Rapid climate change: an overview for economists

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Abstract: The possibility of future rapid climatic changes is a pressing concern amongst climate scientists. For example, an abrupt collapse of the ocean's Thermohaline Circulation (THC) would rapidly cool the northern hemisphere and reduce the net global primary productivity of vegetation, according to computer models. It is unclear how to incorporate such low-probability, high-impact events into the development of economics policies. This paper reviews the salient aspects of rapid climate change relevant to economists and policy makers. The main scientific certainties and uncertainties are clearly delineated, with the aim of guiding economics goals and ensuring that they retain fidelity to their scientific underpinnings.

Keywords: rapid climate change; global warming; greenhouse effect; thermohaline circulation; THC; climate feedbacks; tipping points; economics; climate policy.

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1 Introduction

Anthropogenic climate change is a classic example of intergenerational inequity. The climate system responds to changes in atmospheric greenhouse gas concentrations on timescales of decades or longer, due to the large heat capacity of the ocean (*e.g.*, Open University, 2001). Therefore, the generation of people emitting greenhouse gases will always precede the generation suffering the climatic changes caused.

The climate might change so slowly (*i.e.*, over many decades or centuries) that there is ample time for future generations to adapt to their new climatic regimes. Such adaptation would likely be painful and expensive, but not impossible, at least for the richest nations. However, the possibility of very rapid climatic changes is a current and pressing concern amongst climate scientists. 'Rapid' in this context refers to changes occurring so quickly (*e.g.*, within a decade or two) that adaptation is impossible, even for the richest nations. Rapid climate change could occur if the climate system reaches a tipping point, *i.e.*, a threshold beyond which (due to non-linear climate feedbacks, *e.g.*, Williams *et al.*, 2007) a small further increase in greenhouse gas concentrations triggers a disproportionately large response. Rapid climatic discontinuities may be a key consideration when attempting to select a market instrument to address climate change: for example, they are a major deciding factor in the price-versus-quantities debate (Weitzman, 1974).

This review paper will consider the possibility of rapid climatic changes caused by a reduction in the strength of the ocean's Thermohaline Circulation (THC), so-called because it is driven by variations in the temperature ('thermo') and salinity ('haline') of sea water. The THC is popularly but mistakenly taken to be synonymous with the Gulf stream, although in fact they are distinct. The Gulf stream is a local wind-driven ocean boundary current not at risk of collapse in response to global warming. Not so for the global THC, as we shall see.

Many of the scientific aspects of climate change are now sufficiently certain that the economic aspects can begin to be meaningfully examined. Correspondingly, the economic impacts of climate change have been the subject of a number of comprehensive studies in recent years. According to Munich Reinsurance, one of the world's largest insurance companies, the global cost of environmental disasters has doubled every decade from US$50 billion in the 1960s to nearly US$400 billion in the 1990s (Munich Re, 1999). Extreme weather events have been implicated in corporate performance disappointments (Carbon Disclosure Project, 2002). Leading insurance firm CGNU warned delegates at a World Climate Change Conference that damage to property due to global warming could bankrupt the world by 2065 (Verlander, 2000). Quoting from Munich Re (1999):

> "A number of attempts have been made in recent times to estimate the cost of anthropogenic climate change worldwide. The results of these analyses are unmistakable: in the long term the cost of preventive strategies is much lower than the losses to be expected as a result of climate change."

The most rigorous and comprehensive analysis of the economic aspects of climate change has been the review conducted by Sir Nicholas Stern, Head of the UK Government Economic Service and a former Chief Economist of the World Bank (Stern, 2006). His report concludes that a warming of 2°C–3°C could reduce global Gross

Domestic Product (GDP) by 3% and that a warming of 5°C could reduce it by up to 10%. On the other hand, his report argues that to stabilise atmospheric greenhouse gas concentrations at manageable levels would cost just 1% of global GDP. Stern's conclusions provide a strong economic impetus for favouring mitigation over adaptation, although he does also call for adaptation measures to be funded. Stern has since delivered the 2008 Richard T. Ely lecture at the annual meeting of the American Economic Association in New Orleans, critiquing his own review and arguing that greenhouse gas emissions "represent the biggest market failure the world has seen" (Stern, 2008).

The probability of the THC collapsing this century is thought by experts to be small (Section 5) and is therefore neglected in many economic analyses. If a collapse did occur, however, the impacts would clearly be enormous. It is unclear how to incorporate such low-probability, high-impact events into the development of economics policies. This paper is written by a climate scientist with no formal training in economics. My main intention is to effect a transfer of knowledge from climate researchers to economics practitioners. I will review the salient aspects of rapid climate change relevant to economists and policy makers. I will clearly delineate the main scientific certainties and uncertainties, with the aim of guiding economics goals and ensuring that they retain fidelity to their scientific underpinnings.

