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THE ROYAL SOCIETY

Abrupt climate change: can society cope?

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Consideration of abrupt climate change has generally been incorporated neither in analyses of climate-change impacts nor in the design of climate adaptation strategies. Yet the possibility of abrupt climate change triggered by human perturbation of the climate system is used to support the position of both those who urge stronger and earlier mitigative action than is currently being contemplated and those who argue that the unknowns in the Earth system are too large to justify such early action. This paper explores the question of abrupt climate change in terms of its potential implications for society, focusing on the UK and northwest Europe in particular. The nature of abrupt climate change and the different ways in which it has been defined and perceived are examined. Using the example of the collapse of the thermohaline circulation (THC), the suggested implications for society of abrupt climate change are reviewed; previous work has been largely speculative and has generally considered the implications only from economic and ecological perspectives. Some observations about the implications from a more social and behavioural science perspective are made.

If abrupt climate change simply implies changes in the occurrence or intensity of extreme weather events, or an accelerated unidirectional change in climate, the design of adaptation to climate change can proceed within the existing paradigm, with appropriate adjustments. Limits to adaptation in some sectors or regions may be reached, and the costs of appropriate adaptive behaviour may be large, but strategy can develop on the basis of a predicted long-term unidirectional change in climate. It would be more challenging, however, if abrupt climate change implied a directional change in climate, as, for example, may well occur in northwest Europe following a collapse of the THC. There are two fundamental problems for society associated with such an outcome: first, the future changes in climate currently being anticipated and prepared for may reverse and, second, the probability of such a scenario occurring remains fundamentally unknown. The implications of both problems for climate policy and for decision making have not been researched. It is premature to argue therefore that abrupt climate change—in the sense referred to here—imposes unacceptable costs on society or the world economy, represents a catastrophic impact of climate change or constitutes a dangerous change in climate that should be avoided at all reasonable cost. We conclude by examining the implications of this contention for future research and policy formation.

Keywords: climate change; adaptation; climate impacts; thermohaline circulation; analogues; climate policy

One contribution of 14 to a Discussion Meeting 'Abrupt climate change: evidence, mechanisms and implications'.


UK temperatures may fall 5°C as Gulf Stream drops

Britain heading for a big freeze

By STEPHANIE TODD

SCIENTISTS today warned that Britain is heading for a big freeze – but admitted they cannot yet calculate when it will arrive.

The country's climate could soon mirror that of northern Canada as a result of a reduction in the flow of the Gulf Stream which warms Britain's shores.

Initial research by a Scots-based team has shown that the drop in flow could be as high as 20 per cent in the past 50 years.

They predict that further reductions will see UK temperatures plummet by around 5C.

It would mean estuaries such as the Forth, Clyde and Thames freezing over in winter.

Rapid

They say further monitoring is needed before a date for the freeze can be made.

The discovery confirms fears that despite global warming the UK could be in for a big freeze. Although the slowdown has been

Figure 1. 'Britain heading for a big freeze': cutting from *The Scottish Evening News*, 6 September 2001. (Reproduced with permission from Scotsman Publications.)

1. Introduction

'Abrupt' climate change, like 'dangerous' climate change, has been much discussed, but infrequently defined and only superficially analysed. The recent report from the US National Research Council (NRC 2002) is one major exception. The possibility of abrupt climate change triggered by human perturbation of the climate system is frequently mentioned as a wild card in the climate-change debate: a card invoked both by those who urge stronger and earlier mitigative action than is currently being contemplated (Keller *et al*. 2000; Mastrandrea & Schneider 2001) and also by those who argue that the unknowns in the Earth system are too large to justify such early action (Lomborg 2001). Much of the discussion about abrupt climate change and global warming has taken place in the media (e.g. figure 1) and in the popular literature (e.g. Retallack 2001; see also the discussion about the role of pictures in communicating climate change by Brönnimann (2002)). In the UK this discussion has mostly revolved around the notion of sign-reversal of climate trends, from warming to cooling, linked to behaviour of the thermohaline circulation (THC). This possibility has been known about for 15 years or more (e.g. Broecker 1987), although recent work has begun to elaborate the potential instability mechanisms (Ganopolski & Rahmstorf 2001; Clark *et al*. 2002) and has shown how human-related greenhouse-gas emissions may potentially trigger such instabilities. Yet we remain a long way from understanding the full sensitivity of the system and hence a long way from attaching probabilities to such outcomes. There has also been surprisingly little serious work done on exploring the implications of abrupt climate change for human society, whether in Europe or elsewhere. For example, the chapter on the impacts, adaptation and vulnerability of climate change with respect to Europe (Kundzewicz & Parry 2001) in the Third Assessment Report of the Inter-governmental Panel on Climate Change (IPCC) did not include an assessment of abrupt climate change or its impacts.

