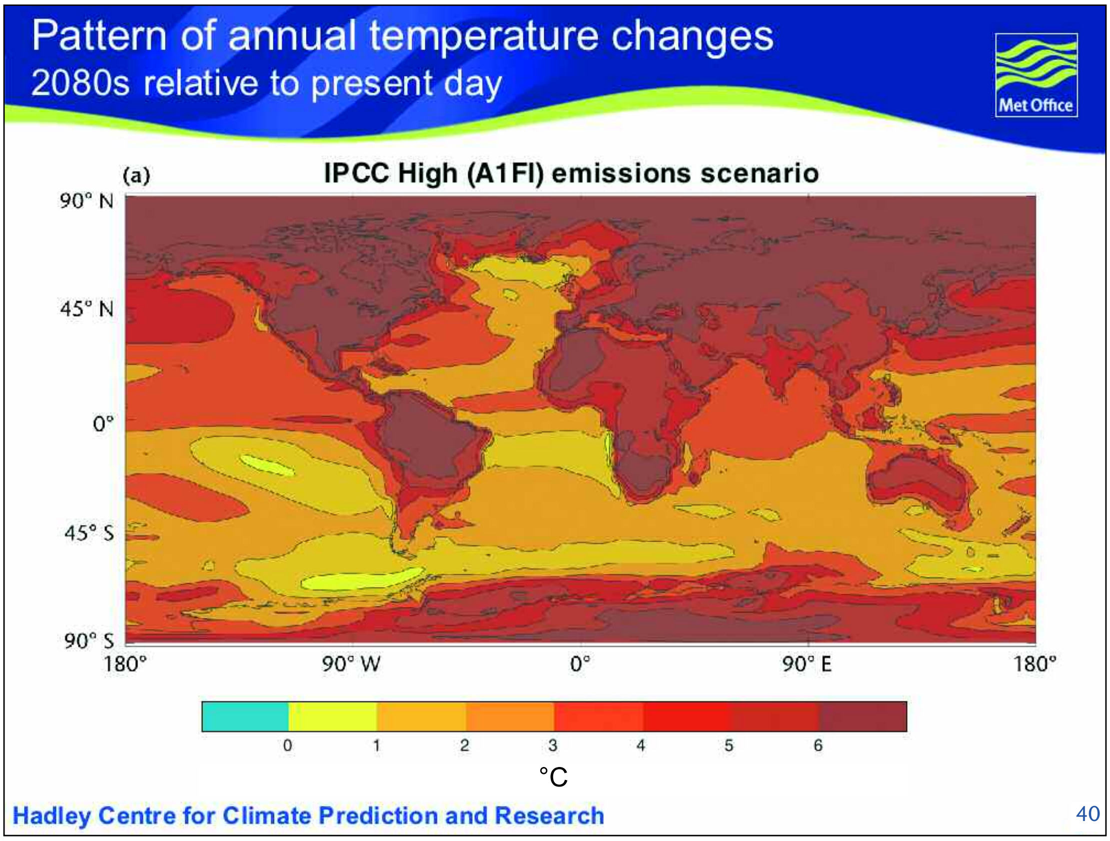
Experiments with the Hadley Centre climate model (HadCM3) have been used to predict climate change arising from each of the four SRES emissions scenarios, and these are shown here. Unsurprisingly, the lowest emissions scenario gives the lowest global-mean temperature rise by 2100, about 2 °C, and the highest emissions scenario gives the greatest warming, about 5 °C. Interestingly, warming over the next three or four decades is similar for each of the emissions scenarios, even though (as can be seen from the previous slide) they diverge sharply after 2000. This partly reflects the long effective lifetime of CO_2 and the large thermal inertia of the climate system. We are committed to much of the rise of the next few decades almost irrespective of emissions over that period. (Part of the reason is that the projections of CO_2 and sulphate aerosol help to offset one another). The other side of this coin is that, if we wish to limit climate change in the second half of the century, then emissions would need to be controlled early in the first half.

These results are from the Hadley Centre model; results from other models can be somewhat different, and this is discussed in the section on uncertainties. The IPCC TAR found that the warming predicted between 2000 and 2100, from the four emissions scenarios and from nine global climate models, ranged from about 1.5 to 6 °C.

Temperatures over land are expected to increase about twice as rapidly as temperatures over the ocean. The warming by 2100 over land areas, where of course we live and work, is predicted by the Hadley Centre model to be in the range 3 °C to 8 °C.

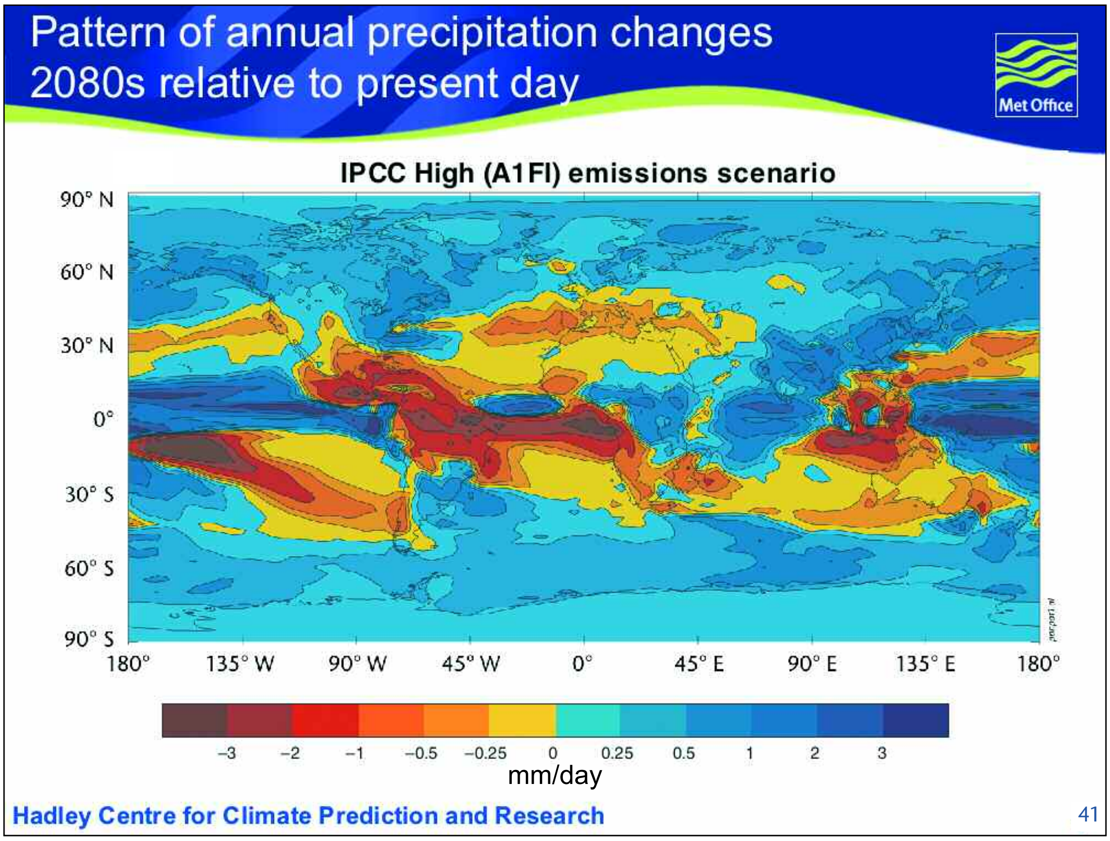
Although the Earth's temperature has varied considerably over the last 1,000 years for natural reasons, the rise over the next 100 years due to human activities is predicted to be very much larger than natural variability, even with the lowest projected man-made emissions.

Reference: T.C. Johns, J.M. Gregory, W.J. Ingram, C.E. Johnson, A. Jones, J.A. Lowe, J.F.B. Mitchell, D.L. Roberts, D.M.H. Sexton, D.S. Stevenson, S.F.B. Tett and M.J. Woodage. Anthropogenic climate change from 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Clim. Dyn. 583–612, 2003.



The climate model predicts not just global-mean temperatures as seen in previous slides, but also the pattern of climate change across the surface of the Earth, and through the depth of the atmosphere and ocean. The above figure shows the rise in temperature of the air near the land surface, and the temperature of the surface of the sea – these are commonly referred to as simply ‘surface temperature’. The change in surface temperature in the northern winter (December–February) averaged over the last 30 years of this century (that is, centred on the 2080s) compared to a recent reference period (1961–1990), assuming emissions follow the SRES High Emissions scenario, is illustrated. Changes in surface temperature range from yellow, where there is very little change, to dark brown, where there is greater warming. It can be seen that land areas are, in general, redder than the ocean areas. This is mainly because as the warming in the atmosphere causes the sea surface to warm, this warmth will be mixed down by turbulence and spread through deeper and deeper layers. This acts to keep temperature rise at the sea surface relatively small compared to that over land. Northern high latitudes, where the disappearance of sea ice acts as a positive feedback, show the greatest warming. On the other hand, there are one or two areas of the oceans which show a minimum in warming, for instance in the southern oceans and in the northern N Atlantic. In these areas there is a rapid exchange of surface water with very deep water; this acts as a heat sink and allows sea-surface temperature to change only slowly.

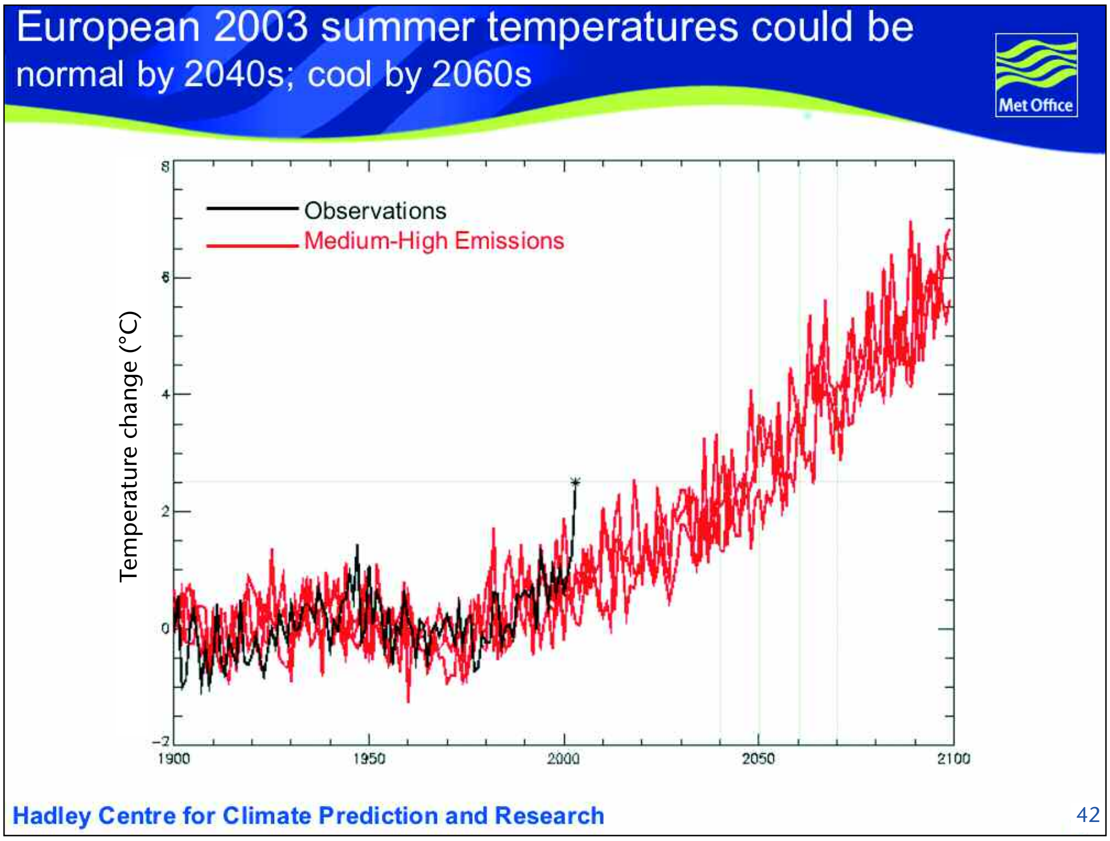
Reference: T.C. Johns, J.M. Gregory, W.J. Ingram, C.E. Johnson, A. Jones, J.A. Lowe, J.F.B. Mitchell, D.L. Roberts, D.M.H. Sexton, D.S. Stevenson, S.F.B. Tett and M.J. Woodage. Anthropogenic climate change from 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Clim. Dyn. 583-612, 2003.



Shown in this slide are predicted changes in precipitation (rainfall and snowfall) under the same High Emissions scenario as the previous slide, and the same season (northern winter) and time frame (2080s). The red areas are those where rainfall is predicted to be smaller and the blue areas where it is predicted to be greater; changes in rainfall are seen to be both positive and negative. Most models find that global average precipitation increases with time, as the hydrological cycle is enhanced by global warming. It changes most in high latitudes and in the Indian monsoon, and changes least in the subtropics. As seen above, the Hadley Centre model predicts substantial changes in rainfall in December-February over northern Brazil, for example.

Confidence in specific areas of rainfall change from climate models is not as great as the confidence in temperature change. Although all the main models see large changes — positive and negative — particularly in the tropical regions, they do not always agree exactly where those changes will be.

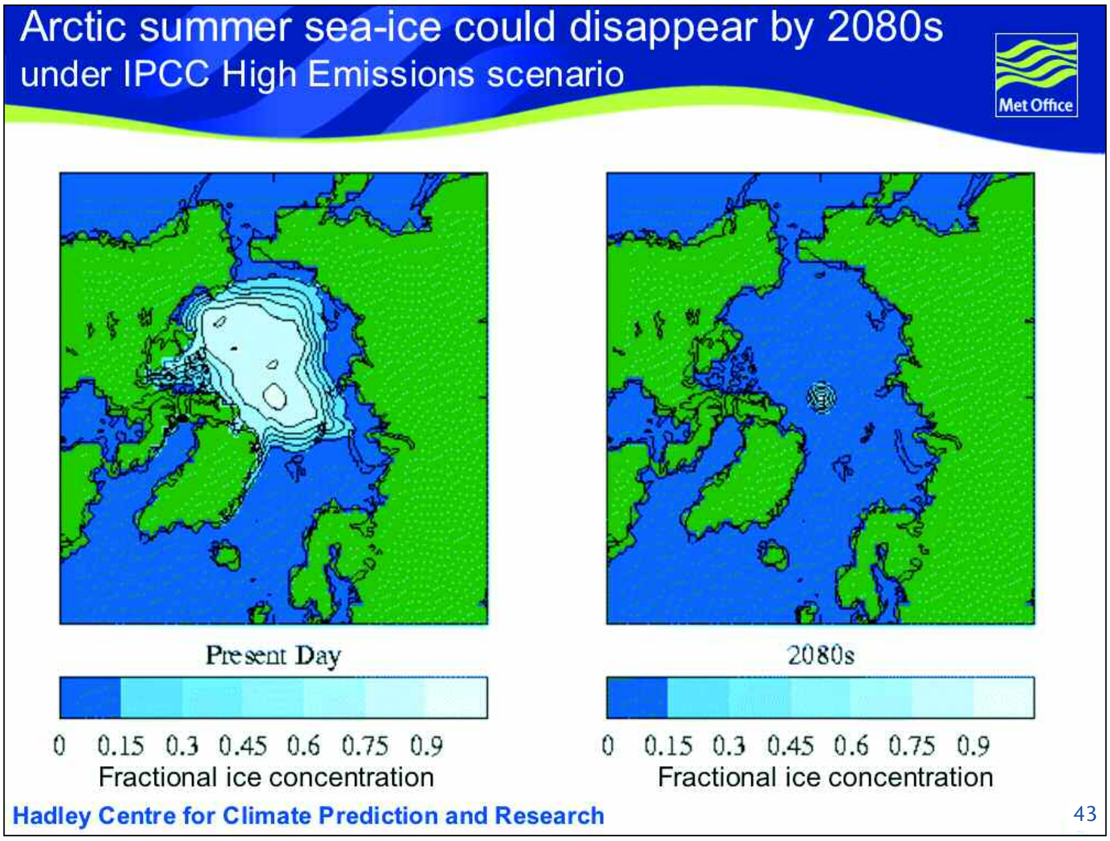
Reference: T.C. Johns, J.M. Gregory, W.J. Ingram, C.E. Johnson, A. Jones, J.A. Lowe, J.F.B. Mitchell, D.L. Roberts, D.M.H. Sexton, D.S. Stevenson, S.F.B. Tett and M.J. Woodage. Anthropogenic climate change from 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Clim. Dyn. 583–612, 2003.