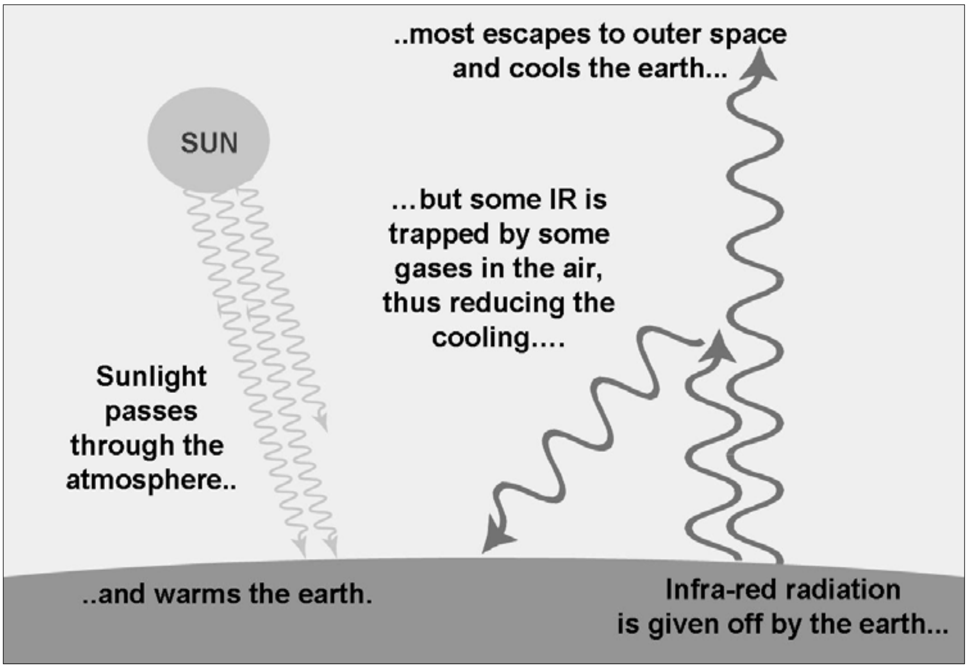
The outline of this paper is as follows. Section 2 summarises the basic science of global warming, including the natural greenhouse effect and its anthropogenic enhancement, the projected impacts, and a case study of urban/rural imbalance in per-capita greenhouse gas emissions in England. Section 3 describes the ocean's THC, and how it depends upon a potentially delicate chain of feedbacks that could be broken or substantially modified under global warming. Section 4 summarises the projected climatic impacts of a collapse of the THC according to computer models. Section 5 describes current efforts to estimate the likelihood of such a collapse, involving observational studies, predictions using computer models, and a simple survey of the opinions of climate experts. I conclude with a summary in Section 6.

2 Global warming

Global warming is caused by the greenhouse effect, which is illustrated schematically in Figure 1. Atmospheric greenhouse gases (including carbon dioxide, CO_2) allow short-wave ultra-violet energy from the sun to reach the surface of the Earth and warm it, but they trap some of the longer-wave infra-red energy that is radiated back to space. The result is that the Earth is warmer than it would be if the atmosphere were devoid of greenhouse gases.

A certain amount of the greenhouse effect is natural. Earth's surface would be perpetually frozen without it, and life as we recognise it could not have evolved. The problem is that human activities have artificially increased the amount of CO_2 in the atmosphere: the more we release, the more heat is trapped, and the warmer the planet becomes. This anthropogenic enhancement of the natural greenhouse effect has warmed the surface of the Earth by around 0.7°C since pre-industrial times. Atmospheric CO_2 levels have increased by around 30% over the same time interval. The cause of this increase has been the burning of fossil fuels (coal, oil and gas, which all contain carbon) to generate energy. For example, a typical car driven 5 km releases around 1 kg of CO_2 into the atmosphere (Taylor, 2002), and £1 spent on electricity releases around 10 kg (Lucas and Williams, 2003).