In this paper we explore the question of abrupt climate change in terms of its potential implications for society, focusing on the UK and northwest Europe and in particular considering the role of the THC. However, in order to do this, we have to first (§ 2) examine in some detail the nature of abrupt climate change and the different ways in which it has been defined and perceived by different traditions in science and different groups in society. The notion of sign-reversal in climate trends is probably more important for policy purposes than abrupt climate change per se, especially since 'abrupt' as used by the palaeoclimate community has different meanings to 'abrupt' as used in more popular discourse. We also have to look backwards in time, and to other geographical regions, to find analogues (§ 3) that may help us understand better the sensitivity of societies, present and future, to abrupt climate change. We then use (§ 4) the example of the 'collapse' of the THC to explore how the implications for society of such an event have previously been conceptualized or examined. These have been based either largely on speculation, or considered only from economic and ecological perspectives. We therefore make some observations (§ 5) about the implications of such an abrupt change from a more social and behavioural science perspective. The paper concludes (§ 6) this largely qualitative exploration of the implications of abrupt climate change for society, and the methods for analysing them, by examining the implications for future research and policy formation.

2. Definitions

The most considered attempt to define abrupt climate change has come from the US National Research Council (NRC) study 'Abrupt climate change: inevitable surprises'. The formal definition adopted by this study was that

> technically, an abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause. The cause may be chaotic and thus undetectably small.
>
> NRC (2002, p. 14)

This follows the reasoning of Rahmstorf (2001), which argues that 'abruptness' should be defined in relation to thresholds and nonlinear behaviour of the climate system rather than simply in terms of magnitude or rate of change. While this definition (let us call it type 1) may help focus attention on certain forms of behaviour in the physical system, it is perhaps not so helpful when viewing social and ecological impacts. Elsewhere in the same NRC report, in the chapter on economic and ecological impacts, a rather different definition was adopted:

> from the point of view of societal and ecological impacts and adaptations, abrupt climate change can be viewed as a significant change in climate relative to the accustomed or background climate experienced by the economic or ecological system being subject to the change, having sufficient impacts to make adaptation difficult.
>
> NRC (2002, p. 121)

This importantly recognizes the role of adaptation in social and ecological systems in determining what may be abrupt or significant climate change, but in fact the definition (let us call it type 2) is so broad that many of the standard climate scenarios

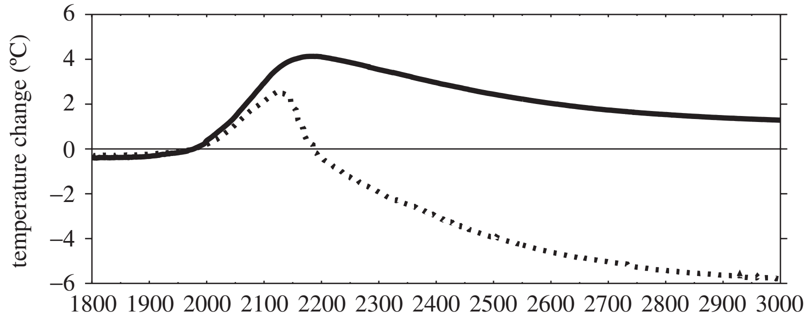

Figure 2. Change in average Atlantic air temperature (°C) for two scenarios: (*a*) a weakening by 20–50% in the THC (solid line); (*b*) a 'collapse' of the THC (dotted line). (Reproduced with permission from Rahmstorf & Ganopolski (1999); data supplied by Andrey Ganopolski.)

for the coming century published by the IPCC (2001) may well fall in the category of abrupt climate change. The same NRC chapter also then goes on to discuss the idea of abrupt *impacts* of climate change, which can of course occur quite independently of the (type 1) definition of abrupt climate change.

Neither of these NRC definitions is particularly suitable for identifying what is distinctive for impact and adaptation studies, and hence for policy, about abrupt climate change compared with non-abrupt climate change. There is a rapidly growing literature on understanding vulnerability and adaptation in relation to climate change, set either in the context of historical climate variability (Burton *et al*. 2002) or in the context of the IPCC climate scenarios (Smith *et al*. 2001). Such work is increasingly taking place in a policy context, both nationally and internationally, where management and investment decisions are already being taken with climate change is one of the influencing factors, i.e. adaptation is already occurring and society is already responding to an experienced and/or anticipated change in climate (see, for example, DETR 2000).