Here, we focus on simulation and prediction (under a Medium High Emissions scenario) of summer warming over southern Europe, using the Hadley Centre model, shown in red. The simulation from 1900 to 2000 agrees well with the observations (black), except for the summer of 2003 (black asterisk) which was much warmer than either the model simulation or the climatic norm (see Slide 29). In the absence of any human modification of climate, temperatures such as those seen in Europe in 2003 are estimated to be a 1-in-1,000 year event. Despite this, it is seen that, by the 2040s, a 2003-type summer is predicted to be about average, and by the 2060s it would typically be the coldest summer of the decade.

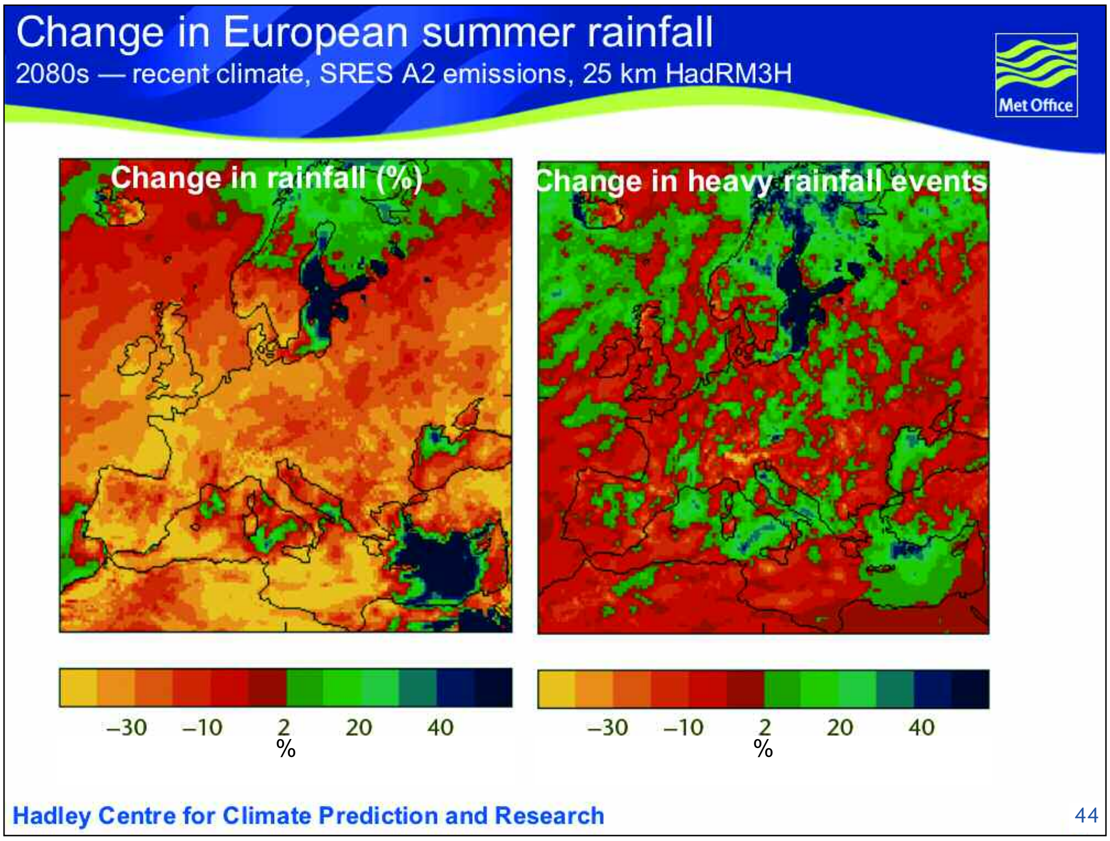
Recent work has demonstrated that hot, 2003-type, European summers would already be being experienced much more frequently (more than once per decade on average) were it not for the cooling effect of man-made sulphate aerosols. Once the shielding effect of these aerosols is removed, the warming commitment from past greenhouse gas emissions will mean that such hot summers are likely to become a regular occurrence, even without any further man-made greenhouse warming.

Reference: Stott, P.A., D.A. Stone and M.R. Allen. Human contribution to the European heatwave of 2003. Nature, 432, 610–614, 2004.



We saw in Slide 34 how the extent of Arctic sea ice has diminished since about the mid-1970s, and how this can only be replicated by models when man-made greenhouse gas emissions are factored into the simulations. Using the same Hadley Centre model, we can predict how Arctic sea ice will change in future. Under the High Emissions scenario we find that ice in the month of September (when it is at its minimum extent in the annual cycle) will have almost completely disappeared on average by the 2080s. Other emissions scenarios lead to a slower reduction in Arctic ice. Reductions are also predicted for other seasons.

Reference: Gregory, J.M., P.A. Stott, D.J. Cresswell, N.A. Rayner, C. Gordon and D.M.H. Sexton. Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. Geophys. Res. Lett, 29, (2002).

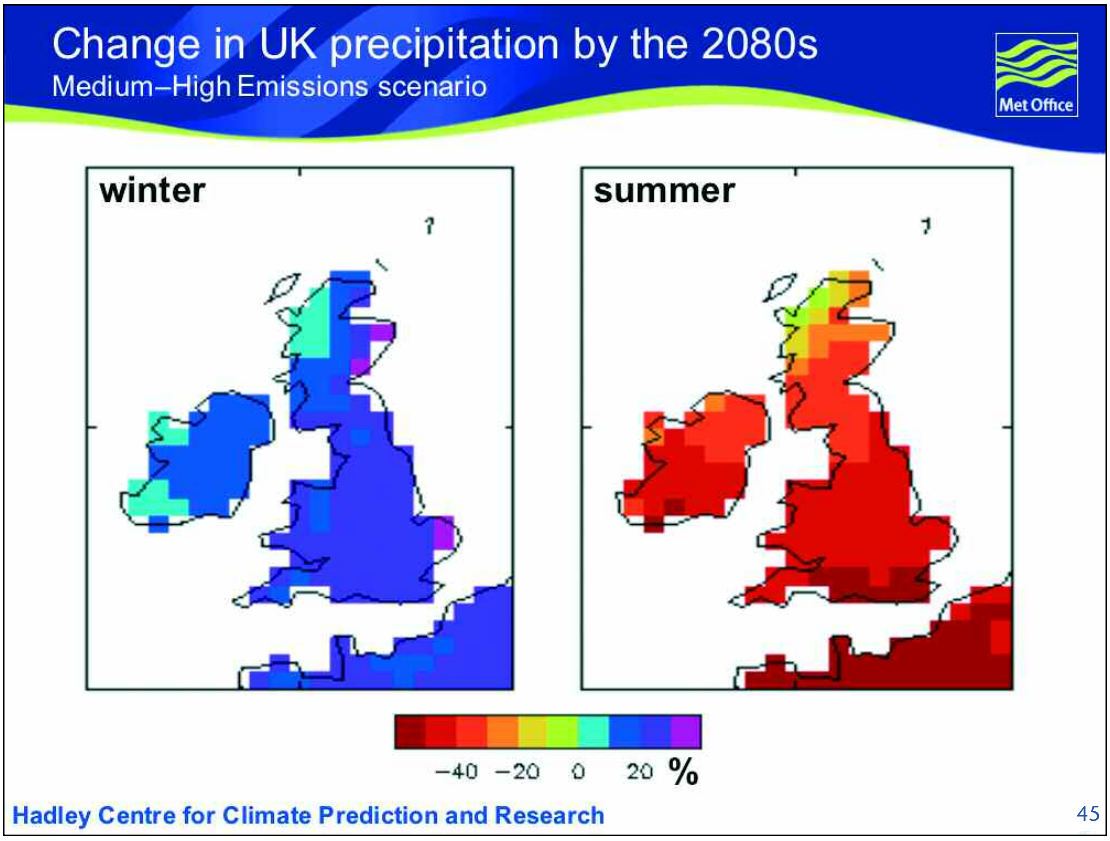


As seen earlier, global climate models generally have a resolution of about 300 km, and this is insufficient to calculate reliably the impacts of climate change. To achieve a higher resolution we 'downscale' global model predictions using Regional Climate Models (RCM), which have a resolution of 25 or 50 km, but over a sub-global domain, typically 5,000 km x 5,000 km. RCMs not only give greater geographical detail, but they take better account of features such as mountains and coastlines, and give a much improved simulation of (and, hence, can be expected to give better predictions of) changes in extremes such as heavy rainfall events. The accuracy of predictions from RCMs is, of course, limited by the accuracy of the driving predictions that are input from global models.

The Hadley Centre RCM (HadRM3) has been used to predict changes at a resolution of 25 km over a European domain by the 2080s under a Medium-High Emissions scenario, and two results are shown above. In the left-hand panel we see the predicted pattern of change in summer-mean rainfall, showing almost all of the continent (apart from northern Fennoscandia) becoming much drier. In the right-hand panel we look at changes to heavy rainfall events. Paradoxically, in some areas, despite the strong summer-average drying, increases in the frequency of heavy rainfall events are predicted.

The Hadley Centre RCM has been adapted to run on personal computers, with a domain able to be set to anywhere on the Earth, in a system called PRECIS (Providing REgional Climate for Impacts Studies). It is made freely available to any developing country, after training provided by the Hadley Centre, so that it can generate scenarios in national centres, validate them using local observational data, and take ownership of them. By mid-2005, eight courses in different parts of the world had trained almost 150 modellers. See www.precis.org.uk for further details.

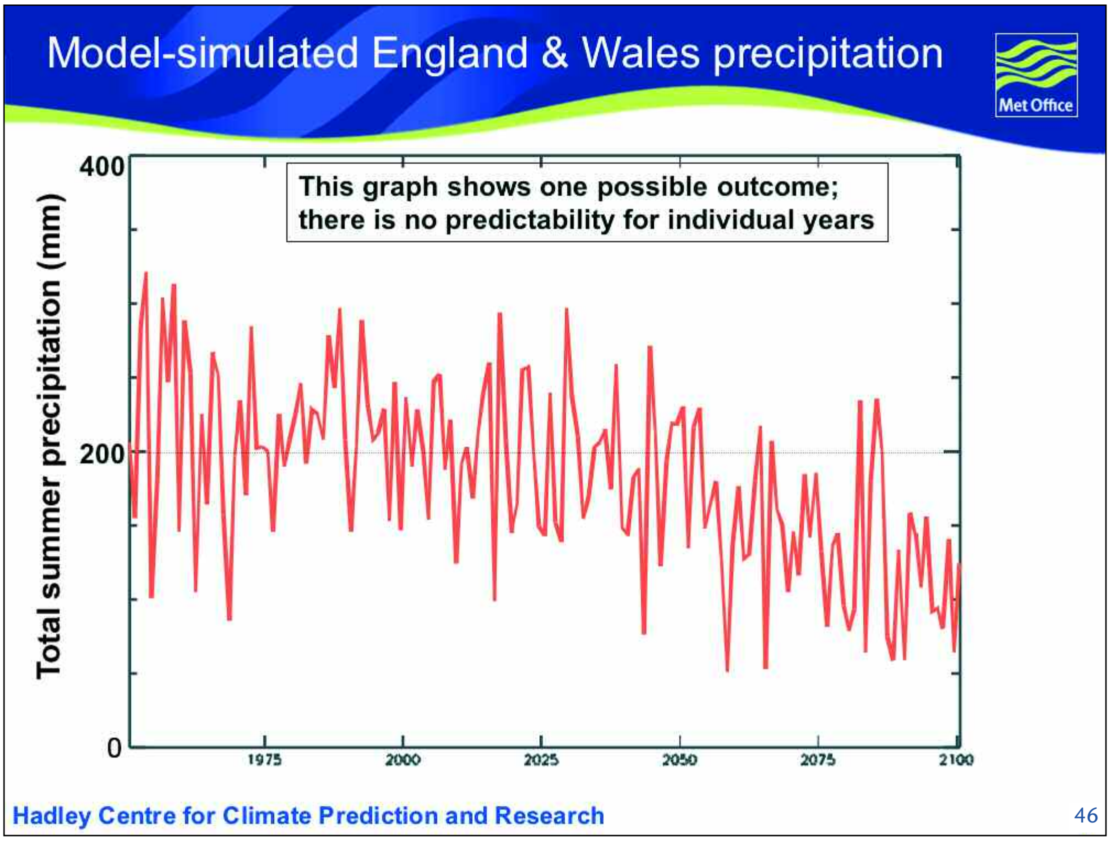
Further reading: Buonomo, E., R. Jones, C. Huntingford and J. Hannaford. The robustness of high resolution predictions of changes in extreme precipitation for Europe. Submitted to Quart.J.Roy.Met.Soc.(2005).



In 1997, Defra set up the UK Climate Impacts Programme (UKCIP) to encourage and facilitate adaptation to climate change. As one of the main tools to help stakeholders, in 2002 UKCIP published a set of detailed climate change scenarios for the UK. These were based on the Hadley Centre global climate model predictions, downscaled over Europe by the Hadley Centre RCM. Scenarios were averaged over 30-year periods centred on the 2020s, 2050s and 2080s, and covered a number of climate quantities such as temperature, precipitation, soil moisture, relative humidity, solar radiation, sea-level pressure, wind speed, etc.