Figure 1 Schematic diagram summarising the greenhouse effect

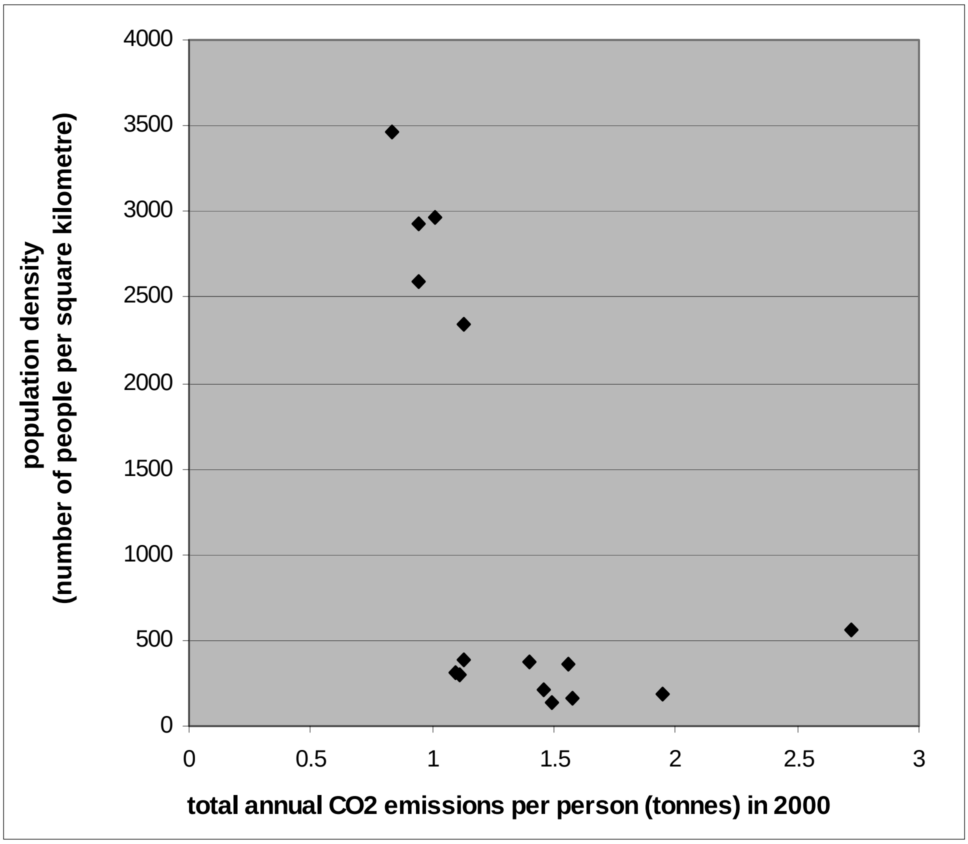


Source: UK Met Office Hadley Centre

It is insightful to compare and contrast the greenhouse gas emissions from urban and rural populations. In a study by Lucas and Williams (2003), the CO_2 emissions of 15 regions of south-east England (Southampton, Brighton, Portsmouth, Reading, Dover, Isle of Wight, Oxford, Canterbury, Maidstone, East Hampshire, West Oxfordshire, Mid Sussex, Ashford, Vale of the White Horse, South Buckinghamshire) in the year 2000 were analysed. The analysis included direct emissions, for example from transport and heating, but excluded indirect emissions, for example from the manufacture and transport of purchased goods. The CO_2 emissions ranged from under one tonne per person per year in Southampton to almost three tonnes per person per year in South Buckinghamshire.

Lucas and Williams (2003) found that the urban dwellers tended to be lower per-capita CO_2 emitters than the rural dwellers. This finding is clear from Figure 2, which is a scatter-plot showing the relationship between population density and CO_2 emissions for each of the 15 regions considered in the study. There is a clear trend: the greater the population per square kilometre (and hence the more urban the area), the lower the emissions. The main reason for the rural/urban imbalance was shown in the study to be road use. In communities which are relatively spread out, there is a greater need to use motorised transport to reach basic services. The problem is compounded by the fact that public transport is often poor in such areas, and so any motorised transport is more likely to be by private car. For example, in a break-down of the emissions by sector, emissions from road use were found to be six times higher per person in South Buckinghamshire than in Reading, which has five times the population density.

Figure 2 Scatterplot showing population density against CO_2 emissions per person for fifteen regions in south-east England in 2000 (see text)



Source: Lucas and Williams (2003)

The projected impacts of the global warming caused by CO_2 emissions depend upon the temperature change that occurs relative to pre-industrial times. The temperature change is related to a quantity referred to by climate scientists as the climate sensitivity (*e.g.*, Forster and Gregory, 2006), the value of which is not known with certainty (*e.g.*, IPCC, 2001; 2007). For temperature increases of up to 5°C, Stern (2006) lists some of the anticipated impacts: falling crop yields, first in developing regions and eventually in developed regions; disappearing mountain glaciers; decreasing water availability; rising sea levels; and increasing intensity of storms, forest fires, droughts, flooding and heat waves.