What this paper is interested in exploring, however, is whether there are qualitatively different insights to be learned about adaptive behaviour in society if it is anticipated that climate will behave in the future in an abrupt as opposed to non-abrupt fashion. This requires a more stringent definition of what we mean by abrupt† climate change. I suggest that there are three dimensions we can use to help us formulate such a definition: rate, severity and direction. If we use the IPCC (2001) scenarios as the default scenarios of non-abrupt climate change, abrupt climate change would imply the following.

Rate. Abrupt climate change, globally, occurs if the rate of warming is greater than *ca.* 0.55 °C per decade, or if the rate of global sea-level rise is greater than *ca.* 10 cm per century (cf. IPCC 2001). For continental, or smaller, regions these threshold rates at which climate change should be viewed as abrupt would certainly be greater.

† The qualifier 'rapid' is also frequently used in this context, as evidenced by the NERC thematic research programme RAPID (http://www.nerc.ac.uk/funding/thematics/rcc/) and by the supporting documents to the ESRC Environment and Human Behaviour programme (http://www.esrc.ac.uk/esrccontent/researchfunding/Env&HumBeh.asp).

Direction. All the IPCC scenarios contain basically unidirectional curves of climate change, at least at global and large-regional scales.† A non-standard abrupt scenario therefore could be when the direction of climate change alters in a sustained manner, for example, when climate substantially warms (or becomes wetter) for several decades and then substantially cools (or dries) for several decades. This is certainly the characteristic of climate change associated with the most frequently cited example of abrupt climate change, the collapse of the THC in the North Atlantic. Figure 2 gives two examples from the work of Rahmstorf & Ganopolski, in both cases with a reversal in temperature trend.

Severity. Strictly speaking, the severity of climate change is not related to abruptness, although there are two aspects here that *are* sometimes related to abrupt climate change: the exceedance of certain climate thresholds, for example, those that may trigger THC collapse‡; and the occurrence of one or more extreme or unprecedented weather/climatic events. The latter, for example, is explicitly discussed as a form of abrupt climate change in the NRC report. An unprecedented event occurring in a given place is abrupt in the sense that the probability of its occurrence suddenly changes from zero to some non-zero value. This may have enormous significance for society. In principle, both of these types of abrupt climate change related to severity *are* embedded in the IPCC (2001) scenarios, and hence conventional vulnerability and adaptation studies are in principle able to consider them. On the other hand, climate models may not be particularly reliable in their representation of the most extreme weather events, and impact and adaptation studies may not often actually make use of the available statistics from such modelling experiments.

Before proceeding to discuss how society may or may not cope with abrupt climate change, it is also useful to distinguish between the *experience* of abrupt climate change and the *anticipation* of abrupt climate change. By focusing on the experience of abrupt climate change, we can use historical examples, or analogues, to explore how societies and ecosystems have responded in the past. The anticipation of abrupt climate change, on the other hand, will lead to a different exploration of climate–society interactions and therefore different forms of adaptive behaviour.

Table 1 gives an example for each type of identified abrupt climate change: experienced versus anticipated and, where the definition is based on rate, direction or severity. We will return to some of these examples later in the paper. Implicit in this two-dimensional framing of abrupt climate change are the questions of permanency and timing. Severity exceedance in particular ought really to be further qualified in terms of frequency or return period if a more robust definitional framework of abrupt climate change were to be developed.

3. Historical analogues

A considerable number of studies have used historical analogues to help understand relationships between weather/climate variability and society (e.g. Rosenberg *et al.*

† Owing to the inter-annual and inter-decadal variability of climate, these curves are not necessarily smooth, although the underlying trends are usually unidirectional. The natural variability of climate becomes relatively larger as the geographic scale becomes smaller.

‡ This example is consistent with the type 1 NRC definition of abrupt climate change.

Table 1. *Some examples of experienced or anticipated abrupt climate change*
('Anticipated' in these examples only implies possibility and not necessarily likelihood.)

	rate exceedance	directional change	severity exceedance
experienced	twentieth century sea-level fall in the northern Baltic; Greenland warming in the 1920s and 1930s	Sahel precipitation from the 1930s to the 1980s	Central European floods of August 2002
anticipated	accelerated global warming due to methane hydrate release	northwest European temperature owing to THC collapse	increase in hurricane intensity due to global warming

1993) and hence to gain insights into the processes of adaptation either by individuals or by institutions. For this paper we are more interested in particular cases where societies have been exposed to abrupt climate change, as we have defined it in the previous section, rather than just climate change or weather extremes in general.