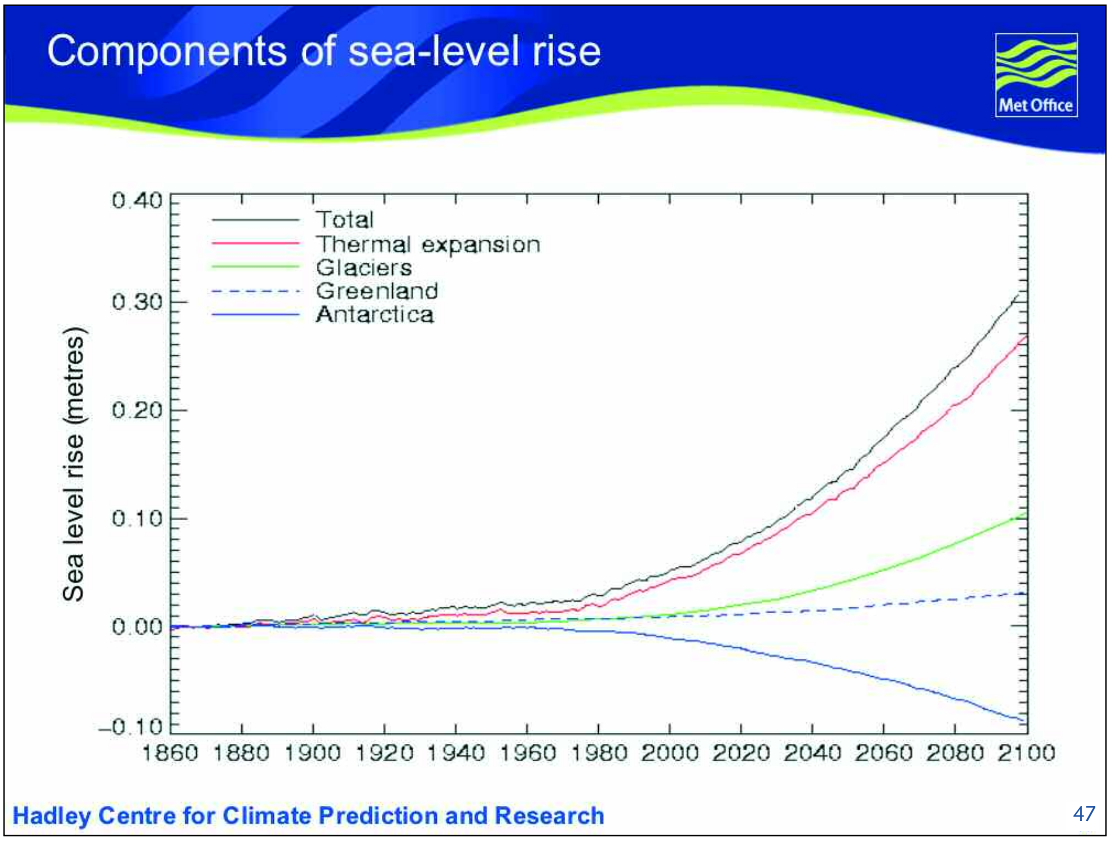
Shown in this slide is an example of the scenario for change in seasonal average precipitation, in winter and summer, by the 2080s compared to recent climate (1961–1990) under the Medium High Emissions scenario. Other scenarios correspond to the three other possible future emissions.

The scenarios replaced earlier ones published in 1998, and work is well underway on the next set of scenarios, likely to be published in about 2008.



The British Isles, being at the boundary of the Atlantic Ocean and the Eurasian landmass, and at the eastern end of Atlantic storm tracks, experiences one of the most variable climates in the world. The North Atlantic Oscillation is the main driver of winter climate variability; in winters when the pressure difference between the Azores and Iceland is greater than the average (that is, relatively lower pressure over Iceland) we tend to wetter, stormier and milder winters; when the NAO is in the reverse phase we tend to drier, calmer but colder winters. This gives rise to a marked variability in winter rainfall.

Summer rainfall is also very variable, as shown in the slide above of total summer rainfall over England and Wales simulated by the Hadley Centre model from 1950–2100. (Note that the model gives a reasonable representation of year-to-year variability but cannot predict rainfall for a particular summer.) The downward trend in summer rainfall during the 21st century due to man-made climate change is clearly seen, but it is noticeable that even in the latter quarter of the century there are still likely to be summers which are wetter than average, even by today's standards.

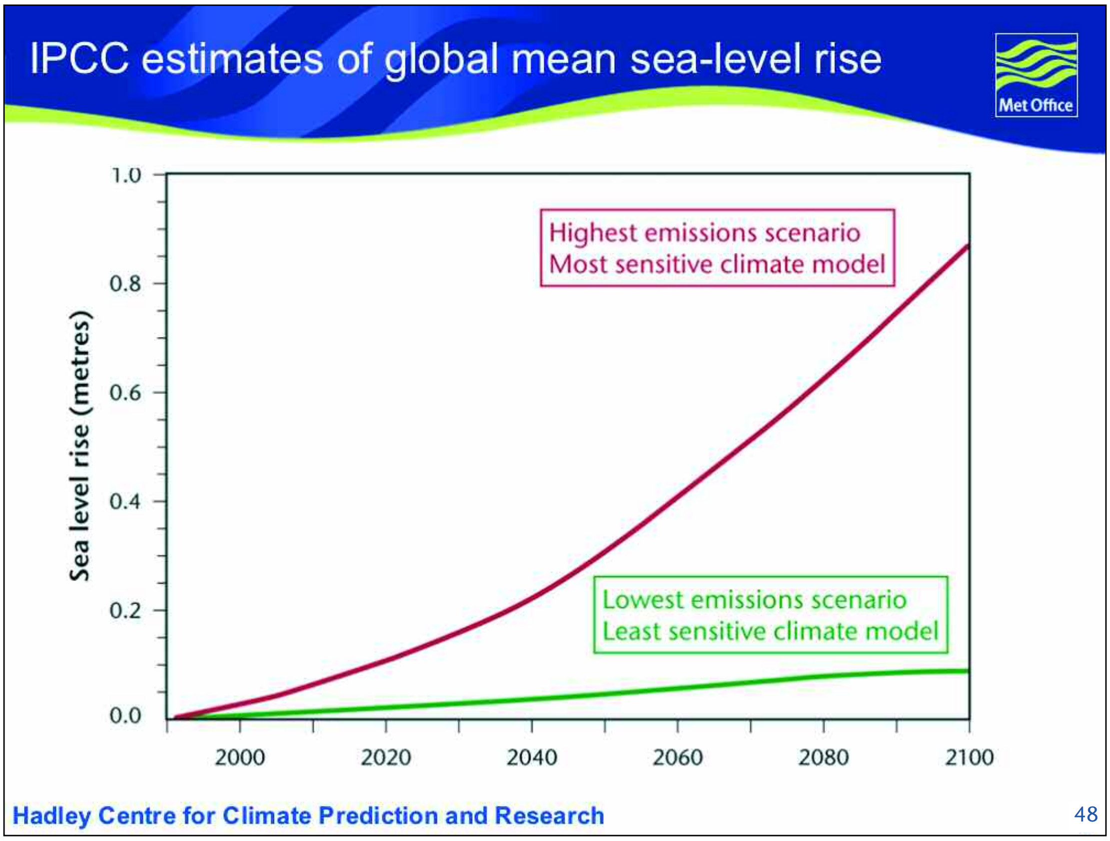


There is substantial interest in the effects of climate change on sea level, as the increased risk of coastal flooding could markedly affect society. Sea level will change due to expansion of oceans as they warm, and due to the influx of water from melting of glaciers and other snow and ice, and changes in the two large ice sheets in Antarctica and Greenland. Above is a plot of changes in sea level predicted by the Hadley Centre model from the years 1860 to 2100, due to each of these contributors, under a Medium-High Emissions scenario*. The dotted blue line shows the expected change of sea level due to changes in the Greenland ice sheet. The green line shows predicted changes due to melting of glaciers and snow on land. The red line shows the major component of sea-level rise which is thermal expansion of ocean waters. Adding these components together gives a predicted sea-level rise from the middle of the last century to 2100 of about 0.4 m, about 0.1 m of which should have already occurred (rather less than has actually been observed), leaving a rise of about 0.3 m over the next 100 years.

Changes in the Antarctic ice sheet are very difficult to estimate, and are shown by the solid blue line above. Snowfall is predicted to increase over Antarctica in the Hadley Centre model, and this will act to reduce sea-level rise. If we take this into account, the total sea level rise may be some 10 cm smaller than the estimates given above, as shown by the black line in the slide. Over the next century or so, the effect of Antarctic melting may overcome any reduction in sea level due to increased snowfall and make Antarctica a net contributor to sea-level rise.

Other models show different estimates for the components and for the total, indicating the need to improve descriptions of all the included processes, and the inclusion of additional ones such as permafrost melt and man-made storage in reservoirs.

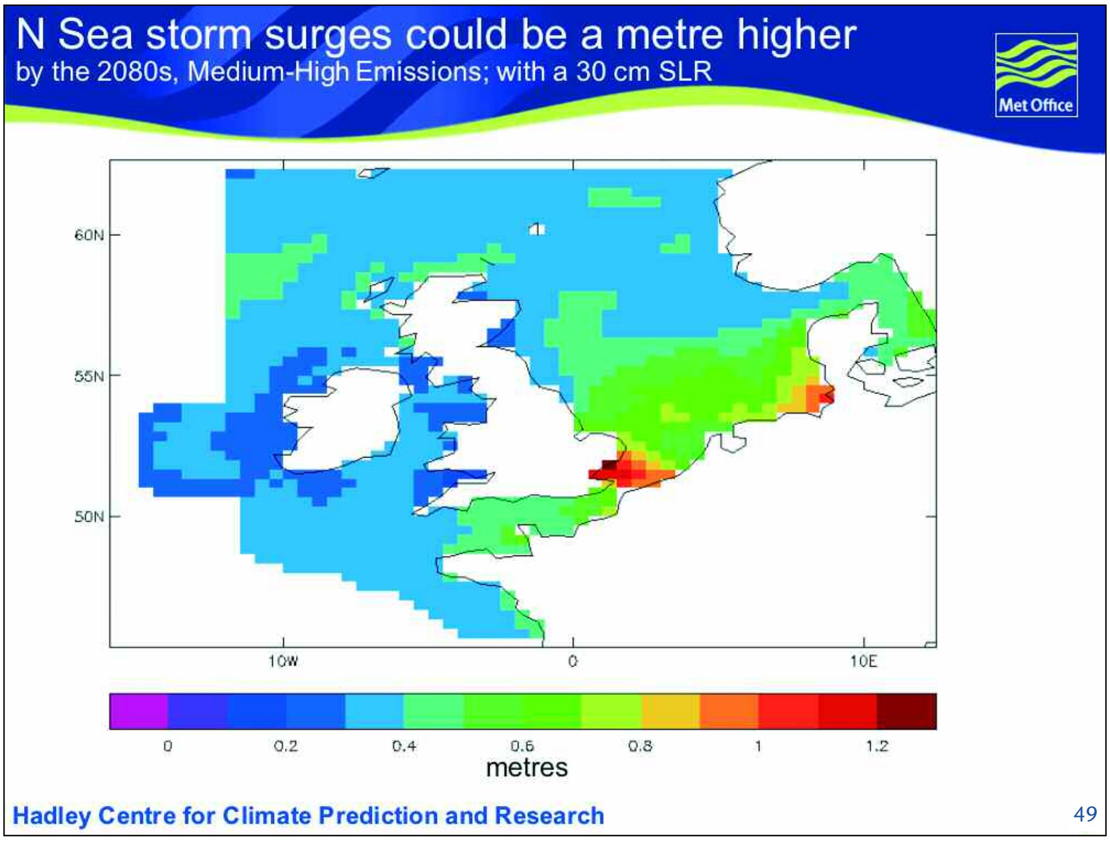
** Gregory J.M. and J.A. Lowe. Projections of global and regional sea level rise using AOGCMs with and without flix adjustment. Geophys. Res. Lett., 27(19), 3069–3072, 2000.*
Further reading: IPCC TAR Chapter 11.



The IPCC Third Assessment brought together estimates of sea-level rise from seven different climate models, each driven with the main SRES emissions scenarios (see earlier slide). The range of predicted sea-level rise was very large; taking the lowest emissions scenario with the least sensitive climate model gave an estimated rise of about 0.1 m over the century. On the other hand, taking the highest emissions scenario with the most sensitive climate model gave a rise of almost 0.9 m. The central value (not necessarily the best estimate) of about 0.5 m corresponds to two to four times the rise in the 20th century.

At a regional scale, changes are predicted to be very different from the global mean, as they depend upon regional ocean heat uptake, changes in currents and in atmospheric pressure. All models show the range of regional variation in sea-level rise is substantial, in some areas twice the global average and in others almost no rise at all. However, there is little agreement between models as to which are likely to be the most and least rapid areas of sea-level rise, although there is some agreement that rises will be larger than average in the Arctic Ocean, the US East Coast and around Japan, and smaller in the Southern Ocean.

Further reading: IPCC TAR Chapter 11 Section 5.

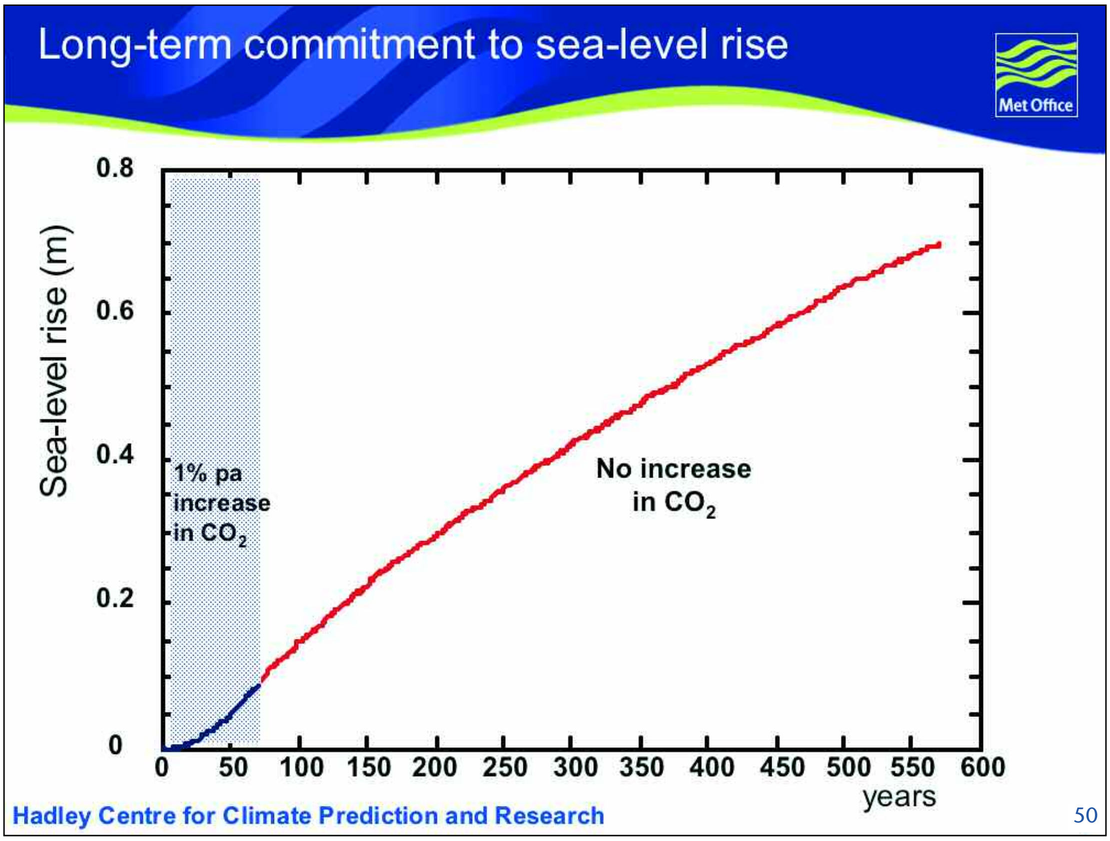


In order to find the future change in sea level along a particular coastline, we must add to the rise due to man-made climate change any effect of land movement. The west coast of Scotland, for example, is currently rising by about 1–2 mm per year, as it recovers from the effect of the massive glaciers of the last ice age (known as isostatic rebound). London, on the other hand, is currently sinking at about 1.5 mm per year.

