# Stabilising climate to avoid dangerous climate change

## — a summary of relevant research at the Hadley Centre

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# The Hadley Centre

The Hadley Centre is the UK Government's centre for research into climate change science. It is part of the Met Office, located within its new Exeter headquarters. Some 120 staff work in the Hadley Centre, researching aspects of climate change, and utilise about half the capacity of the Met Office NEC supercomputer.

The main aims of the Hadley Centre are to:

- monitor climate variability and change on global and national scales;
- attribute recent changes in climate to specific natural and man-made factors;
- understand the processes within the climate system and develop comprehensive climate models which represent them;
- use climate models to simulate climate change over the past 100 years, and to predict changes at global and national scale over the next 100 years and beyond;
- predict many of the impacts caused by climate change.

The Hadley Centre's work is carried out under contract to the Department for Environment, Food and Rural Affairs and the Government Meteorological Research Programme, with additional funding from the European Commission and others.

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## Contents:

# Summary

- What constitutes 'dangerous' climate change, in the context of the UN Framework Convention on Climate Change, remains open to debate
- The physical (chemical and biological) climate system — or components of it — are capable of changing rapidly, and the trigger point for such abrupt changes could provide one of the ways of defining 'dangerous'
- We can also investigate the impacts of relatively gradual change — and their associated costs — to seek ways of defining a dangerous change
- The inertia of the climate system means that we could be committed to dangerous change, many decades before we reach the dangerous level
- Once we decide what degree of (for example) temperature rise the world can tolerate, we then have to estimate what greenhouse gas concentrations in the atmosphere should be limited to, and how quickly they should be allowed to change. These are very uncertain because we do not know exactly how the climate system responds to greenhouse gases
- The next stage is to calculate what emissions of greenhouse gases would be allowable, in order to keep below the limit of greenhouse gas concentrations. This is even more uncertain, thanks to our imperfect understanding of the carbon cycle (and chemical cycles) and how this feeds back into the climate system

# Introduction

The UN Framework Convention on Climate Change (UNFCCC) — signed at the 1992 Earth Summit in Rio de Janeiro — has as its ultimate objective "to achieve... stabilisation of greenhouse gas concentrations in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system".

The level which would prevent dangerous interference, or indeed the way in which this level could be defined, have not yet been determined. There are several possible ways by which 'dangerous' climate change could be defined. One relatively objective way, is to base it on the trigger point for some abrupt change in the physical climate system or one of its components. Other ways, based on socio-economic impacts and costs, might apply in a climate which changes relatively gradually, although impacts and costs tend to be more uncertain (and more subjective) than those in the purely physical system.

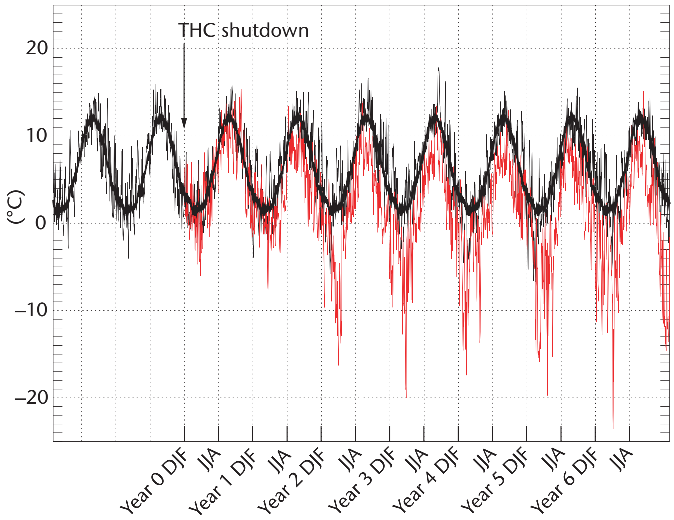
Once a 'tolerable' (i.e. non-dangerous) change has been determined — say, in terms of a global temperature rise — we then have to calculate what this corresponds to in terms of tolerable greenhouse gas concentrations in the atmosphere. Finally, from there, we need to calculate what future emissions would be allowable in order to keep concentrations at tolerable levels.

This booklet does not attempt to come up with an answer to any of these questions, but illustrates some of the wide range of research being undertaken at the Hadley Centre which is contributing to their resolution. It shows possible results of rapid changes in components of the climate system, and discusses some of the uncertainties in deducing tolerable concentrations and emissions and how these might be managed. The research described is undertaken by a number of different groups in the Hadley Centre.

# Defining 'dangerous' based on an abrupt or irreversible climate change

Work at the Hadley Centre concentrates on four components of the climate system which have the potential to change abruptly: the Gulf Stream; the Greenland ice sheet; the carbon cycle; and methane hydrates.

## Changes to the Gulf Stream

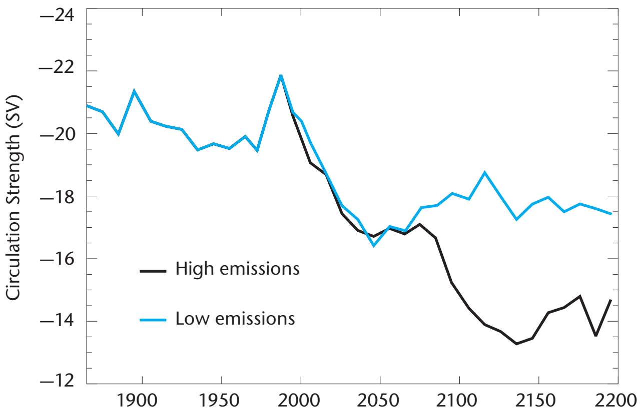



*Predicted daily minimum Central England Temperature following a hypothetical shutdown of the THC in year 0 (red). The black curve shows the modelled climate with no THC shutdown*

Large currents in the ocean transport vast amounts of heat between the equator and higher latitudes. The global current system is generally known by the term thermohaline circulation (THC), as it is driven by changes in ocean temperatures and salinity. In the North Atlantic there are two areas — one in the Labrador Sea and the other between Greenland, Iceland and Norway — where the ocean surface water is cooled by cold winds, becomes more dense, and then sinks. The cool water flows at depth towards the equator with about 100 times the flow of the Amazon, and is replaced by warm surface water flowing from the Gulf of Mexico, which is commonly (if imprecisely) called the Gulf Stream.