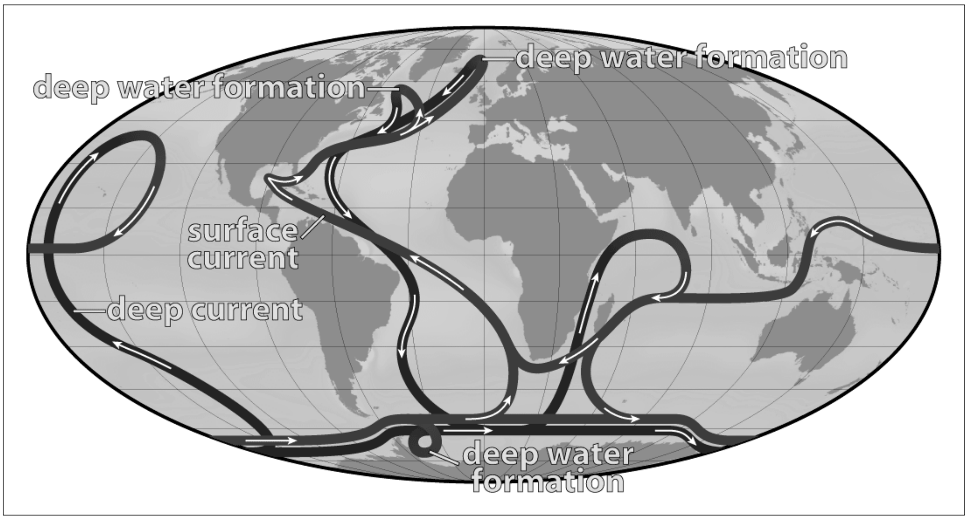
3 The thermohaline circulation

The THC is a global-scale ocean circulation, often referred to as the 'conveyor belt'. As shown schematically in Figures 3 and 4, in the Atlantic ocean the THC brings equatorial surface water northwards. Because this water is warm, evaporation of water molecules to the atmosphere is high. Salty and therefore dense water is left behind, which cools and eventually becomes so heavy that it sinks at high latitudes and returns southwards near the ocean floor. The circulation transports around one petawatt of heat to northern Europe in the Atlantic ocean (*e.g.*, Kamenkovich *et al.*, 2000), which is the equivalent of one million power stations.

The THC is maintained by a self-sustaining cycle of events: water sinks at high latitudes in the Atlantic ocean because it is dense; it is dense partly because it is salty; it is salty because evaporation is high; evaporation is high because it is warm; it is warm because it comes northwards from the tropics; and it comes northwards from the tropics because it replaces the water that sinks at high latitudes. This is the classic chicken-and-egg situation in which it is impossible to define a meaningful starting point to the chain.

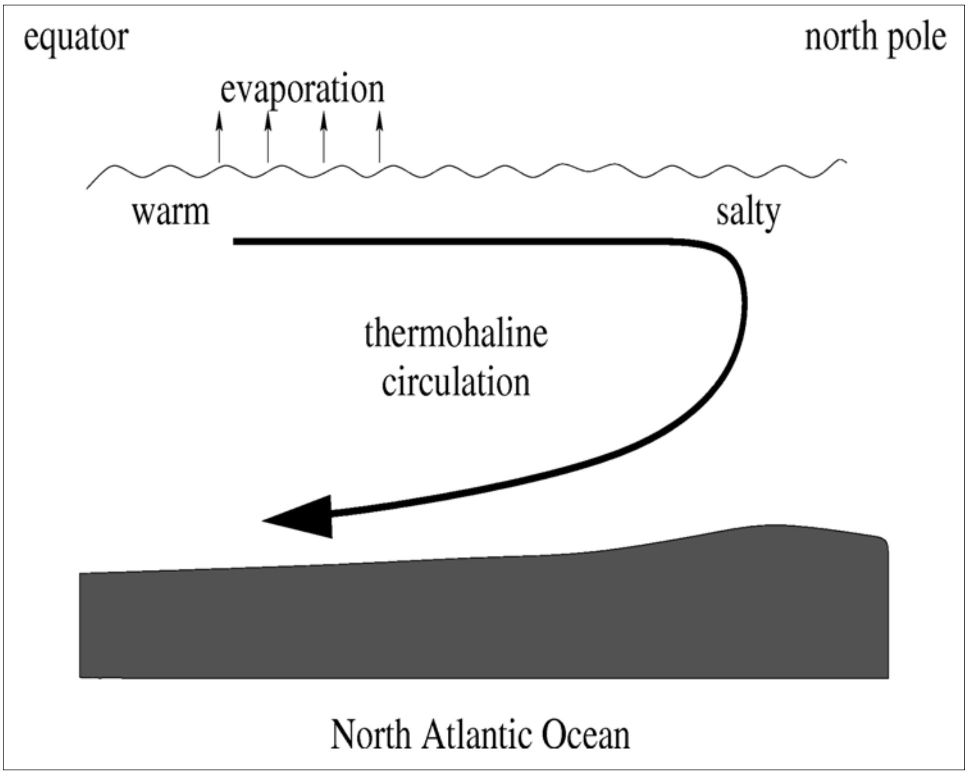
The existence of the THC therefore depends upon a potentially delicate chain of feedbacks. One current concern of climate scientists is that global warming is likely to produce increases in rainfall in the North Atlantic region (*e.g.*, Russell *et al.*, 1995) and an influx of fresh water due to the melting of Arctic ice (*e.g.*, Stroeve *et al.*, 2005). These effects both tend to make the surface waters lighter and less able to sink, which could significantly reduce the strength of the THC, with profound implications for the climate of Europe. Some simple models even suggest the possibility of a complete and rapid collapse of the THC (*e.g.*, Monahan, 2002) although more sophisticated models tend to predict a gradual weakening (IPCC, 2001; 2007).