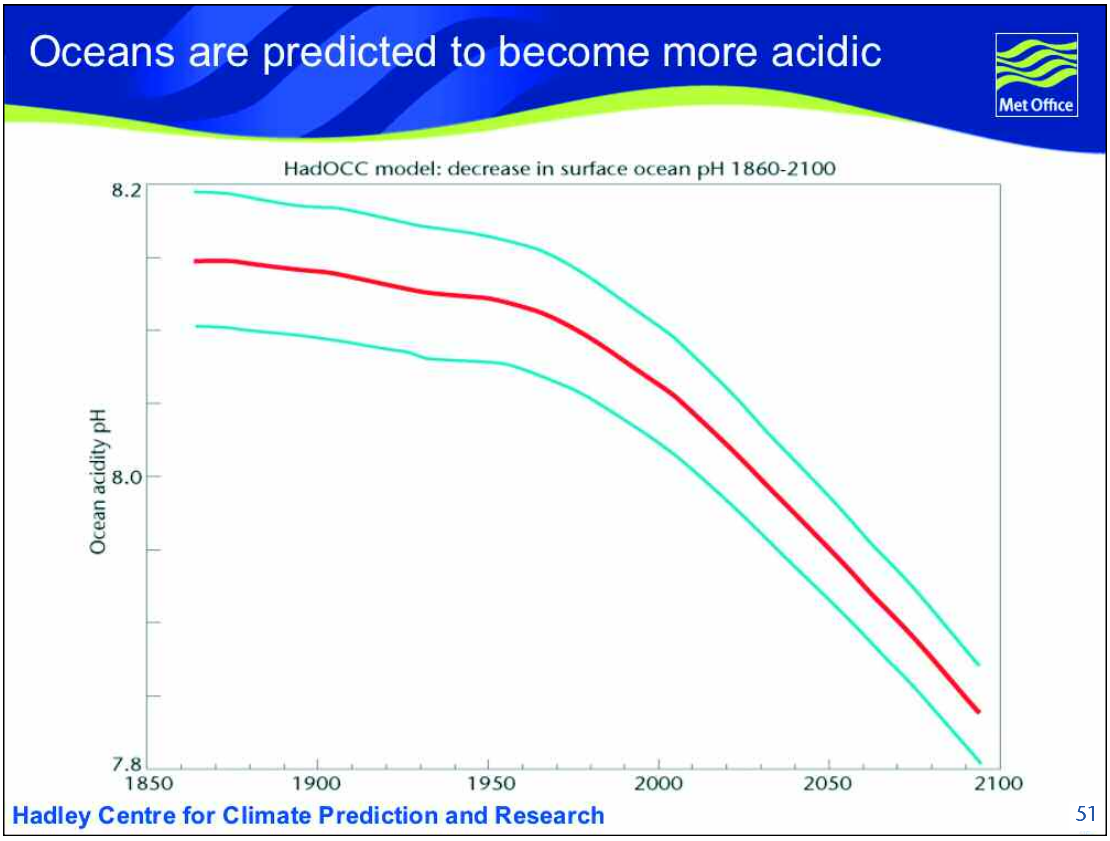
The main consequence of sea-level rise will probably come from an increase in extreme high water levels, which arise from storm surges as mid-latitude depressions or tropical storms and cyclones track across the area. The effect of sea-level rise on storm surges around the British Isles was investigated as part of the development of the UKCIP02 scenarios of climate change. This involved driving a storm surge model developed at the Proudman Oceanographic Laboratory, Liverpool, with meteorological predictions (pressure, winds, etc.) from the Hadley Centre regional climate model. Shown above is the change by the 2080s in the height of a 1-in-50-year high water event, under the Medium High Emissions scenario, with a 30 cm sea-level rise, and including the effects of land movement.

As can be seen, increases of a metre or more in extreme high water levels, three or four times the sea-level rise, are predicted in the Thames Estuary and southern North Sea, whereas surges around Wales change by a similar amount to the mean sea-level rise.

The effect of sea-level rise can also be expressed as a change in the frequency of a given high water level. Under the same scenario as that above, extreme high water events at Immingham, a port in the northeast of England, which currently happen on average every 100 years, are predicted to occur as often as every seven years on average in the 2080s.



Greenhouse effect heating in the atmosphere is rapidly transferred into surface ocean waters. It then slowly penetrates deeper and causes more and more of the ocean depth to expand and, hence, leads to further sea-level rise. This figure shows the sea-level rise due to ocean thermal expansion, estimated from a climate model experiment where CO_2 concentration in the atmosphere was hypothetically increased by 1% per year from time zero to 70 years (that is, until it had doubled) and was then stabilised at that concentration, that is, no further increase occurred. The initial blue line shows thermal expansion while the CO_2 concentration was rising, the continuing red line shows sea-level rise after CO_2 concentration had been stabilised. Despite the fact that CO_2 in the atmosphere did not change after year 70, the sea level carries on rising for many hundreds of years, with only a slow decrease in the rate of rise. So at any time the sea-level rise caused by the man-made greenhouse effect carries with it a commitment to an additional, inescapable, rise.



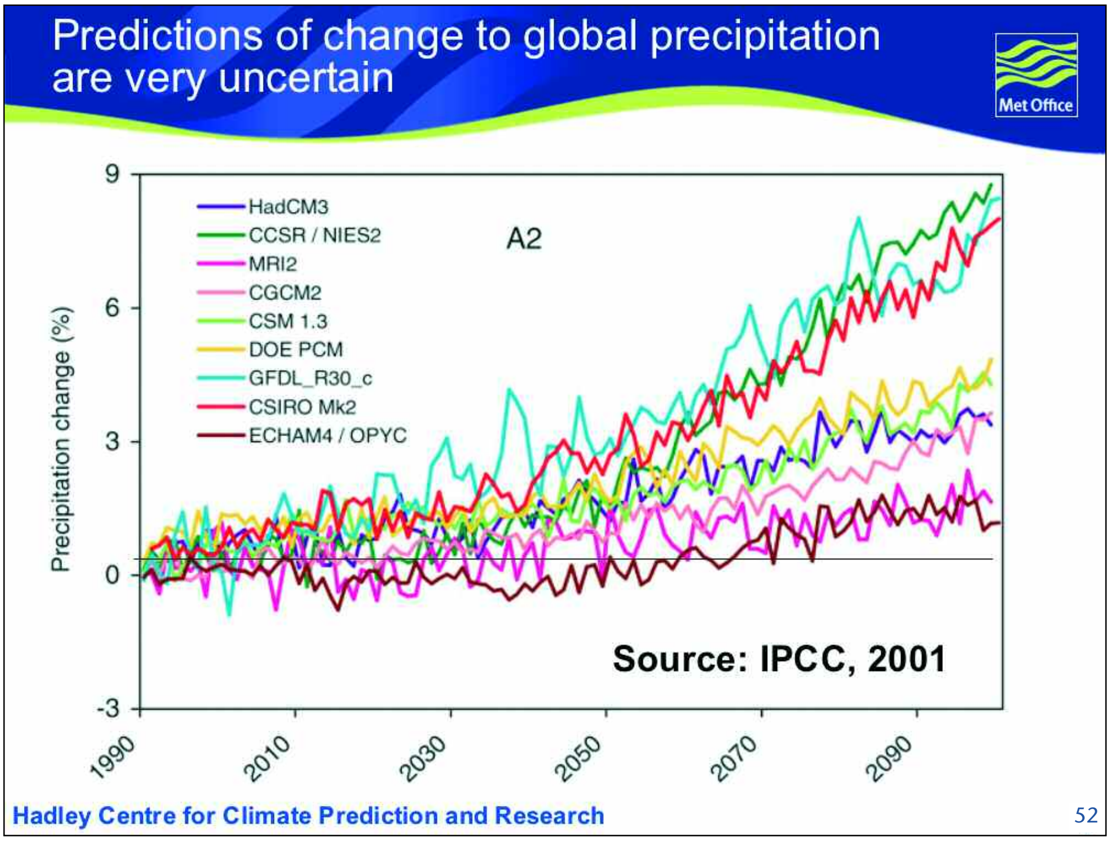
The oceans of the world naturally exchange large amounts of carbon dioxide with the atmosphere. Where oceans are warm, they outgas CO_2 into the atmosphere; where they are cold they take up CO_2 from the atmosphere. The global ocean is also a major sink for man-made carbon dioxide, currently responsible for absorbing about a quarter of it. The increase in concentration of CO_2 in surface waters produced by the absorption of man-made CO_2 will reduce the chemical uptake of CO_2 from the atmosphere; a reduction in this sink will tend to leave more CO_2 in the atmosphere and act to speed up warming (although changes in biological processes, which also control the strength of the ocean sink for CO_2, may offset these chemical changes). Increase in ocean surface temperatures due to human activity will also result in less uptake of CO_2 from the atmosphere.

Basic chemistry tells us that when atmospheric CO_2 is absorbed it acidifies the ocean water. The Hadley Centre coupled climate-carbon cycle model has been used to predict how the surface pH of the ocean will change over the period 1860–2100, and the result is shown in this slide. The red line represents the global average surface ocean pH, and the blue lines either side show the spread of pH at any given time from different oceans of the world and different seasons. The reduction in pH of about 0.1 unit since pre-industrial times simulated by the model is roughly in line with measurements. The model predicts a further reduction of about 0.25 by the end of the century.

The Royal Society reported in June 2005 on the effects of ocean acidification. Its report can be found at www.royalsoc.ac.uk/document.asp?id=3249

Increasing ocean acidity will act to decrease CO_2 uptake, in addition to decreased uptake resulting from increased surface CO_2 concentration and temperature. There is convincing evidence to suggest that acidification will affect calcification, the process by which animals such as corals make shells from calcium carbonate, and this will threaten tropical, subtropical and even cold-water corals. Phytoplankton and zooplankton, which are a major food source for fish, may also be affected. Recent work* concludes that key marine organisms — such as corals and some plankton — will have difficulty maintaining their external calcium carbonate skeletons. Indications are that conditions detrimental to high-latitude ecosystems could develop within decades, not centuries as suggested previously.

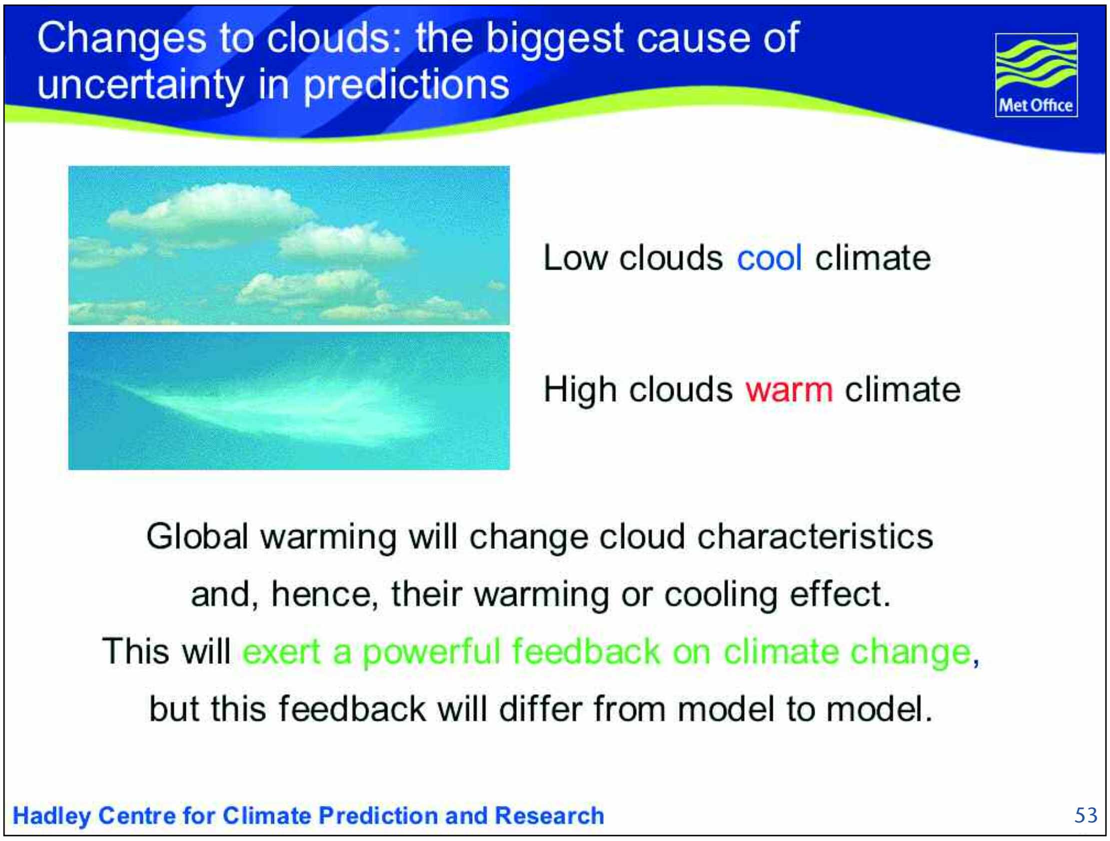
** Orr, J.C. et al. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437, 681–686 (2005).*



There are a growing number of centres which develop and use global climate models. As part of the IPCC Third Assessment, the Hadley Centre organised an intercomparison of predictions from nine climate models, and this slide shows how global-average precipitation changes for each of the models over the course of the century. In each case the models are run with the Medium High (SRES A2) Emissions scenario, so the spread of results arises from differences in the models themselves.