Although it is not always easy to classify such studies as addressing abrupt climate change or not, the majority would fit at least one of the three definitions used in table 1, namely the examination of social responses to extreme weather/climate events (i.e. the severity criterion). So, for example, severe droughts have been suggested as a contributing factor to the demise of the lost colony of Roanoke Island in Virginia (Stahle *et al*. 1998), the abrupt short-term climate shock (mostly cold and damp, 'the year without a summer') that followed the Tambora eruption in 1815 has been documented in terms of near-global effects (Harington 1992), and the abrupt rise in the level of Lake Victoria in the early 1960s (*ca.* 1.5 m within two years) assessed for its impacts of the subsistence economy of the Lake Victoria hinterland (Conway 2002).

There are fewer examples of careful and well-documented studies that have explored the impact on societies of a sign reversal in climate trends, although the classic works of the climate historians Lamb (e.g. Lamb 1982) and Bryson (e.g. Bryson & Murray 1977) on the links between climate change and the fall of the great civilizations of the Holocene allude to the role of abrupt climate change. A more recent example of such study is of the Holocene history of human settlement in the Atacama desert of northern Chile (Nuñez *et al*. 2002). In this sense, 'rapid' climate change is suggested as a moderating factor in the settlement and abandonment pattern of certain tribes, although in this context 'rapid' is not precisely quantified in terms either of climate or of chronology. This deficiency remains a persistent weakness in drawing conclusions for our contemporary world from most of these pre-historical regional climate–civilization analogues.

Two more recent and well-documented analogues from which more can be learnt for our twenty-first-century world, however, are summarized below: the multi-decadal abrupt precipitation change in the African Sahel and the abrupt climate change of the 2002 floods in Central Europe.

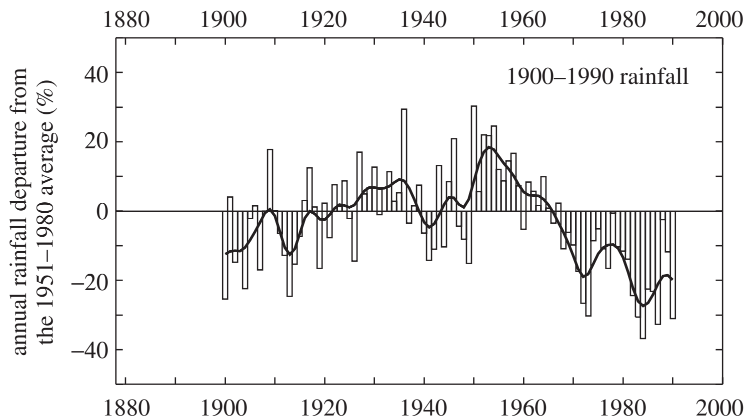

Figure 3. Annual precipitation in the Sahel for the period 1900–1990, expressed as percentage anomalies from the 1951–1980 average. (Data taken from Hulme (2001).)

(*a*) *The Sahel drought*

One of the examples cited in table 1 was the large change in precipitation experienced by the Sahel region of Africa during the middle decades of the twentieth century. The reduction in precipitation of *ca.* 30% between the 1960s and 1980s followed a period of sustained increase in precipitation during the 1920s to 1950s (figure 3). This is the largest multi-decadal regional climate perturbation that has been observed in the instrumental period (Hulme 2001) and provides a good example of a (sustained) directional change in regional climate.

This analogue, with a multi-decadal sign reversal, therefore fits one of our dimensions of abrupt climate change (direction, see table 1). What were the implications of this abrupt climate change for local communities, how did they adapt and what have been the long-term consequences for the region? These questions have been explored by numerous authors in recent decades, one recent compilation being a special issue of the journal *Global Environmental Change* (Batterbury & Warren 2001). It is important that the following three lessons are learnt from this analogue.

(i) The initial impacts of the drought in the 1970s and 1980s were severe, certainly exacerbated by the sign reversal in precipitation. For example, agricultural and water investments made during the wet period of the mid century made no allowance for the possibility of subsequent drying (Todorov 1985). In this sense, climate foresight was not used by the (mostly colonial) powers.

(ii) This abrupt climate change occurred in a region with a weak infrastructure and a rigid institutional framework, at least in the government sector. This might suggest a low adaptive capacity (hence the large initial impacts), although the relationship between institutional arrangement and adaptive capacity is not simple (see Adger & Brooks 2003). These infrastructural and institutional conditions do not apply in northwest Europe, although whether this means European societies are less vulnerable to abrupt climate change is not necessarily obvious.

(iii) Although the short-term impacts were severe, many communities in the region proved to be surprisingly resilient through the deployment of strategic adaptive behaviour (Mortimore & Adams 2001), mobilizing the more flexible informal institutions of a traditional society, and these communities continue to survive and develop into the twenty-first century.