Figure 3 Schematic diagram of the global thermohaline circulation



Source: Robert Simmon, NASA

Figure 4 Schematic diagram of the thermohaline circulation in the North Atlantic ocean



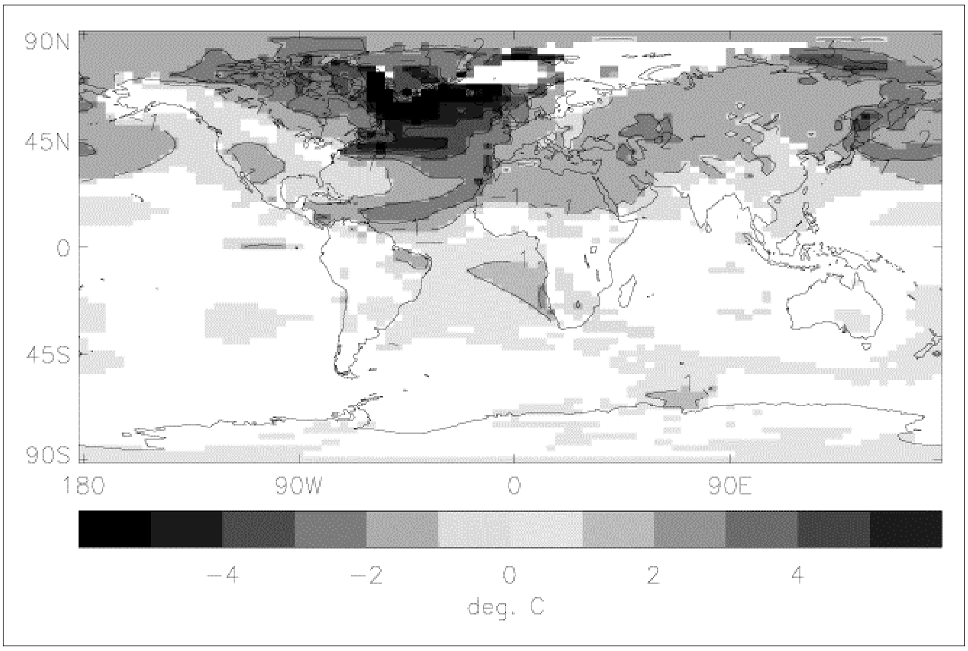
Notes: Warm tropical water moves northwards in the upper ocean. It becomes saltier and cooler as it reaches high latitudes, eventually becoming so dense that it sinks and returns southwards in the deep ocean.

There is mounting evidence that variations in the THC have caused rapid climate changes in the past. For example, ice core records indicate that Greenland cooled by almost 6°C within just a few decades around 8200 years ago. The cause is believed to have been the final collapse of ice sheets as temperatures rose following the termination of the last ice age. The ice sheet collapse caused large volumes of fresh water to enter the North Atlantic ocean, temporarily weakening the THC and causing extremely cold and dry conditions to persist across northern Europe for around 160 years (NERC, 2008).

4 Climatic impacts of a collapse of the thermohaline circulation

Vellinga and Wood (2002) have analysed the climatic impacts of a collapse of the THC using a state-of-the-art computer model. In their study, a shut-down of the THC was artificially induced by adding a massive volume of fresh water to the North Atlantic ocean. As shown in Figure 5, in the decades after the collapse, the surface air temperature in the northern hemisphere cools by 1°C–2°C on average (up to 8°C locally). The southern hemisphere warms by 0.2°C on average (up to 1°C locally).