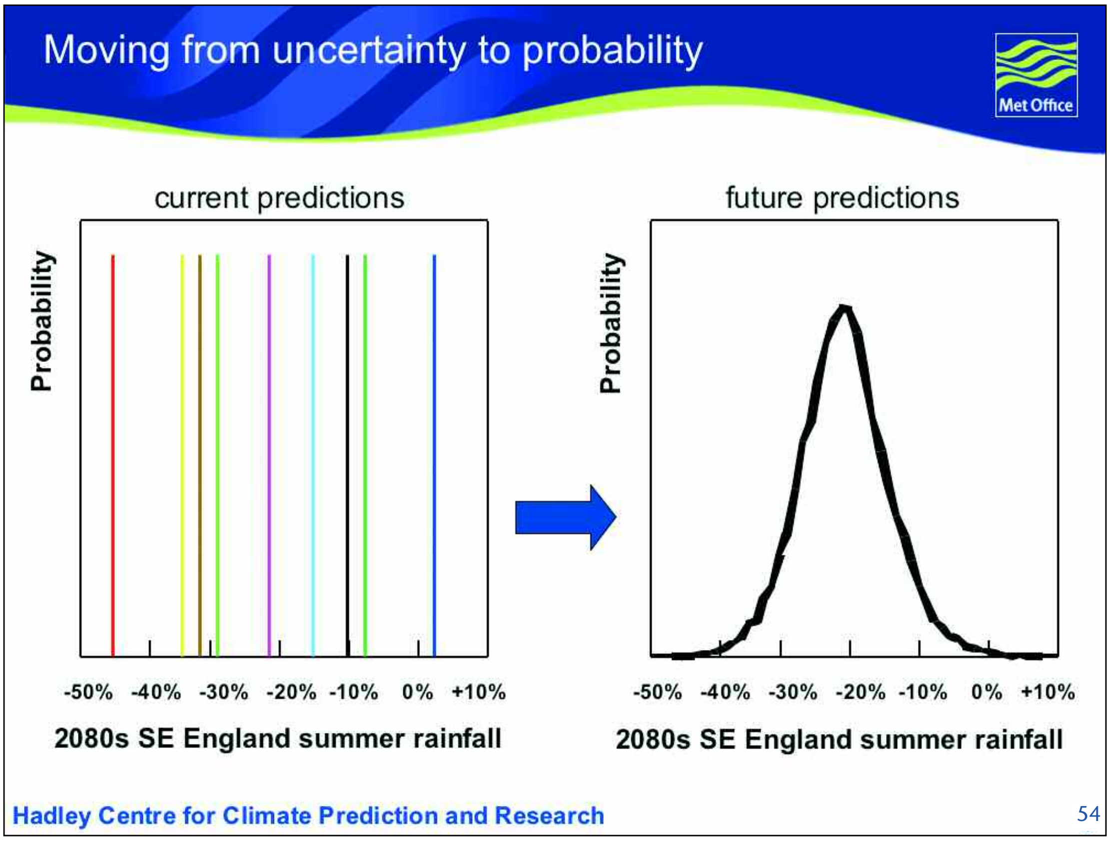
In the case of global-mean temperature, the model predictions range from 1.5 °C to 6 °C, and in the case of precipitation, from about 1.5% to 9%.

Further reading: IPCC TAR Chapter 9 Section 3.



The biggest uncertainty in climate predictions arises because climate models are imperfect representations of the climate system. Clouds, for example, have a great effect on climate. Low clouds reflect sunlight but have little effect on the escape of infrared radiation, so they have a cooling effect on climate. High clouds, on the other hand, trap infrared radiation but do not reflect much sunlight; they have a warming influence. The net effect in the present day is an overall cooling effect.

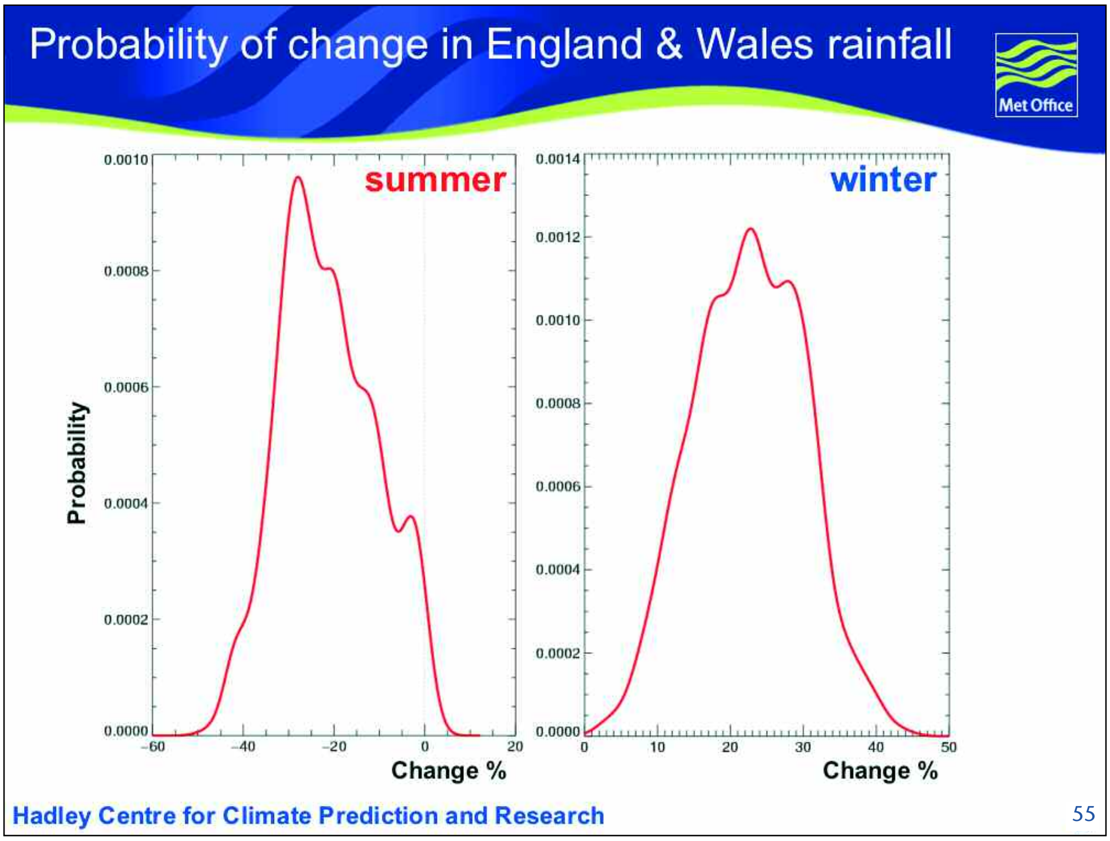
However, changes to the characteristics of clouds — their amount, height, thickness or the size of their water droplets or ice crystals — can drastically alter their climate properties, and hence could change the cooling effect into a warming one. This would be a positive feedback on climate from clouds. Many other processes in the climate system will change, and cause similar feedbacks, positive or negative. Because different climate models represent processes in different ways, the feedbacks from these processes will be different, and this is the main reason why climate models give different predictions for the future.



We have seen earlier that models give a wide range of predictions in global-mean quantities; the uncertainty at a smaller scale is even bigger. If we zoom into the south-east of England, for example, we see that the IPCC TAR climate models give changes to summer-mean rainfall by the 2080s, under Medium-High future emissions, ranging from a small increase to a 45% decrease — shown schematically in the left-hand panel. Because we have no way of assigning the skill of each of the models, all of the predictions must be assumed to have the same (unknown) probability. This is obviously unhelpful to planners trying to adapt to climate change; hydrologists deciding on whether a new reservoir should be built to avoid summer water shortages, for example. If they plan for the smallest climate change then they could be caught out if predictions of greater change come about. On the other hand, if they spend large sums adapting to the highest predictions, these may be wasted if smaller predictions turn out to be more realistic.

The reduction in uncertainty in predictions is unlikely to be rapid, depending as it does on hard-won improvements in our understanding of how the climate system works. Planners therefore wish to move away from the current situation of having a large number of different predictions of unknown credibility, to a situation where the probability of different outcomes (for example, percentage changes in summer rainfall) is known, as in the right-hand panel. They can then use these probabilistic predictions in risk assessments, to decide on the optimum adaptation strategy.

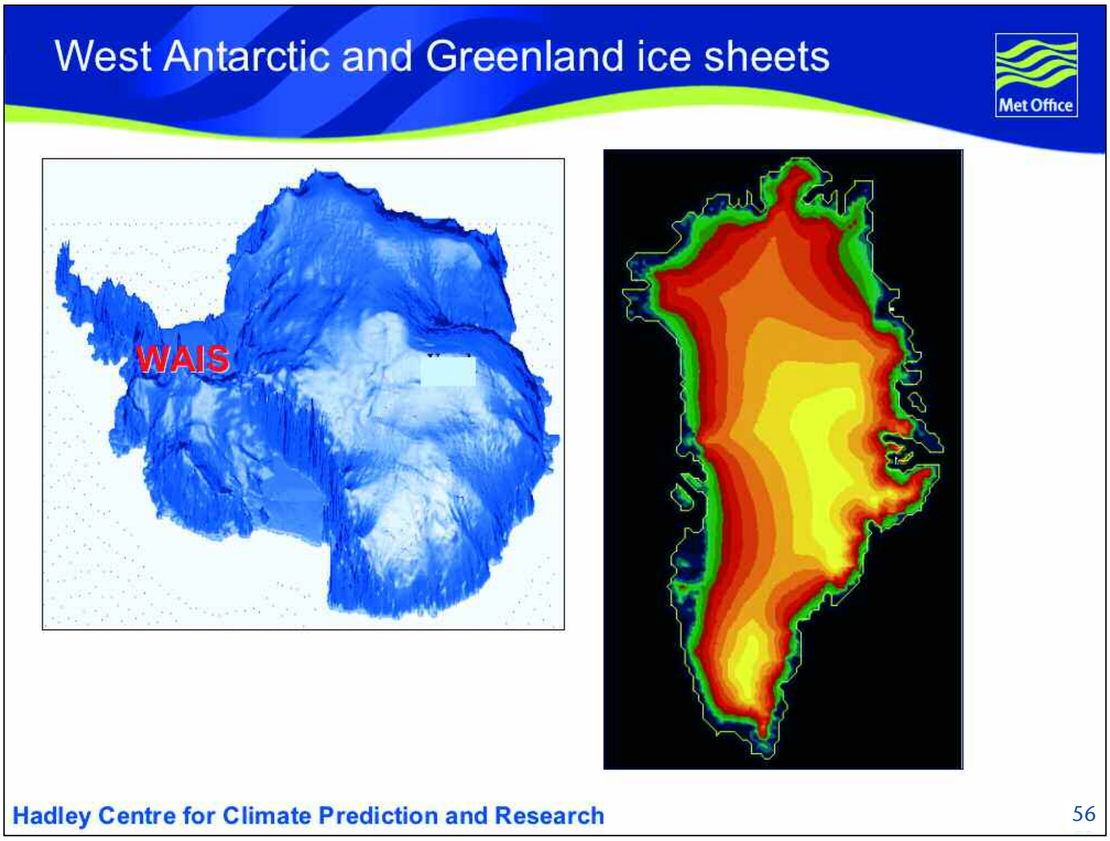
Recognising that, as explained in the last slide, models give different predictions because they use different representations of the climate system, we are approaching this problem in the Hadley Centre by building large numbers of climate models, each having different but plausible representations of climate processes; so-called 'physics ensembles'.



Each member model of the physics ensemble has been used to predict the climate in a world where CO_2 is doubled, and the corresponding change in a particular quantity (seasonal mean rainfall over England & Wales, for example) is taken from the model. We then combined the results from the large number of models in the physics ensemble in the form of a frequency distribution of that quantity. Finally, we gave each model a weight according to its ability to simulate current climate, and weighted the results from all the models to give an estimate of the probability distribution of a change in the required quantity. The results were published in Nature in 2004*. The figure above shows an estimate of the probability distribution of the percentage change in summer and winter rainfall over England and Wales, at a time after CO_2 has doubled.

The next stages are to take these 'doubled-CO_2 world' results and use them to predict changes over the course of the century. We will then downscale the results from this global model to a 50 km or 25 km scale using the Hadley Centre regional model. Because all the models in the current ensemble are variations of the Hadley Centre climate model, we then need to take account of predictions from other climate models, which may have different structures from the Hadley Centre model. This process is complex and will take considerable effort and computing resources, but we aim to have initial probabilistic predictions for use in the next set of UKCIP climate change scenarios.

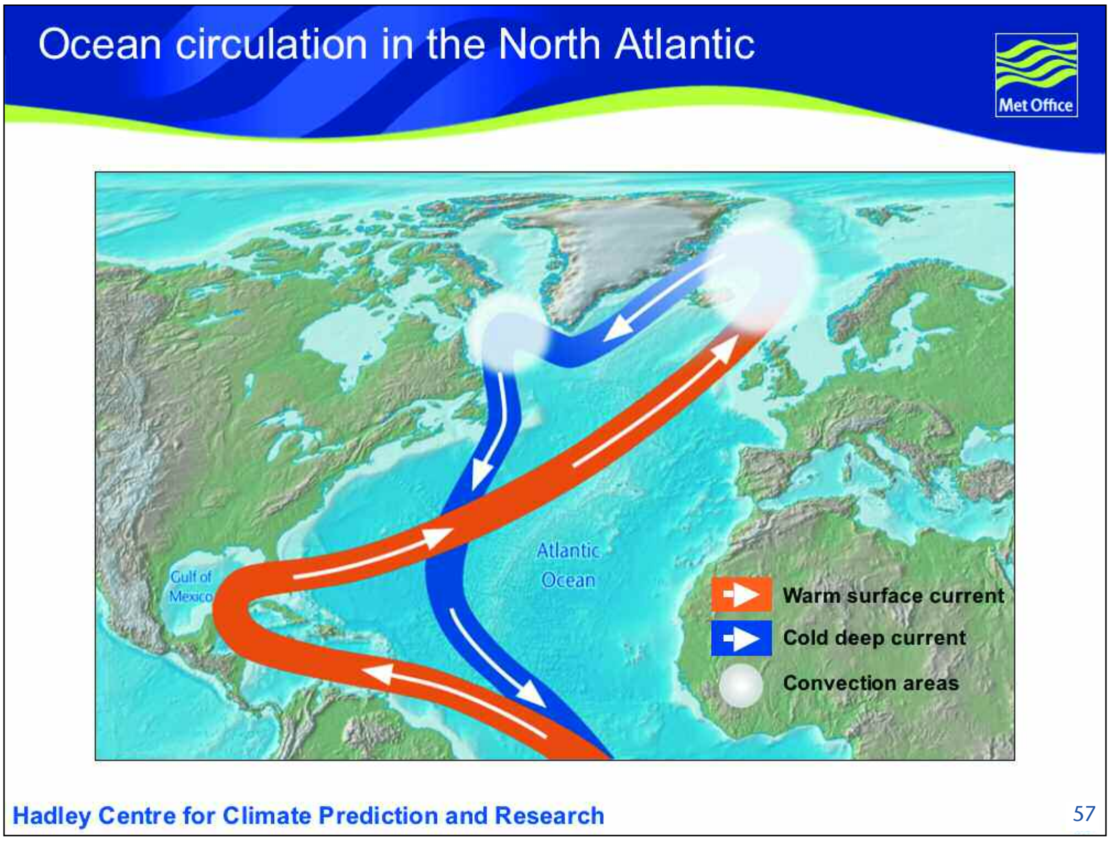
**Murphy, J.M. et al. Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature, 430, 768–772, 2004.*