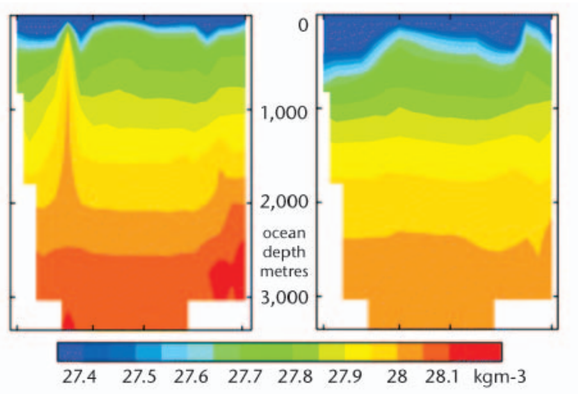
However, this sinking process can be disrupted when fresh water from rain, rivers or melting ice overlays the salty ocean water. An increase in fresh water could slow down or even switch off the Gulf Stream. A 'what-if' experiment using the Hadley Centre computer model shows that if it did, the UK annual temperature would cool by up to 5 °C in a matter of a decade or two. But the effect on extreme temperatures would be worse. The figure above shows that winter daily minimum temperatures in central England could regularly fall well below -10 °C or so. If this were to happen, the disruption to society would be enormous; certainly not as extreme as depicted in the film *The Day After Tomorrow* but enough to disrupt agriculture, transport and other infrastructure. But will it happen?

The Gulf Stream has switched off before — at the end of the last ice age about 13,000 years ago — when meltwater from a huge glacier in Canada is believed to have flowed into the North Atlantic and stopped the sinking mechanism, and Europe cooled by several degrees in only one or two decades.




*The strength of the North Atlantic ocean circulation simulated by the Hadley Centre climate model, with IPCC High future emissions and Low future emissions scenario*

The Hadley Centre climate model, which has a good simulation of the North Atlantic ocean current system, has been used to look at the effect on the Gulf Stream of future man-made climate change. The model projects that the Gulf Stream would slow down by about 20% by the middle of the century, but by no means completely switch off, even with emissions projections at the high end of the range of possibilities. When climate was stabilised in the model at the end of this century following a high emissions scenario, there was a reduction in the current of about 30% by 2200 (see above).




*A cross-section of potential density in the ocean south of Greenland, simulated in a pre-industrial climate (left) and predicted by the 2090s (right). The spike on the left hand side in the pre-industrial climate shows the effect of convection in the Labrador Sea; this convection switches off in the model by the 2020s*

The same model experiment also predicts that one of the sinking areas — in the Labrador Sea — ceases to operate by about 2020, as shown above. The switch off of one of the two 'pumps' driving the Gulf Stream might be thought a large enough change in the physical climate system to be regarded as dangerous. However, the cooling effect on Europe of the decreased Gulf Stream flow was more than offset by the greenhouse-effect warming and has already been taken into account in the climate change scenarios we produced in 2002 for the UK Climate Impacts Programme.

Other comprehensive climate models give different results, ranging from reductions of a few percent to nearly 50%, but none shows a complete switch-off over the century for this scenario of future emissions. However, this wide range of predictions shows that there is no single robust conclusion, reflecting our lack of understanding of ocean currents and their apparent stability. Some recent measurements from research ships in the Arctic seem to indicate that changes are already taking place. So, research continues apace to gain a better understanding of processes in the oceans that could affect the thermohaline circulation. Although we estimate that the chances of a switch-off in the next hundred years are low, we do not know how low, so we are working with others to understand more about the vulnerability of the Gulf Stream.

## Changes to ecosystems and carbon sinks

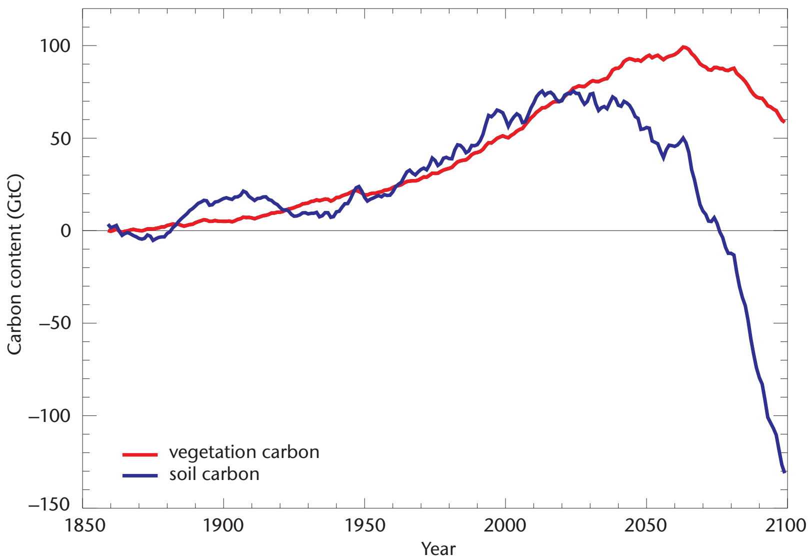
About half the carbon dioxide emitted by fossil fuel burning is absorbed by natural 'sinks' in ecosystems and the oceans. Were it not for this, climate would already be changing faster than it is. But there are concerns that this free service provided by nature may run out in the future, as natural sinks weaken due to changes in climate. One version of the Hadley Centre climate model contains a Dynamic Global Vegetation Model, allowing vegetation type and amount in the model to change as climate changes. Furthermore, the change in vegetation will modify how carbon is absorbed, and so the model also contains a representation of the complete carbon cycle (including soils and oceans).