Figure 5 Change in surface air temperature three decades after the collapse of the thermohaline circulation



Notes: The change is mainly negative over the northern hemisphere and positive over the southern hemisphere. Areas where the change is not significant have been masked.

Source: Vellinga and Wood (2002)

Temperature is not the only variable projected to be affected by a THC collapse. Vellinga and Wood (2002) find that drier soil conditions occur over Europe and Asia due to a stronger reduction in precipitation than evaporation. Colder and drier conditions in much of the northern hemisphere reduce the net primary productivity of terrestrial vegetation. This is only partly compensated by an increase in productivity in the southern hemisphere. The total global net primary productivity of vegetation decreases by 5%, with important implications for food provision.

It must be stressed that in state-of-the-art computer simulations with increasing greenhouse gas concentrations, the THC does not rapidly collapse as it was forced to by Vellinga and Wood (2002). Instead, it gradually slows down, as we shall see in Section 5. The net impacts on the climate of such a slow-down depend upon whether the tendency for *increased* temperatures due to global warming dominates over the tendency for *decreased* northern hemisphere temperatures due to the cooling effects of the THC reduction. The best available evidence at present is that the warming will dominate (IPCC, 2007).

5 Estimating the likelihood of a collapse of the thermohaline circulation

It is an urgent and vital concern to estimate the probability that the THC will collapse in response to anthropogenic greenhouse gas emissions. This section discusses three methods for assessing the likelihood of such a collapse, all of which have been attempted. First, we can make observations and measurements to monitor the present-day THC and look for the early signs of a collapse or a reduction in intensity. Second, we can use state-of-the-art computer models to make predictions about the future strength of the THC. Finally, we can form a subjective estimate of the probability simply by surveying a number of climate experts about their opinions. I will take these three complementary approaches in order, and summarise the key findings of each.

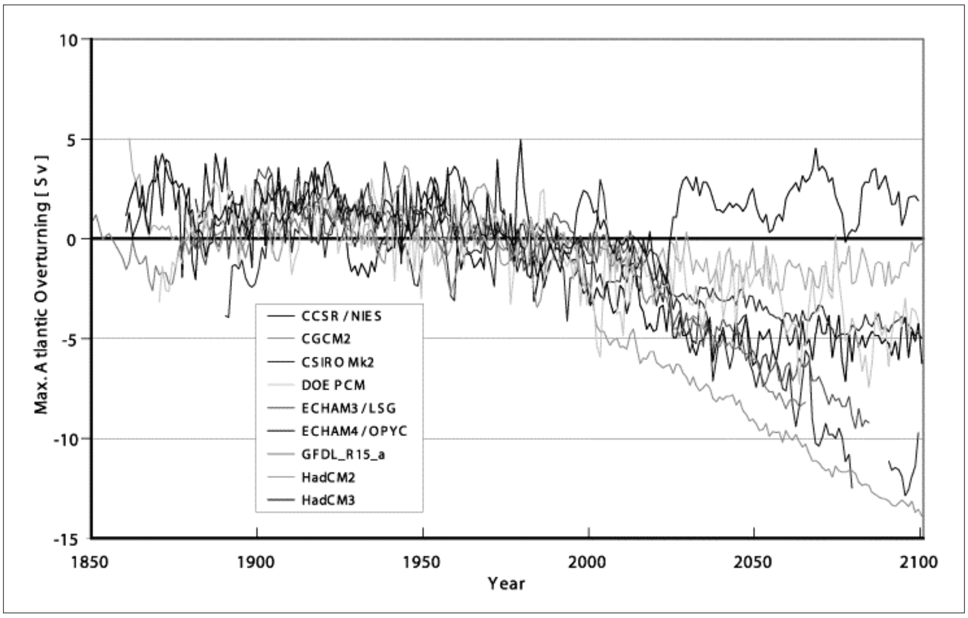
So concerning is the possibility of rapid climate change that the UK's Natural Environment Research Council (NERC) funded a £20 million, six-year (2001–2007) programme to study it. The programme, known as RAPID, aimed to improve our ability to quantify the probability and magnitude of future rapid changes in climate, focusing on the role of the THC. The RAPID programme recently ended, and NERC has announced funding for a £16.1 million, six-year (2008–2014) continuation project named RAPID-WATCH (Will the Atlantic Thermohaline Circulation Halt?).