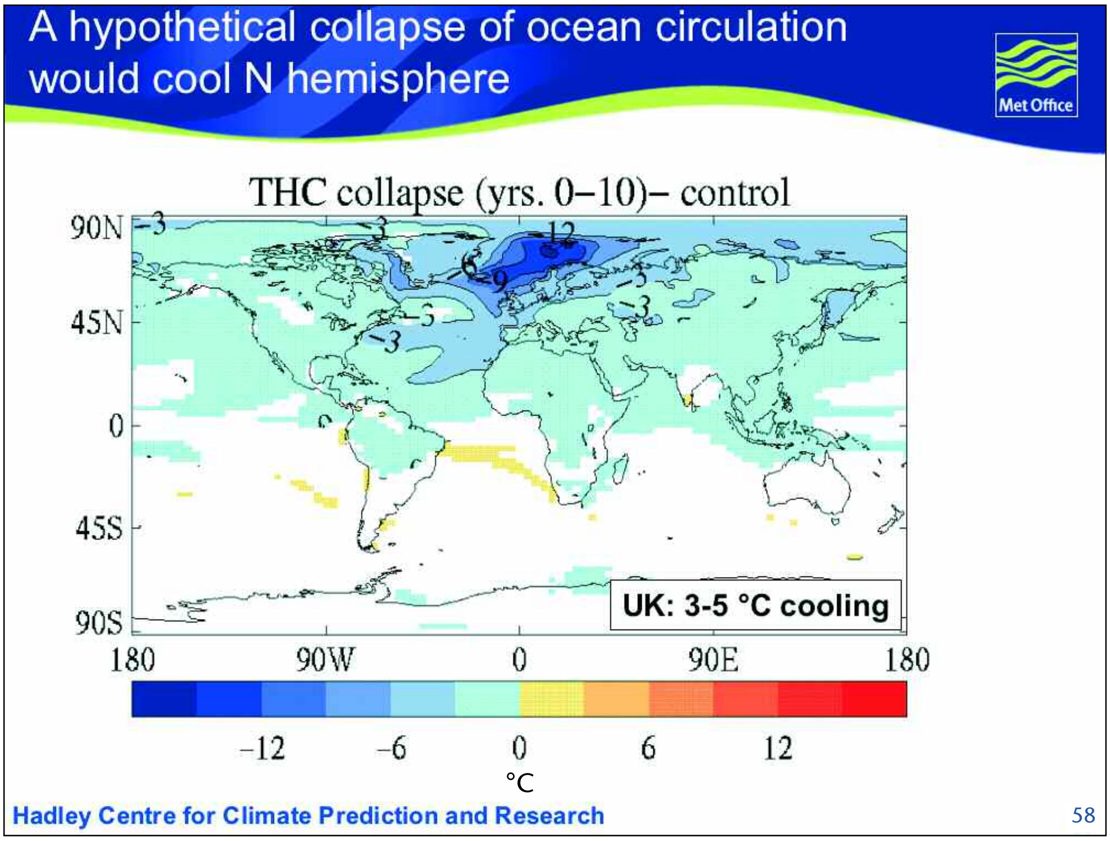
There are two major ice sheets which are thought to be vulnerable to climate change: the West Antarctic Ice Sheet (WAIS) which contains ice equivalent to about 6 m of global sea-level rise, and the Greenland Ice Sheet containing just over 7 m of sea-level equivalent. Very much larger amounts of water are locked up in the remainder of the Antarctic ice sheet, but this is not thought to be vulnerable to a warming of less than about 20 °C.

In the case of the Greenland Ice Sheet, if summer regional temperatures were to rise by about 3 °C, the ice sheet would begin to reduce in size. It would be slow to disappear, perhaps half of it taking about 1,000 years to melt. This critical temperature is predicted to be reached by the end of the century by most combinations of climate models and future emissions scenarios.

The West Antarctic Ice Sheet is grounded below sea level. Its potential to collapse in response to future climate change is still the subject of debate and controversy. The IPCC TAR took the view that a loss of grounded ice leading to substantial sea-level rise from this source was very unlikely during the 21st century. However, recent measurements suggest that the melting of some ice shelves (floating sea ice attached to the coastline) is leading to a speed up of glaciers and, hence, an increase in their discharge into the sea. The implications of this, needed before reliable predictions can be made, have yet to be understood.



There have been some concerns expressed that global warming could lead to massive changes in ocean currents such as the Gulf Stream. Currents in the ocean are responsible for about half the work of the climate system in redistributing heat between the equator and the poles. The current system in the N Atlantic is driven by ‘convection’ which takes place in two areas, near Labrador and in the Greenland-Iceland-Norway sea. Here, the surface water is cooled by arctic winds, and sinks a few thousand metres to the bottom of the ocean. This cool dense water then flows southwards, with a flow equivalent to a hundred Amazon rivers, crossing the equator and heading south. The sinking cold water in the north has the effect of drawing northwards warm near-surface water from the Gulf of Mexico, which travels across the North Atlantic. It is often called the Gulf Stream, but is more properly referred to as the North Atlantic Drift. The heat which it transports towards north-west Europe is part of the reason why countries such as the British Isles and Norway are a lot warmer than, for example, those parts of western Canada at the same latitudes. This global ocean circulation, which extends to other oceans of the world, is known as the thermohaline circulation (THC), as it is driven by differences in temperature and salinity of the water masses.

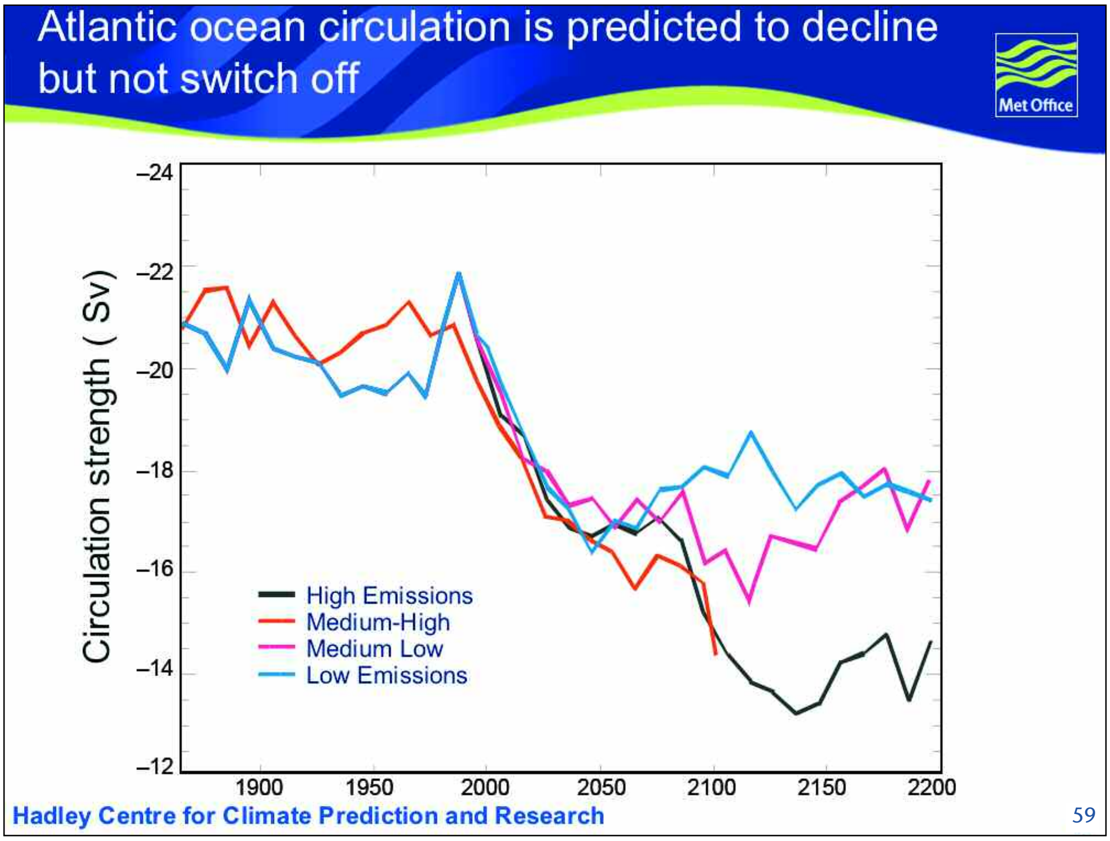


There is strong evidence that the Gulf Stream has switched off more than once over the last ten thousand years, due to natural causes. We also know that there are processes that have the potential to make this happen again. Firstly, the warming of surface waters in the convection areas, due to the man-made greenhouse effect, will reduce their density. Secondly, we expect there to be increased rainfall over the convection areas, and this freshwater will also act to reduce the density of surface waters. Thirdly, increased precipitation in high latitudes in a warmer world will increase the outflow of fresh water from rivers – this has already been observed and, as mentioned earlier, recent work at the Hadley Centre has been able to attribute this to man-made climate change. And lastly, as the amount of sea ice decreases, a further mechanism for driving convection (the seasonal freezing of sea ice which rejects salt and thus make surface waters denser) will also decrease. All these factors will act to reduce the density of surface waters and make them sink more slowly.

What would happen if the north Atlantic thermohaline circulation did switch off? The THC in the Hadley Centre climate model was artificially switched off by 'pouring' fresh water on the ocean surface at the convection areas. The change in surface temperature in the first decade after this was done is shown in the slide above. The whole of the Northern Hemisphere cools, and around the North Atlantic, and particularly the Arctic Ocean, the cooling is very obvious. The UK would cool by some 3–5 °C. The effects on extremes, for example winter minimum temperatures over Central England, would be very marked, and the effect of this on infrastructure would be likely to be far worse than that of a gradual global warming (although nothing like as great or as sudden as depicted in the Hollywood disaster movie '*The Day After Tomorrow*').

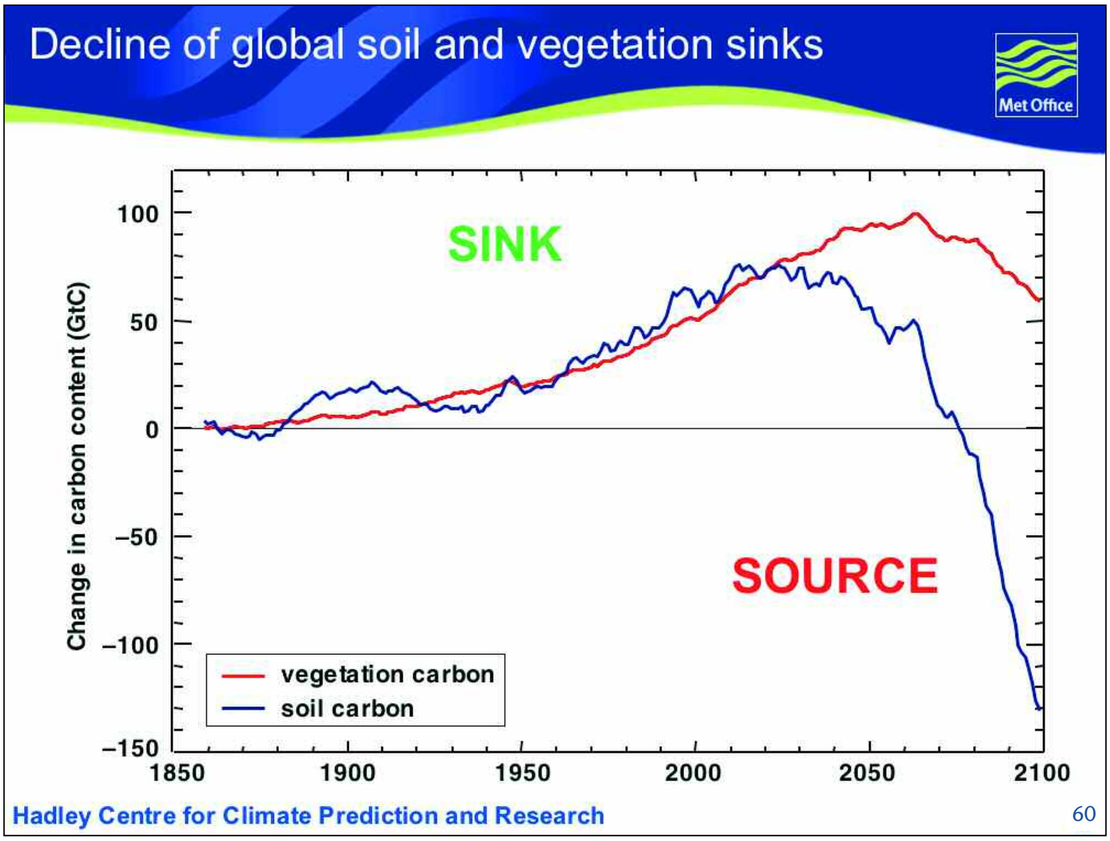
But this is a hypothetical experiment; do we expect the ocean circulation to switch off as the world warms?

Reference: Wood, R.A., M. Vellinga and R. Thorpe. Phil. Trans. Roy. Soc. Lond. (A), 361, 1961–1975, 2003.



The Hadley Centre climate model, which represents well the convection processes and ocean circulation, having been extensively validated against ocean observations, has been used to predict future changes in the ocean circulation. The coloured lines show the prediction of change in the North Atlantic circulation for the four SRES emissions scenarios described earlier. (The unit of current strength is a sverdrup, a million cubic metres of water per second). It is seen that all of the emissions lead to a decrease in the circulation strength of about 15–25% by 2100. This will, of course, lead to a corresponding reduction in the amount of heat transported towards the UK, but this is more than offset by the direct greenhouse warming. As they are derived from the same model experiment, this reduction is taken into account in the UKCIP02 climate change scenarios shown earlier. When the experiment is continued, with greenhouse gas concentrations stabilised in 2100, so; the Low and Medium Low scenarios show no further decline.

Although other climate models reviewed in the IPCC TAR show different rates of decline of the ocean circulation, none of them shows a complete switch-off of the Gulf Stream by 2100.