(*b*) *The Central European floods*

A second example of abrupt climate change, following one of the definitions in table 1, concerns the Central European floods of August 2002. The abrupt change in this instance was a severe flooding event—in places with an estimated return period of 1-in-500 years—which had severe consequences for large areas of southeastern Germany, the Czech Republic and Hungary. It is recognized that crisis events, whether environmental or not, offer a window of opportunity for change in human behaviour (Johnson *et al*. 2003). As in the case of the extensive nationwide floods in the UK in the autumn of 2000, this severe flooding in Central Europe, while causing many billions of euros of damage, will likely lead to improved systems of flood prevention, early warning, and flood management in future. Abrupt climate change in this sense therefore imposes a short-term cost on society, but also acts as the trigger for learning and adaptive behaviour such that future events of similar magnitude are likely to impose reduced costs.

The above two examples, from the Sahel and from Central Europe, reveal both the usefulness and the limitation of using historical analogues of abrupt climate change to gain insights about the likely impact of future abrupt change on society. They also show very clearly that models of physical impact or economic damages that do not take into account this learning behaviour are not likely to yield realistic insights about future climate–society interactions (Smith & McCloskey 2001).

4. Scenarios for the collapse of the THC

With this general background established, we now explore in more detail probably the most frequently cited example of abrupt, or rapid, climate change: the possible collapse of the THC. This example (see table 1) falls in the category of an anticipated abrupt climate change, defined as a sign reversal of climatic trend, in this case a switch from current and future climate warming over the North Atlantic and northwest Europe to a future cooling.† How has this possibility been represented in scenarios of future climate, what studies have explored the implications for society of such a possibility and how have these studies been conducted?

Although the Working Group I report of the IPCC Third Assessment contained statements about the possibility of future THC weakening and even collapse (Cubasch & Meehl 2001), in the 'Europe' chapter of the Working Group II report assessing regional vulnerability, impacts and adaptation options (Kundzewicz & Parry 2001), THC collapse and consequent changes in European climate were not included, nor obviously therefore was mention made of the impacts for society or environment of such an outcome.

What relevant climate scenarios do we have to use as the basis for such an exploration? The standard IPCC (2001) and associated climate scenarios, based on a

† According to some models, THC collapse may induce sign reversal in climate trends further afield than just this region, although this is less well established.

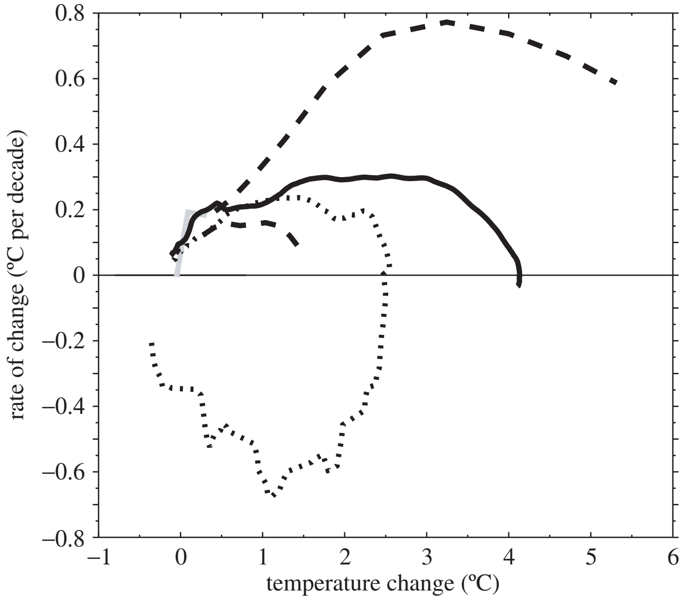

Figure 4. Atlantic air-temperature change (relative to 1900) plotted as magnitude of change (horizontal axis) versus decadal rate of change (vertical) for the period 1961–2200 estimated for the two THC scenarios shown in figure 2 (dotted line, collapse; bold line, weakening) and for two end-of-range IPCC (2001) scenarios (B1 and A1FI) out to 2100 (dashed lines).

suite of climate-change experiments using coupled atmosphere–ocean general circulation models (GCMs) subjected to different rates of greenhouse-gas forcing, mostly simulate a reduction in the strength of the THC, sometimes by up to 15 or 20%, but certainly not a collapse over the duration of the twenty-first century. In these scenarios, warming over northwest Europe is slightly reduced relative to southern or Eastern Europe, but these are marginal geographic differences in future climate change. For example, the UK Climate Impacts Programme (2002) (UKCIP02) scenarios (Hulme *et al*. 2002), adopted by the UK government for planning purposes, are based on such model results and out to 2100 contain a range of warming over the UK of between *ca.* 2 and 4 °C (compared with perhaps 3–6 °C for Eastern or southern Europe).