A major component of RAPID was the establishment of a network of 22 monitors stretching across the Atlantic ocean at 26.5°N to measure the present-day THC. Each monitor consists of a wire that stretches from the sea floor to near the ocean surface. Measurements from the array began on 29 March 2004. The first measurements were reported by Bryden *et al.* (2005) and suggested that the THC had declined in strength by 30% over the past 50 years. This alarming finding was based on five historical snapshot measurements of the THC in 1957, 1981, 1992, 1998 and 2004. The finding was criticised because it is difficult to distinguish a real trend from natural variability with measurements from only five years. The most recent measurements from the network do indeed confirm that the THC can vary in intensity by a factor of eight annually (Cunningham *et al.*, 2007; Kanzow *et al.*, 2007).

Since it is difficult to assess whether the apparent observed decreases in the THC are part of a long-term trend or are simply natural variability, we must turn to computer simulations to fill the gap. Climate models are some of the most complicated computer programs ever written, because the climate is one of the most complicated physical systems ever studied by humankind. Governed by a combination of the laws of fluid dynamics, thermodynamics, radiative energy transfer and chemistry, the climate system is composed of the atmosphere, oceans, ice sheets and land. Each of these four subsystems is coupled to each of the other three, through the exchange of immense quantities of energy, momentum and matter on a dizzying range of spatial and temporal scales.

There exist many different climate models, each of which can be used to predict the fate of the THC under global warming. The results of the comprehensive IPCC (2001) analysis of THC predictions are shown in Figure 6. Unfortunately, different computer models give quite different predictions: although most models show a decrease by 2100, the size of the decrease varies from model to model. This is because state-of-the-art climate models divide Earth's surface into large boxes, each measuring around 100 km by 100 km. Crucially, the many important processes and mechanisms that take place on smaller spatial scales are not explicitly modelled (Williams, 2005) and are treated in different ways in different models. This problem persists in the more recent IPCC (2007) analysis (which nevertheless concludes that it is 'very likely' that the THC will slow down this century). We must wait until computing power increases before this problem can be solved.

Figure 6 Response of the thermohaline circulation to a particular greenhouse gas forcing scenario in a group of state-of-the-art climate models



Notes: Shown is the annual mean relative to the mean of the years 1961–1990. The thermohaline circulation is measured in Sverdrups (Sv), where 1 Sv means one million cubic metres of water per second.

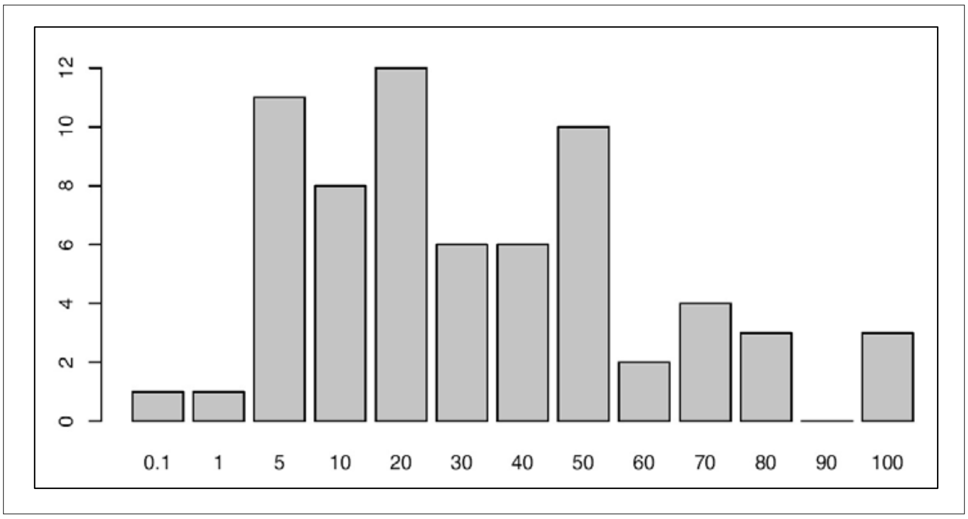
Source: IPCC (2001)

Given the inadequacies of observations and models, an alternative approach to determining the likelihood of THC collapse is simply to ask a number of experts for their opinions. Such an approach was taken by Challenor (2005), who obtained a picture of the views held by leading UK climate researchers. He conducted a survey of delegates at a rapid climate change conference at the University of Swansea in 2005. This is clearly more of an experiment in the social sciences than the physical sciences, but the results are nevertheless informative. Each delegate was asked two questions:

1 "What do you think is the probability of the THC weakening rapidly enough to have a discernable impact on the climate of the UK and NW Europe by 2100?"

2 "Do you consider yourself to be an expert, have some expertise, have little expertise, or be complete amateur?"