As $CO_2$ and temperatures increase due to man's activities, several things happen. Firstly, extra $CO_2$ acts as a fertiliser and increases the growth of vegetation — particularly in northern forests where warming also encourages growth — and this helps to offset man's emissions (although new tree growth may darken the surface and act to warm the planet). But in some parts of the world, where rainfall decreases and higher temperatures increase evaporation, vegetation will die back.

Thus, instead of carbon being drawn from the atmosphere, it will actually return to the atmosphere to enhance already increasing concentrations. The same thing happens in much greater quantities and on a global scale in soils, as microbial activity is accelerated in a warmer climate and more carbon dioxide is emitted.

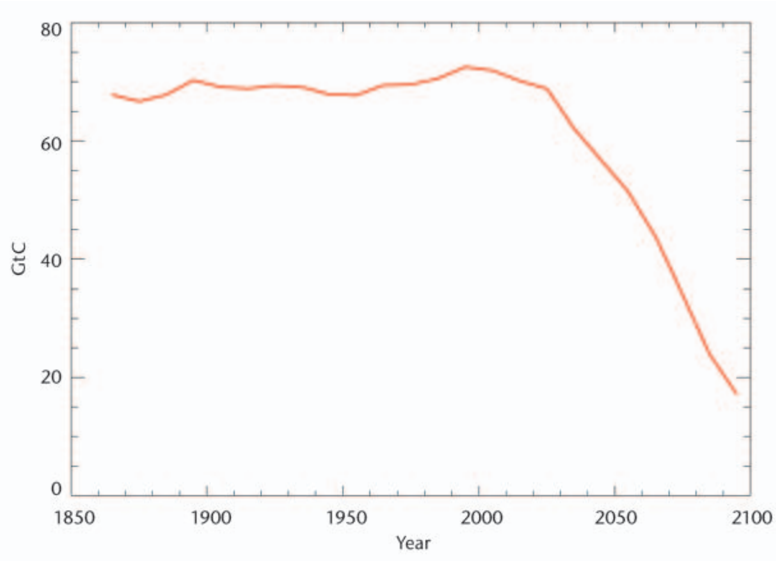
The combined effect of all these changes to the amount of carbon stored in ecosystems is shown below. The strength of the vegetation sink starts to diminish in the latter half of this century, and by the final decades it turns into a net source. Soils change even more quickly, and are predicted to become an additional source of carbon before the middle of the century.

Changes in global soil and vegetation carbon amounts




*Change in the global amount of carbon stored in vegetation and soils, simulated by the Hadley Centre climate model coupled to a dynamic vegetation and carbon cycle model*

In the Hadley Centre climate model, the Amazon region is predicted to suffer a particularly strong warming and large reduction in rainfall, and these lead to trees dying back and the region being able to support only shrubs or grass at the most. The figure below shows an abrupt change in the amount of carbon (vegetation plus soils) stored in Amazonia; by the end of the century more than 75% of the carbon has gone.




*Change in the total carbon stored in Amazonian vegetation and soils, simulated by the Hadley Centre climate model coupled to a dynamic vegetation and carbon cycle model*

The ocean also plays a large part in the carbon cycle. It provides a 'chemical sink' for carbon dioxide by simply absorbing more of it. It also provides a 'biological sink' as carbon is absorbed by phytoplankton and higher life forms. We know that these processes can be sensitive to climate change; for example, a warmer ocean can absorb less $CO_2$ and, as surface waters saturate, the ocean carbon sink will weaken if the circulation does not transport the carbon to depth.

All these processes are also represented in the model. The net effect is predicted to be a reduction in uptake (by about 0.5–1GtC/yr) due to climate change, leaving more $CO_2$ in the atmosphere. In addition, increasing the $CO_2$ absorbed in the oceans makes them more acidic, which can affect some life forms that turn carbon into calcium carbonate, and hence the strength of the biological sink.

Although $CO_2$ is far and away the most important anthropogenic greenhouse gas, other constituents which are changed by human activities — such as methane, nitrous oxide and aerosol particles — act to change the earth's climate. In future, changes in other greenhouse gases are likely to contribute the equivalent of an additional 50–150ppm of $CO_2$ to the warming effect. Thus, if we estimate that we need to stabilise climate at $CO_2$ concentrations of 550ppm, this might mean — in practice — stabilising $CO_2$ itself at concentrations of, say, 450ppm, allowing for an equivalent of a further 100ppm of $CO_2$ from other greenhouse gases.

In the same way as feedbacks between climate and the carbon cycle can modify future concentrations of $CO_2$ (as described above), feedbacks between climate and chemical reactions in the atmosphere will act to modify the concentrations of some of the other greenhouse gases. An example is methane, which shows a smaller rise in concentrations when climate feedback is included, than without it.