More stylized experiments using atmosphere–ocean GCMs have been able to simulate large-scale collapse of the THC when the rates of greenhouse-gas forcing are sufficiently large (Stouffer & Manabe 1999), or when a collapse of the THC has been deliberately engineered in the model by injecting large amounts of fresh water into the North Atlantic (Vellinga & Wood 2002). In these cases, the detailed climatic implications for northwest Europe have either not been explored or are not realistic since they remain sensitivity experiments only. Vellinga & Wood (2002), for example, cited a relative cooling of 1–3 °C within 30 years over northwest Europe after THC collapse, although, since no increases in greenhouse-gas forcing were represented in this experiment, these figures should not be taken as the basis for any realistic scenario. This sensitivity work has recently been extended to examine the response of ecosystems worldwide to such THC collapse scenarios (Higgins & Vellinga 2003).

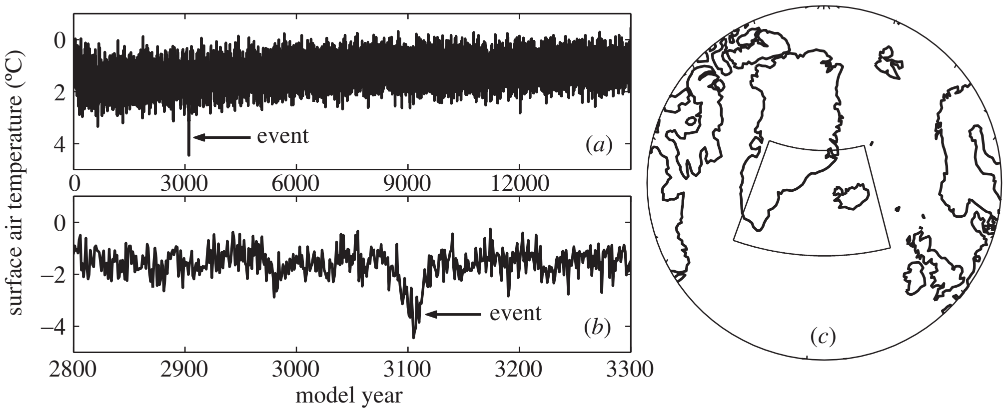

Figure 5. Time-series of surface air temperature averaged over southeast Greenland and the neighbouring ocean for a 500-year period in a model experiment. Note the abrupt cooling around year 3100. (Reproduced with permission from Hall & Stouffer (2001). Copyright 2001 Macmillan Publishers Limited.)

Other modelling work has explored THC behaviour using intermediate complexity models (Ganopolski & Rahmstorf 2001) or simple models (Schneider & Thompson 2000) and shown that the THC is indeed sensitive to both the rate and magnitudes of greenhouse-gas forcing. Neither of these types of experiments really provide the detailed geographic climatic information that could be used to explore regional impacts and adaptation, although work is underway attempting to downscale these types of results from the CLIMBER model to explore their implications for regional climate and for primary sectors of northwest European economies: food, timber and fisheries (Stefan Rahmstorf 2003, personal communication). Figure 4 shows one example of the regional temperature changes suggested by such experiments, expressed in terms of both magnitude and rate of change. This form of expression emphasizes the uniqueness of the THC-collapse scenario in terms of the decadal rate of cooling during the twenty-second century. Magnitudes of temperature change, on the other hand, fall within present and expected future ranges.

A different type of information again is that reported by Hall & Stouffer (2001), where they showed the existence of abrupt climate change over southern Greenland in an unforced coupled atmosphere–ocean GCM experiment, i.e. where abrupt climate change was triggered by random internal variability.† In this case, a prolonged cooling of *ca.* 3 °C over 30–40 years was induced over an area of several million square kilometres of the North Atlantic before the system recovered to its previous equilibrium (see figure 5).

In this context it is also worth mentioning some work, conducted or on-going, that seeks to estimate the probability of THC collapse given some prior set of assumptions about system behaviour and rate of forcing. Thus, Schneider & Thompson (2000) map out a risk space where the likelihood of the collapse of the THC is estimated as a function of the global climate sensitivity, the rate of greenhouse-gas forcing and of the initial strength of the oceanic circulation. Along similar lines, work is proposed

† The role of natural climate variability compared with human-induced climate change will be discussed in § 5 *c*.

that would use Monte Carlo simulation approaches to estimate the probability of THC collapse, or of winter temperature over a certain region falling below a certain threshold, using a hierarchy of climate models (Peter Challenor 2003, personal communication).