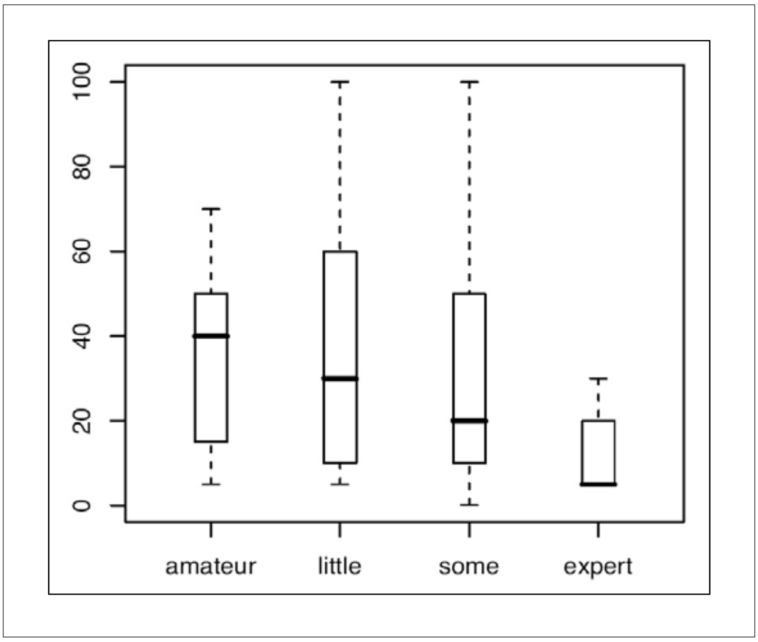
Figure 7 Histogram of the probability of the thermohaline circulation weakening rapidly enough to have a discernable impact on the climate of the UK and north-west Europe by 2100, according to delegates at a rapid climate change conference (see text)



Note: The number of respondents in each probability class (regardless of expertise) is plotted against the estimated probability in percent.

Source: Challenor (2005)

Figure 8 As in Figure 6, but with the probability estimates broken down by expertise



Notes: Dashed lines indicate the full ranges within which the respondents fell. Boxes indicate the widths of the distributions and thick lines indicate the means.

Source: Challenor (2005)

There were 67 respondents, of whom 5 considered themselves to be experts, 29 to have some expertise, 21 to have little expertise, and 12 to be amateurs. As shown in Figure 7, when expertise is disregarded the distribution of respondents' probabilities for the first question is broad and ranges from 0.1% to 100%. It is more instructive to break down the responses by expertise. As shown in Figure 8, the respondents' probabilities generally decrease with increasing expertise. In other words, the experts considered a collapse of the THC to be much less likely than the amateurs. The broad distribution of responses even within the group of experts (which ranged from 5% to 30%) mirrors the spread in the computer model predictions and emphasises the large uncertainty exhibited by both the science and the scientists.

6 Summary

We are experiencing the global warming created by our parents and grandparents, and we are creating further global warming for our children and grandchildren. Global warming might occur so slowly that we can adapt to the new climatic state, but tipping points could be reached beyond which the climatic changes are so rapid that adaptation becomes impossible. The THC plays a crucial role in the climate of the northern hemisphere. If it reached a tipping point and shut down, then northern hemisphere temperatures would drop rapidly and global food production would suffer.

Neither observations nor computer models nor experts can confidently assess the probability of a THC shut-down. The findings reported in Section 5 indicate the existence of a considerable amount of uncertainty in the science. This uncertainty hinders an assessment of the economic implications, reinforces the need for further research, and suggests a precautionary principle-based response until the science is better understood.

Economists face the difficult task of modelling incommensurable quantities, such as the economy, climate and social inequality, which are measured using different metrics. Progress with this analysis is possible only if weights are attached to each quantity, in order to convert them into the single common metric of economic cost. The scientific uncertainties of Section 5 translate into uncertainties in the weight that ought to be attached to climate change in such analyses. This frustrates the decision-making processes that the analyses are meant to inform. Furthermore, the issue of weighting is not merely scientific but also depends upon which concessions society is willing to make in order to protect the climate. The new discipline of Green Economics, with its long-term perspective and willingness to engage with the natural sciences (Kennet and Heinemann, 2006), seems uniquely placed to respond to these challenges.

It is difficult but essential to consider the possibility of low-probability, high-impact events when developing policy. Future generations cannot participate in present-day decision making and so we must act on their behalf. The small risk of rapid THC collapse is acknowledged but has not yet been integrated into the thinking on climate change adaptation. In sustainable construction, for example, virtually all adaptation is geared towards a warmer climate, disregarding the possibility (albeit small) of a THC collapse and a cooler northern hemisphere. There remain fundamental unanswered questions about the sort of adaptation that we must build into our current policies and practices, if future generations are to cope with the challenges that climate change will bring.

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