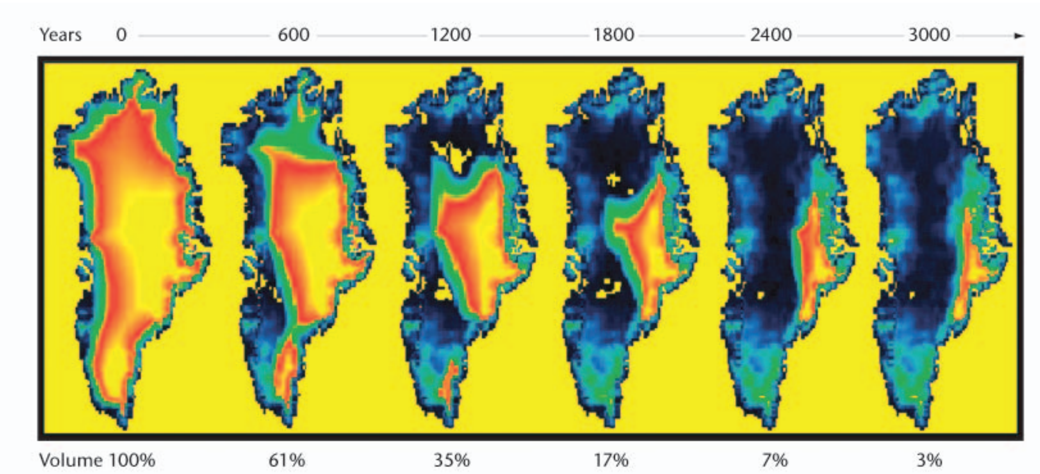
## Melting of the Greenland ice sheet

The Greenland ice sheet is more than three kilometres thick in places and contains nearly three million cubic kilometres of ice. If it were to melt, sea levels around the world would rise by about seven metres, inundating many coastlines and most of the world's great cities in developing and developed countries alike. The Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR) estimated that the ice sheet would begin to contract once local warming reaches about 3 °C — equivalent to a global warming of about 1.5 °C — and a complete meltdown, taking millennia, would be inevitable. By looking at a range of climate sensitivities from different IPCC models, we have estimated that this warming will occur by 2100 in most of the IPCC models, even if emissions were on a course to stabilise at 550ppm $CO_2$ or its equivalent.

To estimate how quickly Greenland would melt, we have coupled a high-resolution model of the Greenland ice sheet — from the Alfred-Wegener Institut (AWI) in Germany — to the Hadley Centre climate model. This simulates the effect of climate change on the ice sheet, and the feedback from this to climate. The evolution of the ice sheet has been estimated for a pessimistic, but plausible, scenario in which atmospheric $CO_2$ was increased to four times pre-industrial concentrations (that is, about 1100ppm) and then stabilised.

The figure below shows that about half the ice would melt in the first 1,000 years, with almost all melting after 3,000 years. The meltwater contribution to sea-level rise would peak at about 5 mm/year, which is considerably more than the recent rate (1–2 mm/year). This contribution from Greenland would be in addition to sea-level rise due to thermal expansion of the oceans.

*Change in the ice sheet volume predicted by the Hadley Centre climate model coupled to the Alfred-Wegener Institut ice-sheet model, following a quadrupling of atmospheric $CO_2$ in year 0. Yellow indicates thick ice while blue indicates thin (or no) ice*



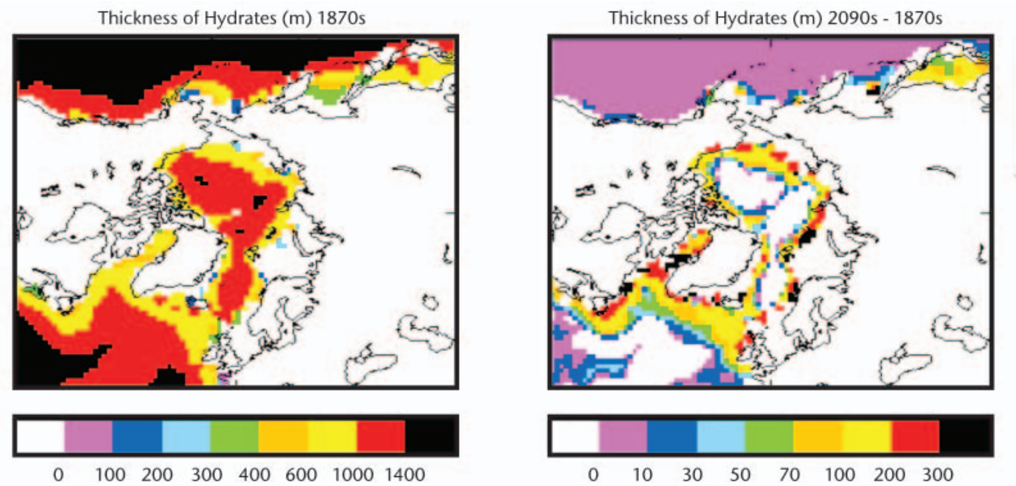

Some model runs which the Hadley Centre and AWI carried out earlier, showed that once Greenland begins to melt, it would not be possible to ever regrow it to its present size, even if $CO_2$ was reduced to pre-industrial concentrations (itself an unrealistic task). However, these estimates were done with a relatively simple coupling between climate and ice sheet, and we are now investigating this in more detail with colleagues at AWI, using the fully coupled climate-ice sheet model.

## Increasing natural methane emissions

Methane hydrates, also known as methane clathrates, are structures consisting of frozen methane gas locked into a water-ice lattice. They are found in areas of the ocean which are sufficiently cold and at sufficiently high pressure to keep them stable — that is, at the floor of deep, cold oceans — with a much smaller quantity in Arctic permafrost. It is estimated that some 10,000 GtC are locked up in methane hydrates; twice as much as in coal, oil and natural gas reserves. If ocean warming penetrated sufficiently deeply to destabilise even a small fraction of this methane and release it into the atmosphere, it could lead to a rapid increase in greenhouse warming.

The Hadley Centre has mapped the joint temperature and pressure condition for methane hydrate stability onto the model, to estimate the maximum quantities of methane hydrates that could potentially be supported in the different areas of the oceans' floors under a pre-industrial climate (left hand panel). We have also estimated the maximum potential quantities supportable under a scenario of climate change for the end of the century. Calculations of the differences between these two states (right hand panel) illustrate where methane hydrate could potentially be destabilised.

*Thickness of layer where methane hydrates could potentially exist in the pre-industrial climate (left) and the reduction in this layer by the 2090s, as simulated by the Hadley Centre climate model*




This calculation does not yet include the effect of sea-level rise — some of which will act to stabilise hydrates — but it seems unlikely that this will prevent at least some methane release. Work continues to refine the calculations, including consideration of the potential contribution from melting permafrost on land. Estimates of future emissions will require observational data on the current extent of hydrate deposits.