In the absence of well-developed and authenticated scenarios of abrupt climate change associated with THC collapse, others have reverted to creating synthetic scenarios to represent possible climate outcomes. For example, Klein Tank & Können (1997) generated 'typical' weather years for the Netherlands assuming heat advected from the warm North Atlantic was reduced (a surrogate for THC collapse). This resulted in more cold winters and cool summers overall, although there was little change in the most extreme daily weather: extreme winter cold and extreme summer heat. An even more arbitrary approach to the creation of a synthetic THC collapse scenario was adopted in a recent report, suggesting that two additional scenarios should be considered when developing climate policy—a scenario in which the THC shuts down within the next two decades, inducing 3–5 °C cooling over the North Atlantic by the 2020s, and one in which the THC shuts down a century from now (Gagosian 2003). The plausibility of at least the former of these scenarios seems dubious.

5. Thermohaline circulation collapse: can society cope?

Given the paucity of credible and/or appropriate scenarios of THC collapse, there has been an understandable paucity of studies that have seriously tried to evaluate what the impacts of such a collapse would be for northwest Europe; virtually none have explored the implications of such an anticipated abrupt climate change for current decision making about adaptation policy. On the other hand, there have been a few preliminary attempts at integrated assessments of the mitigation policy implications using coupled climate–economy models (we summarize some of these issues in § 5 *a*). What this means is that to a large extent we are left with speculative statements about what THC collapse might mean for Europe or for the world. For example, none of the following recently made statements are rooted in substantive environmental, economic or social research.

> The consequences of such a thermohaline circulation collapse might include decreased fishery and agricultural yields ... and damages to natural ecosystems....
>
> Keller *et al.* (2000, p. 19)

> Neither the probability and timing of a major ocean circulation change nor its impacts can be predicted with confidence yet, but such an event presents a plausible, non-negligible risk.
>
> Smith *et al.* (2001, p. 951)

> Such rapid climate change [over as short a period as 10–20 years] would make adaptation to, and mitigation of, the impacts exceedingly difficult for the affected countries.
>
> Srokosz (2002, p. 66)

> A sudden strong cooling could be catastrophic for agriculture, fisheries, industry and housing as crops fail, fish stocks shift to colder-water species and heating and insulation costs rocket.
>
> NERC (2002)

> . . . the current state of affairs . . . [is only a] . . . modest probability that THC changes will yield unmanageable outcomes beyond a local scale.
>
> O'Neill & Oppenheimer (2002, p. 1972)

With the exception of the last quotation, most conjectures indicate large risks and high costs, and many other examples of similar sentiments could be cited from the more popular literature.

It is also true that abrupt climate change (again the example of the THC collapse is frequently chosen) is often used as an indicator of what in the end might constitute dangerous climate change and therefore, according to the objective of the UN Framework Convention on Climate Change, a specific outcome to be avoided through policy intervention. A good example of this was the analysis of O'Neill & Oppenheimer (2002), who used THC collapse as one of three outcomes that would constitute dangerous climate change. This criterion was selected using the assumption that a 3 °C or more warming over the next 100 years would lead to an unacceptable risk of THC collapse. However, as argued by Dessai *et al*. (2003), it is debatable whether this type of top-down approach to defining danger can, on its own, be applied appropriately to the question of what constitutes dangerous climate change.

(*a*) *Economic analyses*

A small number of studies (e.g. Keller *et al*. 2000; Mastrandrea & Schneider 2001) have been conducted using climate models and economic models, or coupled climate–economy models, to explore the implications of abrupt climate change on climate mitigation policy. Both of the studies cited above have used as their example of abrupt climate change the THC collapse (although both also state that they are interested in identifying generic insights for mitigation policy associated with a wider range of abrupt climate changes). Instructive as these exercises may be, it is important to realize that they do not provide a basis for evaluating how important THC collapse may be for society, or how well society would cope with such collapse. In both cases, and in other similar studies, the economic damages caused by THC collapse are simply assumed, thus

> . . . a thermohaline collapse may temporarily increase climate damages by up to 3% of gross domestic product in Western Europe.
>
> Tol (1998)

> . . . the potential economic impacts of thermohaline circulation collapse are likely to exceed 0.1% and potentially exceed 1% of gross world product.
>
> Keller *et al*. (2000, p. 34)

Similarly, Mastrandrea & Schneider (2001) use a global damage function which simply assumes higher damages would result when abrupt climate changes occur. The authors admit that such a function is arbitrary and not based on any bottom-up analyses. They claim such a global function is plausible, test the sensitivity of their analysis to different assumed values, but maintain the belief that

> ... even in a distant society [a century or more from now], the advent of abrupt climatic changes would reduce adaptability and thus increase damages.
>
> Mastrandrea & Schneider (2001, p. 436)

But what would these damages actually be? Fisheries, agriculture, wildlife and forestry are the sectors most frequently cited (cf. Keller *et al*. 2000; NERC 2002) in support of major impacts from a THC collapse, yet using conventional measures, these sectors account for a tiny proportion of economic production and activity in the countries of the North Atlantic periphery. The true value of these ecosystems and services will of course be higher than a simple GDP measure (see Balmford *et al*. 2002), yet it remains hard to argue, without strong evidence, that 100 or more years from now it is abrupt climate change that will be the factor that most damages remaining fish stocks, new systems of agricultural production, or ecosystem functioning.