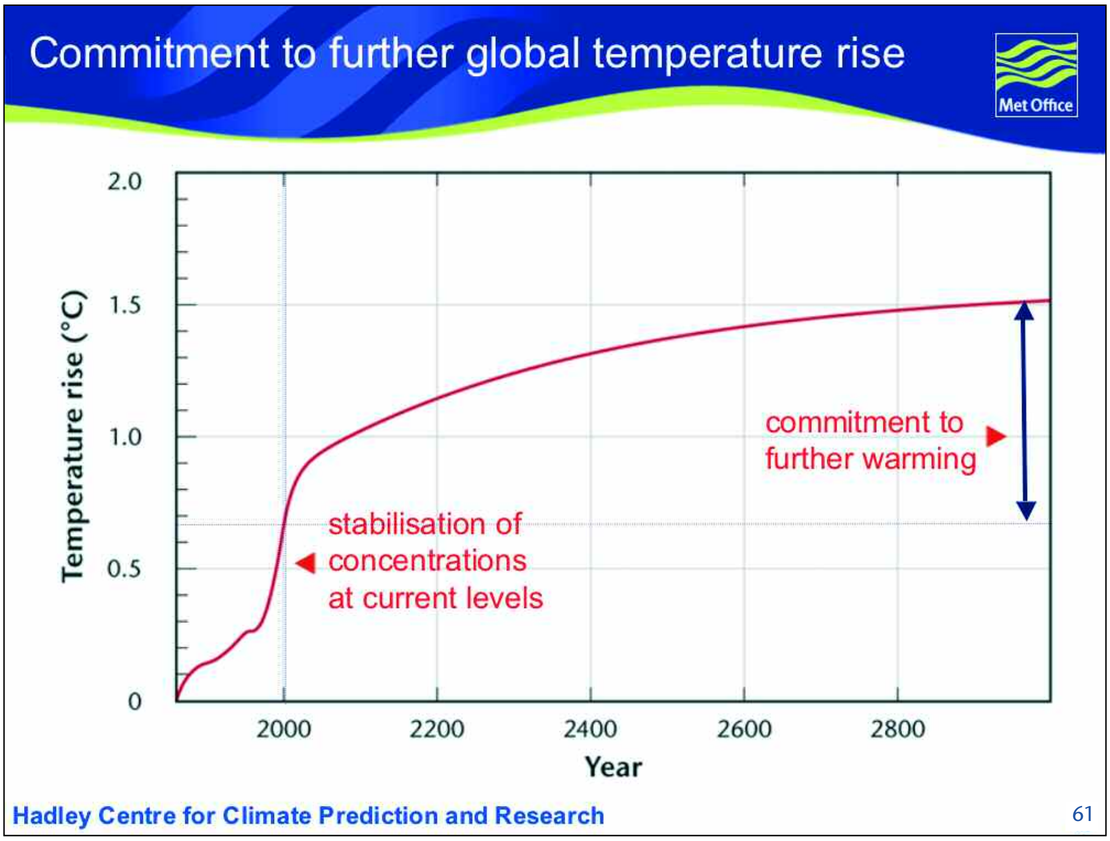
In an earlier slide we saw that, averaged over the 1980s, of the 7 GtC/yr emitted from human activities, about 3 GtC/yr remained in the atmosphere and about 2 GtC/yr was absorbed by the oceans and by vegetation on land. The two 'sinks' together take up about half of our emissions and moderate CO_2 concentrations and reduce man-made global warming. However, this may not always be the case in future. As global temperatures rise, and rainfall patterns change, we believe that several changes to carbon absorption will take place. Firstly, in the right conditions, CO_2 fertilises vegetation and speeds up its growth; this will absorb more of our CO_2. Secondly, higher temperatures and more rainfall will encourage growth of high latitude forests, and this will also help to mop up more of our CO_2. However, as soils get warmer, the microbial action which breaks down humus works faster, and this will cause more CO_2 to be emitted into the atmosphere. Lastly, higher temperatures (and thus higher evaporation) and lower rainfall are predicted for some forests in the tropics, and this is predicted to cause them to die back, with their carbon store being returned to the atmosphere.

The Hadley Centre coupled climate-carbon cycle model has been used* to estimate changes to the amount of carbon stored in oceans, vegetation and soils. The figure above shows the trend in the latter two from 1860 to 2100. It can be seen that soils and vegetation initially act as excellent sinks of carbon, and their carbon content steadily increases.

However, as explained above, by the middle of the first half of the century the gradually warming soils then begin to emit more CO_2 than they absorb, so they act as a source rather than a sink. The same thing happens with vegetation, but on a slower timescale; there the sink-source transition is predicted to happen in the second half of the century.

The reduction in natural carbon sinks, and their eventual change into carbon sources, allows more man-made CO_2 to remain in the atmosphere, and so concentrations build-up faster — a positive feedback between the climate and the carbon cycle. Under one business-as-usual emissions scenario, CO_2 concentration in the Hadley Centre model was predicted to rise to 750 ppm by 2100, accompanied by a warming over land of about 5 °C. When the feedback between climate and the carbon cycle was included in the model, CO_2 was predicted to rise to 1,000 ppm, and global mean temperature over land to 8 °C, under the same emissions scenario. This first estimate of the strength of the feedback has since been repeated by other modelling centres, which unanimously agree that climate change will reduce the natural absorption of CO_2 by the biosphere, although they find a variety of different strengths, so more research is needed to reduce uncertainties. But the potential for enhancement of global warming from this feedback has been clearly demonstrated.

** Cox P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell. Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model. Nature, 408, 184–187, 2000.*



The ultimate objective of the UN Framework Convention on Climate Change is to achieve "...stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Even after greenhouse gas concentrations are stabilised it will take a long time for a balance to be reached between the amount of energy coming in from the Sun and the amount lost to outer Space in the form of infrared radiation. If greenhouse gas concentrations were stabilised today (taken as the year 2000), which (in the case of carbon dioxide) would require a reduction in emissions of about 70%, we predict that global average temperature would keep rising and eventually warm a further 1 °C above today's temperature, as shown in the above slide, with estimates taken from a simple energy balance model rather than a full GCM. This is because of the inertia of the climate system, particularly the ocean, which has a large thermal capacity.

We have also used a full GCM to explore global temperature rise to 2100 due to two scenarios chosen for the IPCC 4AR. These follow an SRES emissions profile to 2100, after which the radiative forcing in the model is then held constant for a further 100 years. The temperature following stabilisation at 2100 after the lower (B1) emissions scenario rises a further 0.5 °C between 2100 and 2200; that following stabilisation after the A1FI emissions rises almost a further 1.5 °C. There are indications that estimates of commitment using the full GCM are less than those using a simple model.

Climate change: some frequently asked questions, with answers

Reports referred to in the answers

IPCC	Intergovernmental Panel on Climate Change, set up in 1988 under two UN bodies
TAR	Third Assessment Report from the IPCC, published in 2001
4AR	Fourth Assessment Report from the IPCC, due to appear in 2007
SRES	IPCC Special Report on Emissions Scenarios, published in 2000
UKCIP02	Climate Change Scenarios for the United Kingdom, launched by Defra/UKCIP in April 2002

Q1: How do we know that the climate is changing?

A1: Although several aspects of climate are changing, temperatures provide the clearest evidence. For many decades, temperature near the surface has been carefully measured at thousands of locations on land and at sea. There are a large number of measurements of temperature close to the Earth's surface which are global in extent, from which we can form a global average, going back to 1860. These all show temperatures higher in the past few years than at any time during the instrumental period, even allowing for measurement uncertainties and gaps in the data. Global average land and sea temperatures, shown in Slide 24, show considerable variability from year to year, but a clear underlying trend which shows rising temperatures until about 1940, a slight downward trend from about 1940–1975, and a rise of about 0.5 °C between 1975 and the present day.

Three independent types of temperature measurement — air temperature taken at land climate stations and on ships at night (when the interfering effect of solar radiation is absent) and the temperature of the sea surface — all show (see Slide 25) good agreement from 1900 until the last couple of decades, when land temperatures have been rising at a faster rate than sea temperatures (as predicted to be the case for a global warming due to increased greenhouse gases).

Temperatures have also been measured in the atmosphere; over the last 50 years or so by weather balloons, and by satellite remote sensing since 1979. In the mid-troposphere, about 5 km above the surface, there has been a global-mean warming — see Slide 31. Although data are sparse in tropical regions, according to sensors on weather balloons, there seems to have been little change in temperature in the tropical mid-troposphere over the past 25 years, which is not what models predict. This discrepancy and its implications are the subject of ongoing research.

Q2: Could recent climate change be largely the result of natural variability?

Slides 27 and 28 showed how the observations of warming over the past 30 years or so cannot be replicated in the climate model if only natural factors are included, but can be replicated once man-made factors are added. This work used global-mean warming, and it is possible that the good agreement with observations could be as a result of offsetting errors in the model, for example by the model exaggerating the effects of man-made greenhouse gases and man-made cooling aerosols.

For this reason, more detailed studies have been done looking at the patterns of changes in temperature across the surface of the Earth and through the depth of the atmosphere. The results from these enabled IPCC to pronounce in the TAR that "...most of the observed warming over the past 50 years is likely to have been due to the increase in greenhouse gas concentrations", which in turn have been due to emissions from human activities, notably fossil fuel burning.

Since the TAR in 2001, several new studies have strengthened this conclusion. So, whilst we cannot absolutely exclude natural variability as the cause of warming over the past few decades, and it may have played some role, it is very unlikely that this will have been the sole reason. Our best estimate is that most recent warming is due to man's activities.

Q3: Isn't the apparent warming due to urbanisation?

No. Slide 26 shows the results of a recent analysis at the Hadley Centre of temperature trends over the last 50 years deduced separately from measurements on the most windy nights and the least windy nights, from the same stations. If urbanisation were causing the observed warming, one would expect calmer nights to have warmed more, as it is in these conditions that the heat island effect would act to warm the station compared to its rural surroundings. In fact, Slide 26 shows no difference between trends on windier and calmer nights, confirming that urbanisation is not to blame.

Q4: Hasn't climate variability been shown to correlate with solar variability?

Yes. Slide 9 shows an estimate of how solar irradiance has changed over the last 150 years. There appears to have been an upward trend from about 1900 to 1960, but thereafter little long term change (just the effects of the 11-year solar cycle). Simply working from the change in the amount of solar irradiance striking the Earth, we can calculate that this would have given a rise in global temperature of about 0.1 °C; this is also shown on the slide. Even if the Sun had a much larger influence on climate than currently thought, changes in the Sun could not explain the warming since the 1970s.

There have been theories which seek to explain recent global warming as due to changes in the Sun's magnetic activity (which is somewhat different from the behaviour of its irradiance). We know that increasing solar activity tends to reduce the number of galactic cosmic rays entering the Earth's atmosphere. Some theories argue that galactic cosmic rays are important for the formation of clouds, and we certainly know that clouds are an important influence on climate. In this way, the theory links changes in solar magnetic activity with changes in climate. However the link between cosmic rays and clouds is unproven, and even if cosmic rays did cause variation in clouds, this may not be in the right sense to explain climate change.

Q5: Aren't greenhouse gases like methane much more potent than CO_2, particularly if a short time scale is considered?

Yes. The warming effect of methane and other greenhouse gases per kilogram emitted is generally greater that that of CO_2. IPCC defines a quantity called Global Warming Potential which compares the warming effect of a greenhouse gas over a given time period (usually taken as 100 years) with that of CO_2 (which is given a value of 1). Most gases are more 'potent' than carbon dioxide, largely because the atmosphere already contains quite high concentration of CO_2, and hence its absorption of infrared radiation (the mechanism for the greenhouse effect) is already quite saturated. In fact, the additional infrared it traps is proportional to the logarithm of its concentration. For other gases, such as methane, infrared absorption is still far from saturated, and this is the main reason why its GWP is higher than that of CO_2. The value of the GWP for a gas reflects not only its infrared absorbing capability, but also its lifetime in the atmosphere and its density. By definition, the GWP of CO_2 is unity; that of other gases is given in the text accompanying Slide 17.

Of course, the warming effect of a particular gas will be a combination of its GWP and its total emissions, and because man-made emissions of CO_2 are much greater than any other gas, its warming effect will be greater, despite its low GWP. This is illustrated in Slide 17, where roughly two-thirds of the man-made warming effect over the next 100 years are projected to be due to CO_2 emissions.

Q6: Surely the oceans and the land surface absorb large amounts of man-made CO_2?

Yes they do, although it is by no means certain that they will continue to absorb as much as they do now. We estimate for the decade of the 1980s (see Slide 11) that fossil-fuel burning injected on average about 5.4 GtC/yr (billion tons of carbon, in the form of carbon dioxide, per year) into the atmosphere. In addition, changes to land use, mainly deforestation, added another 1.7 GtC/yr. We observe that atmospheric concentrations of CO_2 are rising at about 2 ppm per year, which equates to an increase in the burden of carbon of some 3.3 GtC/yr. Of the remaining 3.8 GtC/yr, we estimate that oceans absorb about 1.9 GtC/yr and vegetation and soils a further 1.9 GtC/yr. Thus, the ocean and land provide a free 'buffering' service by absorbing about half of the carbon we emit. However, this may not always be the case in future. As global temperatures rise, and rainfall and temperature patterns change, we believe that several changes to carbon absorption will take place, as described in Slide 60. The net result of these changes is predicted to be a reduction in the strength of the carbon sink in vegetation and soils, leaving more of the carbon dioxide that we emit left in the atmosphere, and a more rapid increase in CO_2 concentration and temperature rise than without this reduction in sinks. Although there is agreement amongst modellers that climate change will reduce the natural absorption of CO_2 by the biosphere, different models estimate different reductions. But the potential for enhancement of global warming from this feedback has been clearly demonstrated.

Q7: As natural emissions of carbon dioxide are very much greater than those from human activities, surely the effect of man is insignificant?

The exchange of 'man-made' carbon dioxide between man-made emissions, atmosphere, ocean and land, is about 7 GtC per year, as shown in Slide 12, which also shows much larger natural exchanges between atmosphere and ocean (about 90 GtC/yr) and atmosphere and land (about 60 GtC/yr). However, these natural exchanges have been in balance for many thousands of years, leading to the pre-industrial concentration of CO_2 remaining steady at about 280 ppm (see Slide 14). The effect of the additional man-made emissions is to unbalance the budget and lead to the rise in concentrations seen since about 1850, also shown on Slide 13.

Q8: Will aerosols help reduce climate change or even result in cooling?

There are many different types of aerosols — small particulates — in the atmosphere which are affected by human activity. Some, such as black carbon (soot), are emitted directly from man-made processes, and some are generated from other man-made emissions, such as the sulphate aerosols which are formed in the atmosphere from sulphur dioxide emissions from power stations, transport, etc. Some, such as mineral dust from deserts, are entirely natural, but their concentration in the atmosphere (and hence their effect on climate) could be changed if man-made climate change leads to desertification.

As can be seen from Slide 20, some aerosols, such as sulphates, predominately act to reflect back solar radiation (both directly and indirectly, see Slide 18) and hence exert a cooling influence on climate. Others, such as black carbon, absorb solar radiation and have a warming effect. The slide also shows how very uncertain the warming and cooling estimates of these aerosols is, compared to the relative certainty of the effect of greenhouse gases. Nevertheless, it is very unlikely that there has been sufficient aerosol cooling to have offset the warming effect of man-made greenhouse gases, and in the future, as concentrations of cooling sulphate aerosols are likely to decline, their lessening cooling effect may have the consequence of accelerating warming. Indeed, recent Hadley Centre estimates are that the exceptionally hot 2003 summer over continental Europe would happen typically more frequently than every decade in the absence of cooling from sulphate aerosols.

Q9: What is global dimming and what relevance does it have to climate change?