We have also looked at natural methane gas emissions from wetland areas, and calculated how these would change as wetlands change and temperatures rise. We estimate that by the end of the century, man-made global warming could release as much extra 'natural' methane from wetlands as human activities are expected to emit by that time.

# Defining ‘dangerous’ when climate changes gradually

An alternative to defining ‘dangerous’ from the onset of abrupt changes to the physical climate system, is to base it on the impacts and costs resulting from changes which might occur more gradually.

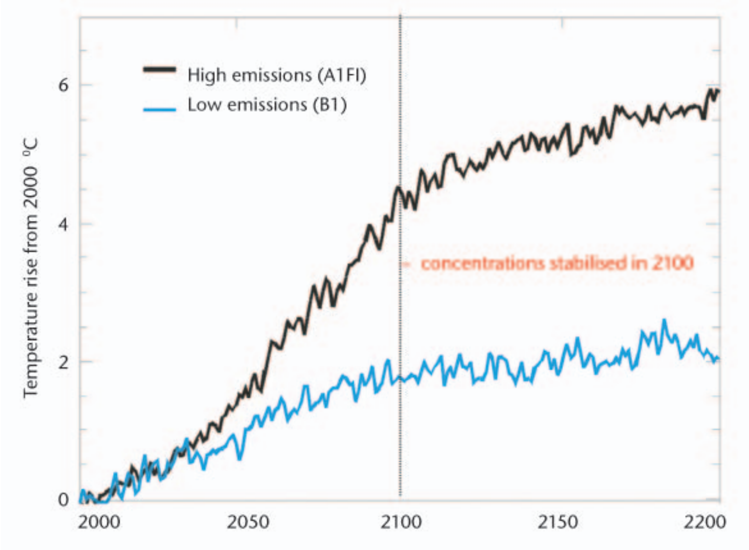
Some years ago, climate change scenarios from Hadley Centre models were input into a range of impacts models to investigate the effects on ecosystems, agriculture, water resources, coastal communities and health. The impacts of unmitigated increases in emissions were compared to those where emissions led to stabilisation at 550ppm or 750ppm of carbon dioxide (or its equivalent in terms of a mixture of greenhouse gases such as methane, nitrous oxide, etc).

More recently, the impacts on these sectors of climate change from the IPCC SRES emissions scenarios has also been published, again using the Hadley Centre climate model. IPCC has now asked climate modellers to show the effect on climate of stabilising greenhouse gas (and aerosol) concentrations at 2100, following the SRES emissions over the 21st century, for inclusion in its Fourth Assessment to be published in 2007.

## Climate change from IPCC stabilisation scenarios

We have used the HadCM3 model to explore climate change due to each of these scenarios, and the following figures show results from two of them. The first of these scenarios (High emissions — A1FI) assumes rapid growth in $CO_2$ emissions over the 21st century, giving a $CO_2$ concentration by 2100 of about four times pre-industrial levels (1100ppm). The second example (Low emissions — B1) shows $CO_2$ emissions rising and then falling slowly through the century and leaving about double the pre-industrial $CO_2$ concentration (550ppm) in the atmosphere by 2100. In both cases, the emissions scenarios include other greenhouse gases and aerosols, and concentrations of these in the atmosphere are stabilised after 2100.

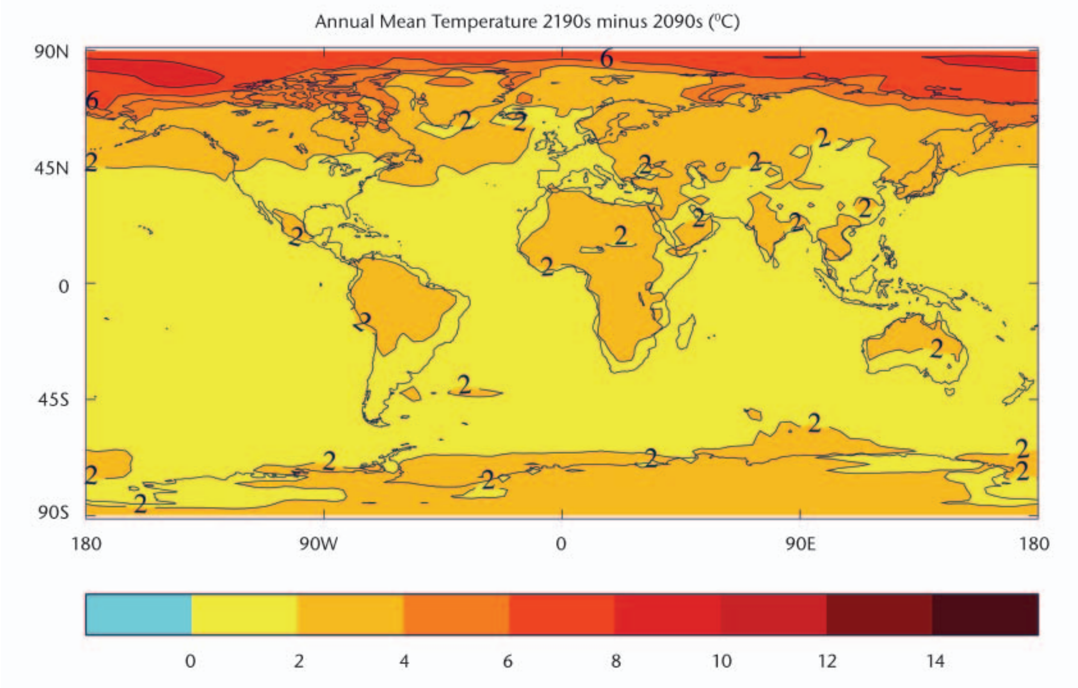
The next figure shows the global warming calculated by the Hadley Centre model for these two stabilisation scenarios, and is a good illustration of the effect of the inertia of the climate system. For the IPCC low emissions scenario, the climate warms by about 1.8 °C by 2100, and stabilisation at this level leads to a further 0.5 °C warming up to 2200. The high emissions scenario gives a warming to 2100 of about 4.5 °C. After stabilisation there is a further rise of about 1.5 °C up to 2200, (and a further rise of a few tenths of a °C beyond that, not shown).



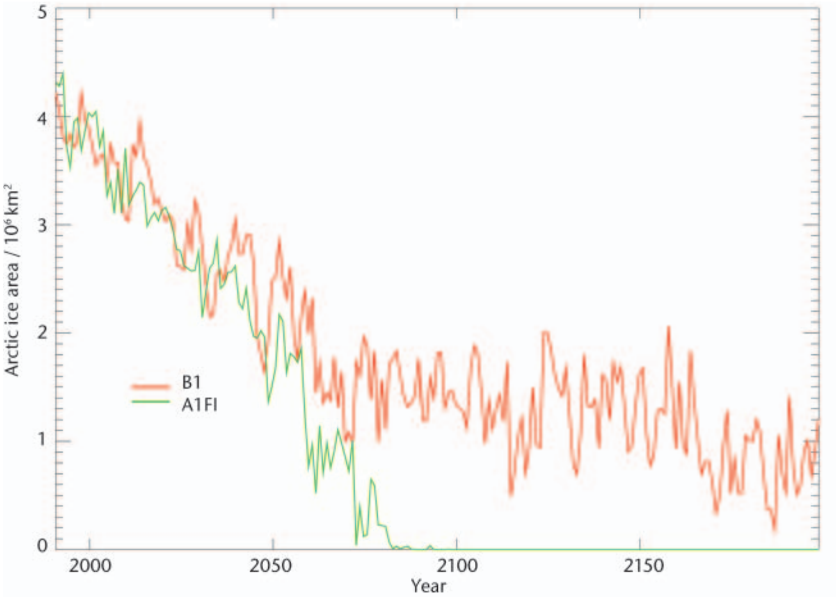

*Change in global mean temperature from 2000 due to the IPCC High- and Low-emissions scenarios, with stabilisation of concentrations of greenhouse gases (and aerosols) at 2100, as predicted by the Hadley Centre climate model*

The pattern of further temperature rise over the 22nd century, after concentrations of greenhouse gases are stabilised, is shown in the figure below. We need to take account of the fact that any ‘safe’ level of climate change that we can identify — for example 2 °C above pre-industrial — is the level to which we may ultimately be committed, rather than the actual change when emissions are curtailed.

*Commitment to change in annual temperatures over the course of the 22nd century, following stabilisation of greenhouse gas concentrations in 2100*



*Change in area of Arctic summer sea ice from the High- and Low-emissions scenarios, with forcing stabilised in 2100*

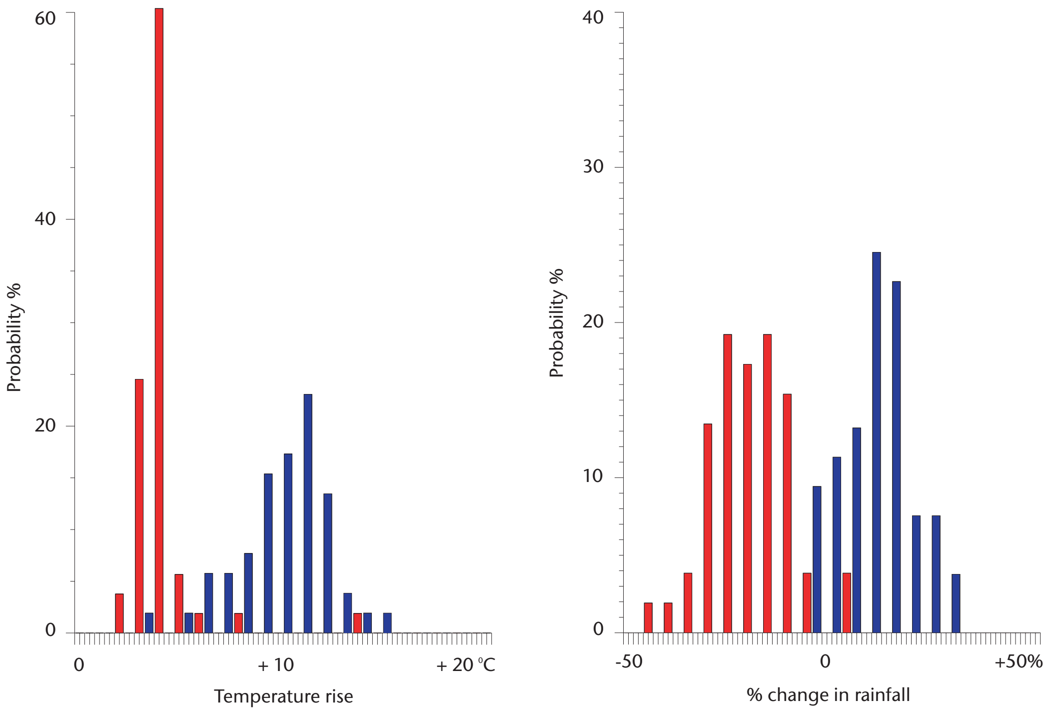



## Changes in Arctic sea ice

The Hadley Centre maintains the long-term record of sea-ice cover and sea-surface temperature, known as HadISST. This shows that until the 1960s, the extent of Arctic sea ice was relatively constant, but since 1970 it has decreased by about 7.5% (a million square kilometres). Using only natural factors — such as internal 'chaos' and solar and volcanic changes — we were not able to reproduce this change with the Hadley Centre model. However, when human activity is also taken into account, model simulations are in good agreement with observations, implying a man-made cause for the melting of Arctic ice.