'Global dimming' is the term used to describe the observations from surface instruments showing a general reduction in the amount of solar radiation reaching the ground since about 1960, globally amounting to 2–3% per decade, up to about 1990. The dimming is variable from place to place, with some sites even showing a brightening over the period, but greatest in northern mid-latitudes. However, more recent research indicates that this trend reversed in about 1990 and since then there has been some 'global brightening', although being indirectly measured from satellites these more recent estimates may be less robust. It seems likely that the reductions, and perhaps the recent increases, may be due to changes in aerosols such as sulphates and soot (black carbon). The most recent version of the Hadley Centre climate model (HadGEM1), which includes both sulphate aerosols and soot, does simulate a reduction in surface solar radiation, though not as great as that actually observed. Neither the observations nor the implications for predictions of climate change are yet clear, and this is a subject of active research.

Q10: How reliable are climate models?

Climate models are a mathematical description of the processes in the Earth's climate system; atmosphere, ocean, land, cryosphere. The representation of climate processes in the model are based on experimental measurements in the real atmosphere, ocean etc, and these can be chosen within the constraints of these experiments to give the best possible agreement between model simulation of current climate and observations. We evaluate their reliability in a number of ways. Firstly by comparing their representation of the current climate and observations, including not just means but variability and extremes. Secondly, by driving them with the best estimates of changes to climate forcings over the last 150 years (natural, such as volcanoes and solar radiation, and man-made such as greenhouse gases and aerosols) and comparing the simulation of climate change from the model (sometimes called a 'hindcast') with observations of trends (in, for example, global mean temperature) over the same period. This is shown in Slide 28. Lastly, some validation can be carried out by comparing model simulation of climates many thousands of years ago with reconstructions of climate of the period (so called palaeoclimatologies). Validation exercises such as these provide compelling evidence that, at least in terms of gross temperature response, the model is effectively reproducing what has been observed, and this gives us confidence that the models are adequate tools for the prediction of future climates, albeit with the sort of uncertainty described in Slide 52 (at a global mean scale) and in Section 3.5 of the UKCIP02 report (at the scale of the UK). More detail on model validation and performance can be found in Chapter 8 (Model Evaluation) of IPCC TAR.

Q11: Weather forecasts aren't accurate for more than a few days ahead, so how can we possibly predict climate over the next 100 years?

Although they are made by the same sort of mathematical model, weather forecasts and climate predictions are really quite different. A weather forecast tells us what the weather (for example, temperature or rainfall) is going to be at a certain place and time over the next few days; it might say, for example, that there will be a band of heavy rain moving across Somerset tomorrow mid-morning.

A climate prediction tells us about changes in the average climate, its variability and extremes. For example, it might say that the average temperature of summers in Somerset in 40–60 years time will be 4 degrees higher than it is currently, it will enjoy on average 25% more rain in winter with three times the current number of heavy rainfall events, and 50% less rain in summer. It will not make a specific forecast such as: it will be raining in Somerset on the morning of 15 October 2044.

Q12: Shouldn't we wait until the predictions are more certain before taking action to control or prepare for climate change?

This is not a scientific question and, hence, outside the remit of this booklet. However, there are a couple of scientific points that can be made which are very relevant to the policy process. The first is that reducing the uncertainty in predictions takes time, because it requires (a) a better understanding of the processes in the atmosphere, ocean, cryosphere and on land, which control climate, and (b) improvements to models to reflect this new understanding and to run at a higher resolution, which in turn demands greater computer capacity. Progress is being made on both these fronts, for example the resolution of the newest Hadley Centre model (HadGEM1) is eight times greater than the previous model, HadCM3, and includes new processes such as the effect of soot and the ridging of sea ice. Nevertheless, benefits from detailed research into climate processes which informs the models, and the development of the models themselves, take time to feed through into improved predictions.

The second point is that, because of the large inertia of the climate system, at any given time past greenhouse gas emissions will have warmed the world but also have committed us to a further warming even if no further greenhouse gases were to be emitted. The longer we leave any decision and action to control climate change, the greater the commitment to future climate change (and its impacts) that will have built up.

Q13: Will ice sheets melt with climate change?

The two major ice sheets are on Greenland and in the Antarctic. The Greenland Ice Sheet contains enough water to contribute about 7 m to sea level, and the West Antarctic ice sheet (WAIS), which is the part of the Antarctic ice sheet most vulnerable to climate change, contains about 6 m.

A sustained rise in local temperatures of about 3 °C, equivalent to a global-mean warming of about 1.5 °C, which is likely to be reached by the end of the century if man-made emissions are not controlled, would melt the Greenland Ice Sheet, although it is estimated that this would take a few thousand years. A major collapse of the WAIS is thought to be very unlikely during the 21st century, although recent measurements suggest that contributions to sea-level rise from this source may be greater than previously estimated.

Q14: Isn't the evidence of temperature change in the Arctic and Antarctic inconclusive?

Although there is a clear rising trend in globally average temperature, there are large variations in trend from region to region. This is a consequence of natural variability of climate, which gets larger as we focus on smaller and smaller areas. This results in some areas warming less than the global average — or even cooling — and some areas warming more. In addition, naturally variability tends to be greater at high latitudes. These two factors lead to the Arctic and Antarctic having a wide variety of temperature changes. For example, the Antarctic Peninsula has warmed dramatically over the past 50 years, whereas at the same time some inland areas of east Antarctica have cooled. However, recent research suggests that changes to the winds over Antarctica, which may have been brought about by stratospheric ozone depletion, have played a significant role in the peninsular warming and the continental interior cooling.

Q15: How likely is the Gulf Stream to stop flowing? Will this make Europe colder?

The Gulf Stream (or North Atlantic Drift, to give it its proper title) brings warmer water from lower latitudes to the north-east Atlantic, and gives NW Europe a milder climate than it would otherwise have.

The mechanism driving circulation in the N Atlantic, of which the Gulf Stream is a part, is shown in Slide 57. This mechanism could be affected by man-made global warming in several ways, for example by increased rainfall over the N Atlantic, and hence there is the potential for the Gulf Stream to be reduced, or even switched-off, by man's activities.

When we use the Hadley Centre climate model to look at the response of the N Atlantic ocean circulation to future man-made emissions, shown in Slide 59, we see that reductions of about 20% by 2100 are predicted, rather than a complete shutdown. Other good climate models see greater or lesser reductions, but none produces a shutdown over the next 100 years.

The Hadley Centre model has also been used to investigate the impact on climate of a hypothetical shut-down of the THC. It predicts that whole of the northern hemisphere would be cooled, especially the N Atlantic; the UK might see a cooling of 3–5 °C. Daily minimum temperatures in central England in winter could plunge by 10 or 20 °C, and this would likely have a bigger effect on UK society than global warming. However, as was pointed out above, this is a 'what-if' scenario and not a prediction.

The model predictions of only partial shut-down of the THC seem reassuring, but we do not fully understand the reasons for the stability of the ocean circulation, and there have been recent measurements in the N Atlantic which seem to be at variance with model simulations. Hence, research continues to quantify the risk of this potentially high-impact outcome of climate change.

Q16: Isn't another ice age due soon? And won't it counteract global warming?

Over the past half million years or more, the world has alternated between ice ages and interglacials (periods between ice ages), with interglacials occurring every 100,000 years or so. We have been in the present interglacial for about 10,000 years. Evidence is strong for this behaviour to be due to changes in the Earth's orbit around the Sun, and the angle of its rotational axis, usually referred to together as 'astronomical forcing of climate'. This theory was formalised by Milankovic in the 1920s, and has been well confirmed by records from ice cores, ocean sediments, etc. Thanks to our knowledge of orbital mechanics these astronomical changes can be predicted, and it appears that astronomical forcing will be of little significance over the next 40,000 years or so, so the next ice age will be a very long time hence. Thus is it on a very different timescale to man-made global warming and cannot counteract it; if no action is taken to limit fossil-fuel emissions, for instance, climate will have changed very substantially by the time the next ice age starts.

Q17: Will natural methane emissions enhance man made emissions?

Substantial quantities of methane are emitted naturally from wetlands, and this emission is expected to change as wetlands change. Changing rainfall patterns will cause some wetland areas to increase in extent, others to decrease, and increases in temperature will act to increase emissions from wetlands. One version of the Hadley Centre climate model includes a description of wetland methane, and this predicts an increase in natural wetland emissions by the end of the century equivalent to the amount of man-made emissions projected for that time, thus leading to a more rapid rise in methane concentrations, and hence warming.

On the other hand, the chemical reactions in the atmosphere which destroy methane are expected to become more efficient in future, largely as a result of increased water vapour. This will act as a negative feedback on methane amounts.

Methane is also stored in permafrost, and it is likely that some of this will be released as surface warming extends into the permafrost and begins to melt it.

Finally, huge amounts of methane are locked up in methane hydrates (methane clathrates) in the oceans. They are currently at high enough pressures and temperatures to make them very stable. However, penetration of greenhouse effect heating into the oceans may destabilise them and allow some of the methane to escape into the atmosphere. The potential for this to happen is very poorly understood. There is concern that this may be another positive feedback not yet included in models, although there is little evidence for this from the behaviour of methane during the large temperature swings between ice ages and interglacials, and in particular over the last 50,000 years.

Q18: Are ozone depletion and climate change part of the same thing?

Not really, although there are links between the two. The depletion of ozone in the stratosphere over Antarctica (the 'ozone hole') was first discovered by scientists from the British Antarctic Survey in the mid-1980s. It is caused mainly by emissions of man-made chlorofluorocarbons (CFCs), which find their way into the stratosphere where they decompose into chlorine compounds which destroy ozone each autumn. Despite the fact that emissions of CFCs have been very severely cut back by the Montreal Protocol, because they have a lifetime of order 100 years, their concentration in the atmosphere has only recently started to turn down, and the ozone hole is expected to remain as large as it is now for decades to come, before it slowly recovers.

Links with climate change are threefold. Firstly, the CFCs which deplete ozone, and also some of their ozone-friendly replacements, are greenhouse gases and so also contribute directly to global warming. Secondly, the reduction in stratospheric ozone, both over Antarctica and more generally globally, acts to cool climate slightly; see Slide 20. Lastly, there is concern that increasing concentrations of CO_2 from fossil-fuel burning, because it is cooling the stratosphere (see Slide 31), aids the formation of the small particles in the stratosphere on which chemical reactions take place, and may be prolonging the ozone hole.

Q19: What will the impacts be of man-made global warming?

The impacts of climate change on society and economies will be many and various, in sectors such as agriculture, water resources, ecosystems, health, coastal communities, etc. It is too broad a topic to be covered in this Q&A section, but is comprehensively addressed in the report from Working Group 2 of the IPCC TAR, which also contains a shorter Technical Summary and Summary for Policymakers.

Recent UK research on the global impacts can be seen in the April 2004 special edition of the journal Global Environmental Change, edited by M. Parry.

Q20: Will increased CO_2 in the atmosphere stimulate plant growth?

Plant growth depends upon several factors. Plants require sufficient warmth, moisture, light and nutrients in the soil to photosynthesise, that is, to draw down CO_2 from the atmosphere into the body of the plant. If these other environmental factors are adequate then higher concentrations of CO_2 in the atmosphere will indeed enable plants to grow more rapidly. However increasing CO_2 concentration also changes climate, and if this becomes too warm or too dry then plants will no longer be able to take advantage of the CO_2 fertilisation effect. Hence there is a balance; over the past century the enhanced growth has dominated and vegetation across the globe has acted as a vital sink for man-made CO_2 emissions. But, as described in Slide 60, our research indicates that in future the beneficial effect of higher CO_2 concentrations will be reduced as the associated climate change in some areas will reduce the ability of vegetation to absorb man-made CO_2.

A further concern is the sensitivity of plant growth to concentrations of ozone, which is expected to increase in the lower atmosphere due to reactions between man-made emissions such as nitrogen oxides and hydrocarbons. Ozone can have a damaging effect on plant stomata and so there is a risk of reduction in vegetation productivity as ozone increases.

Q21: What do the different emissions scenarios driving the climate change predictions represent?

Future emissions of greenhouse gases from human activities will depend upon factors such as population growth, economic development, energy use, technological change, society's attitudes and political leadership. Obviously, we cannot know how all these factors will change, and what pathways emissions will follow in the future, but we can generate possible scenarios; the Intergovernmental Panel on Climate Change did this in its Special Report on Emissions Scenarios (SRES) in 2000. It considered various 'storylines' of how the world will develop and used models to estimate emissions which would follow from these storylines. All of the emissions scenarios are 'non-interventionist'; that is, they assume no policies to reduce emissions for the purpose of mitigating climate change.

Scenarios of climate change over the UK were published in 2002 for Defra and the UK Climate Impacts Programme (UKCIP02). They were based on climate predictions from Hadley Centre models, down to a resolution of 50 km. The headline predictions were for warming throughout the year but particularly in summer; less rain in summer but more rain in winter; greater frequency of heavy rainfall events in winter; reductions in snowfall and frosts; continued rise in sea level; increase in the frequency or height of coastal high water events. There is considerable regional variation in the changes; in broad terms they are expected to be greatest in the south and east, smallest in the north and west. The scenarios report stressed the uncertainty in the scenarios and suggested some ways of handling this. More detail is available from www.ukcip.org.uk

Q22: Isn't climate change going to be a good thing in the UK?

It may indeed be more pleasant to have warmer temperatures in autumn, winter and spring. However, summers in the UK, especially in the south-east and in cities, could be uncomfortably warm, leading to heat-related medical problems and aggravating respiratory conditions. There is a well known link between high temperatures and mortality rates. The exceptionally hot summer of 2003 resulted in 22–35,000 additional heat-related deaths across the continent of Europe, and some €10 billion uninsured crop losses. On the other hand, less cold conditions in winter would lead to fewer deaths from hypothermia.

Of course, climate change means much more than simply an increase in temperatures. The summers will probably become drier as well as hotter, leading to an increased risk of drought and pressure on water resources. Winters are likely to bring heavy rainfall events more frequently, with increased risks of urban and river flooding. As sea level rises, our coastline, especially in the south and east will be increasingly at risk, and more frequent high water events would be particularly damaging if the level of protection is not raised.

Q23: How will climate change impact on our lives in the UK?

Climate change will have impacts not only on the environment, but also on society and the economy. To find out more about these, please contact the UK Climate Impacts Programme, which is based at the University of Oxford. Visit www.ukcip.org.uk, for further information.

Q24: Which of the UKCIP02 climate scenarios is most likely?

The four climate change scenarios developed for the UK are based on four possible future pathways of man-made greenhouse gas emissions, derived from the IPCC SRES report, as shown in Slide 38 in the case of CO_2. IPCC states that these should not be regarded as equally probable, but there is no information on the relative likelihood of each. Some organisations are attempting to develop probabilistic emissions scenarios, but these are not yet at the point where they are reliable enough to be used as the basis for climate change scenarios. In the case of the UK climate change scenarios, it is best to consider the full range, rather than trying to identify one scenario as the most probable.

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Martin	Holt
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Matt	Huddleston
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Bruce	Ingleby
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Geoff	Jenkins
Venkata	Jogireddy
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