The Hadley Centre model predicts that with the IPCC 'high emissions' (IPCC SRES A1FI) scenario, there would be essentially no Arctic sea ice in September (the month when sea ice is at its minimum) by about 2080. Even with the lowest emissions scenario (IPCC SRES B1), about 60% of the ice is lost by the end of the century, as shown in the figure above. If climate is stabilised then, there is a continuing further loss of summer sea ice, down to about 25% remaining by 2200. As in recent decades, the fractional change in sea-ice volume is predicted to be even bigger than that in sea-ice extent.

*Probability of different levels of change in summer maximum daily temperature (left panel) and rainfall (right panel) for Prague, showing the different behaviours of the seasonal mean (red) and daily extreme (blue)*




## Changes in extremes

Many of the impacts of climate change are likely to be due to changes in extremes, and these can sometimes be counter-intuitive. The above figure shows changes in summer temperature and rainfall for Prague, resulting from a doubling of $CO_2$ concentrations in the atmosphere. The left hand panel shows change in temperature for both the summer mean (red bars) and the extreme hottest day (blue bars). The right hand panel shows similar predictions for changes in rainfall, summer mean and wettest day. Changes are shown, not as single deterministic values from one model, but as a probability distribution from many models, thus quantifying the large uncertainty in predictions arising from the modelling process.

The most noticeable feature is that changes in extremes in some areas can be very different from those in the seasonal mean. For Prague, extreme temperatures are predicted to rise by a much greater amount than the mean. And in the case of rainfall, a clear reduction in the summer mean is accompanied by an increase in extreme rainfall events.

Hence, if we want to calculate the impact of climate change properly, we do have to make sure that this includes the effect of extremes, as these can be very different from mean quantities and are likely to dominate. Because this can be difficult to do off-line (that is, with climate scenarios feeding into separate impacts models), modellers at the Hadley Centre are starting to build impacts models into the coupled climate model — starting with crop models developed at the University of Reading — to take full account of extremes.

# What does a given level of dangerous climate change mean for concentrations?

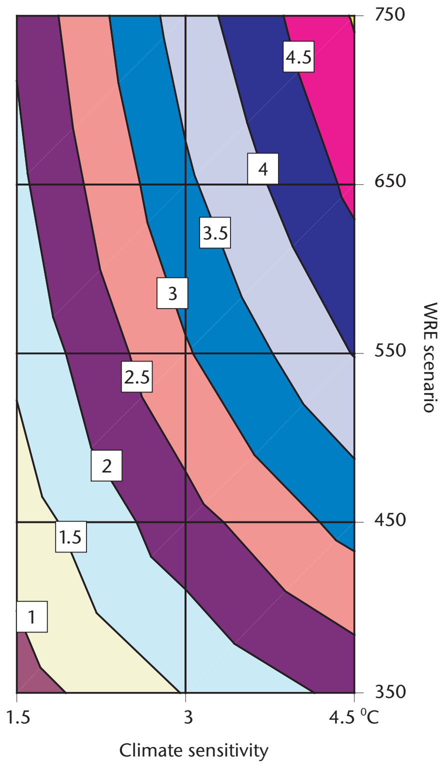
Assuming we know what the tolerable climate change is — for example, in terms of temperature — how low do we need to keep greenhouse gas concentrations to prevent this temperature being reached?

The relationship between increased concentrations of greenhouse gases and global average temperature rise is often expressed in terms of 'climate sensitivity', defined as the warming which would ultimately occur following a doubling of $CO_2$ concentrations. For a particular climate model, the climate sensitivity will be mainly governed by the strength of climate feedbacks — for example, due to changes in clouds or sea ice — and this (and, hence, the climate sensitivity) can vary greatly from model to model. In the IPCC 2001 Assessment, the range was from 2 °C to 5.1 °C.

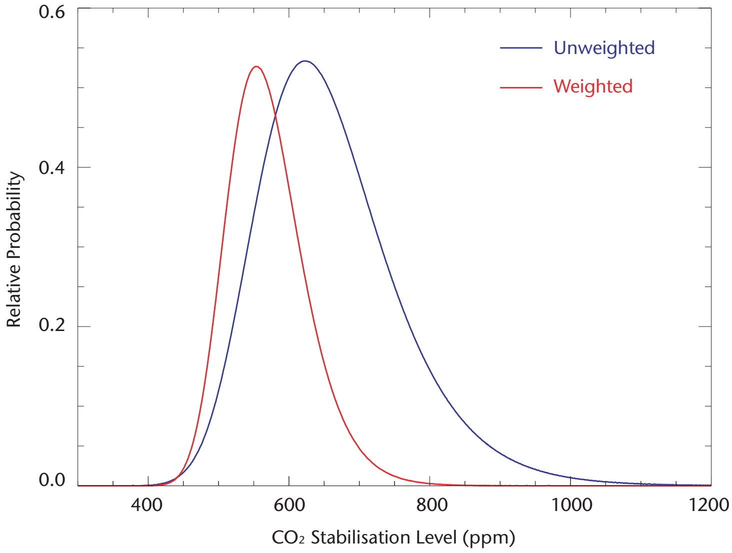
For a given level of global warming which could be called dangerous, this uncertainty in climate sensitivity translates into an uncertainty in allowable greenhouse gas concentrations. This is illustrated in the figure below, using the UEA/NCAR MAGICC 4.1 model, showing the temperature rise to 2150 resulting from different WRE stabilisation scenarios (stabilising $CO_2$ at 350ppm, 450ppm etc) with climate sensitivity varying from 1.5 °C to 4.5 °C.

If the temperature rise by 2150 was required to be kept to 2 °C, for example, a climate sensitivity of 3 °C would mean stabilising $CO_2$ (or its equivalent) below 350ppm. If the climate sensitivity was at the bottom end of the range — say 1.5 °C — stabilisation could be as high as about 700ppm and still allow temperature rise to be limited to 2 °C. On the other hand, if climate sensitivity was greater than 3 °C, stabilisation at concentrations well below those of today would be required.

On the next page we describe how we are developing techniques for coping with this uncertainty in climate sensitivity, using probabilistic methods.




*Global mean temperature rise to 2150 calculated by the MAGICC 4.1 model as a function of the WRE stabilisation scenario (350ppm, 450ppm....750ppm) and the value of climate sensitivity*




*The relative probability of being able to limit global mean temperature rise to 2 °C relative to present day, as a function of the level at which $CO_2$ (or its equivalent) is stabilised*

Clearly, when calculating to what level the $CO_2$ concentration should be allowed to rise to prevent climate change becoming dangerous, the large uncertainty in climate sensitivity is unhelpful to policy-makers.

It is expected that the uncertainty will narrow as models become more sophisticated, but this will not happen quickly. Instead, we aim to cope with this uncertainty by quantifying it in the form of probabilistic estimates. To do this, we build a large number of climate models, each having a different (but plausible) representation of components of the climate system (clouds, land surface, etc) and, hence, a different strength of the feedbacks between them and different climate sensitivity.

We use each of these models to calculate the stabilised $CO_2$ concentration which would lead to a particular stabilised temperature rise — for example, 2 °C above the present day — and plot all the values on a curve, shown in the blue line in the figure above.

Next, we evaluate the reliability of each of the climate models by comparing its simulated present-day climate with observations, and use this to weight each value of the required stabilised $CO_2$ concentration.

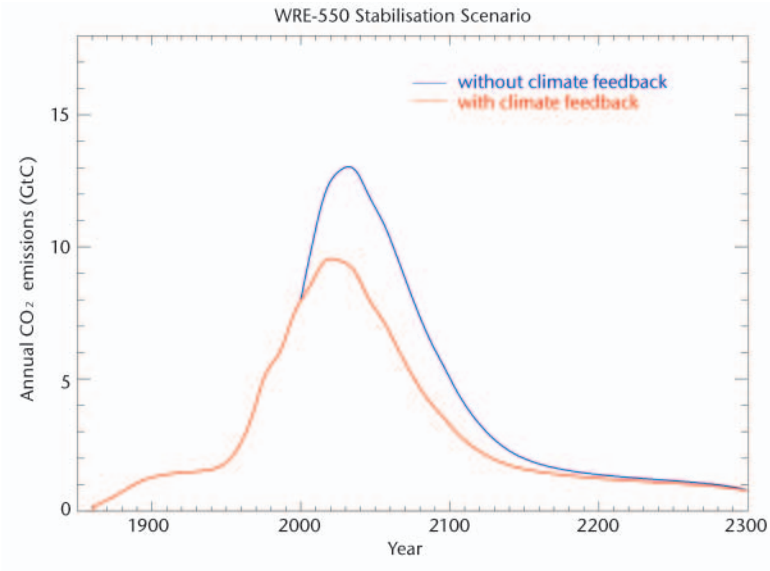
Finally, we arrive at a curve showing the probability of different levels of stabilisation being necessary to limit temperature rise to 2 °C; the red line in the figure above. Work using an initial 53 models shows that the level of concentration at which $CO_2$ would need to be stabilised in order to limit global-mean temperature rise to 2 °C above present day, would be in the range of about 490ppm to 670ppm (5% and 95% confidence levels), with probability as shown in the figure.

Note that this work is in its infancy and so far has used only models which are based around the Hadley Centre climate model. During the next couple of years we will include other changes — for example to the model structure and from other climate models — and use better estimates of model reliability to build up a more robust probability distribution of climate sensitivities. This will allow policy-makers to assess the risk to climate of different levels of stabilisation of greenhouse gases.

# What does a 'tolerable' level of concentrations imply for global emissions?

Once we have decided what level of concentrations (of $CO_2$, for example) is safe, we then have to calculate what emissions are 'allowed' so as not to exceed it. In principle this would seem to be fairly straightforward. In the case of $CO_2$, assuming roughly half of all global emissions remain in the atmosphere as at present, then for every 1 GtC emitted, concentrations would rise by about 0.2ppm.

However, there are many feedbacks in the current climate system whose strength may change in the future. For example, in an earlier section on the carbon cycle, we showed how (based on a model which couples climate, ecosystems and the carbon cycle) warming will reduce the ability of vegetation and soils to continue to absorb man-made $CO_2$. If the same model is used to calculate the emissions which would be allowed in order to keep below a certain stabilisation level, then estimates are very different from those with a model which does not include this feedback.




*Emissions of $CO_2$ which would be consistent with the WRE550 stabilisation scenario, estimated by the Hadley Centre climate model with and without the inclusion of carbon cycle feedback*

The figure above shows that the emissions which would be allowed in order to stabilise $CO_2$ concentration at 550ppm (for example, the oft-quoted WRE 550 case) — as predicted by the Hadley Centre coupled climate-carbon model — are much less than those calculated previously. The cumulative emissions from the present to 2300 are reduced by about 25%, from 1,350 GtC to 1,000 GtC.

Once the rate that global emissions have to be limited to in order to prevent dangerous climate change has been identified, this total then needs to be allocated to specific countries.

This allocation is, of course, purely a political decision, but it is one in which science can play a role. For example, the UNFCCC Subsidiary Body on Scientific and Technological Advice (SBSTA) has asked member states to investigate the utility of the 1997 Brazilian Proposal as a possible way of doing this. The Brazilian Proposal suggested that the relative extent to which individual (developed) countries have already changed climate (for example, temperature or climate forcing) could inform targets for their future emissions. Work on this takes place under the MATCH programme, and the Hadley Centre has been involved for some years. There are, of course, other methodologies which can be used to inform the debate on national emissions reductions.

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