It is also important to recognize in this context that the significance of future climate change in any economic analysis, and hence its influence on near-term policy, depends fundamentally on discount rates. This is especially true in the case of abrupt climate change causing possible damage far into the future (2100 or beyond). The present value of such enhanced damages, however calculated, is particularly sensitive to discounting. Mastrandrea & Schneider (2001) discuss this problem in the context of abrupt climate change and explore alternative formulations.

(*b*) *Social analyses*

What has been lacking in the few studies that have been made of the implications of abrupt climate change in the North Atlantic is an appreciation of the nature of adaptation, the role of information in decision making, and how that information is perceived and with what authority. More fundamentally still, the lack of serious social science analysis of abrupt climate change and its implications has meant that it has remained possible for different research communities, and hence for decision-makers and the public, to imply quite different things by using the same language. For example, the words 'abrupt' or 'rapid' imply a quite different time-scale to a scientist reconstructing the Holocene or the Quaternary from that of a social scientist analysing social, political or institutional change. In the former case, rapid changes are measured in terms of decades or centuries, as in the following quotes.

> ... superimposed on these general trends are abrupt events on time-scales of decades and centuries that strongly affect human societies ....
>
> Gasse (2002, p. 538)

> Rapid freshening of the deep North Atlantic Ocean over the past four decades.
>
> Dickson *et al*. (2002), title

In contrast, rapid or abrupt changes in society are usually measured in terms of months or years. The collapse of the former Soviet Union, for example, occurred in less than three years, while the 'global war against terrorism' developed in a matter of months. This confusing of time-scales between two different types of processes—one set physical and one set social—is a major cause of misunderstanding in the discussion about abrupt climate change.

Other social dimensions of the analysis of abrupt climate change and its implications for society that have been lacking include the following examples.

Further understanding of the institutional and behavioural dimensions of adaptation is needed (Adger 2001); abrupt climate change has quite different implications for adaptation decisions that are structural (i.e. that require long-term investment), compared with those that are either regulatory or behavioural. Investments aimed at 'climate-proofing' infrastructure have to be anticipatory to be efficient, while behavioural change is likely to be concurrent or even reactionary and triggered by iconic extreme weather events. Regulation is probably somewhere in between structural investment and behavioural change.

Adaptation is a continuous process in response to external forces or anticipated futures and involves the processes of signal detection, evaluation, decision and feedback (Hertin *et al*. 2003). Statements about whether or not we may experience abrupt climate change in the future will therefore influence adaptation decisions and strategies now. The perception and interpretation of such statements, and the authority with which they are regarded, then become critical in understanding how the possibility of abrupt climate-change influences such decisions. In this sense, trust is more important than truth (although the two are related).

A different approach to the economics of adaptation is needed (Neil Adger 2003, personal communication). Not only do the costs (financial, economic and environmental) of specific adaptation strategies need estimating, but the transaction costs associated with making adaptation decisions and with seeking information on which to base such decisions also need to be considered in the same framework. Thus adaptation decisions involve the formulation of expectations of future impacts (e.g. whether associated with continued warming or warming followed by cooling), while adaptation actions can turn out to be efficient, redundant or maladaptive depending on the adequacy of the foresight and on the timeliness of the decision (see § 5 *c*).

The above examples and discussion are intended to point out the rather inadequate basis upon which most commentaries about the significance of abrupt climate change, in particular the collapse of the THC, are founded. This is not to say that abrupt climate change, as defined here, would have *no* serious adverse consequences for the North Atlantic region, or even for the world. The contention is that we have not studied nor understood sufficiently the way in which climates and societies interact with each other, over the time-scales concerned and in view of the evolving anticipation of the changes in climate that lie ahead of us. There is a confusing of time-scales between the physical and social processes that are important; a symptom of this is the paucity of credible and appropriate regional transient scenarios that incorporate abrupt climate change and that can be used to explore impacts, economics and adaptive behaviour; and inadequate attention has been paid to the nature of information about abrupt climate change, how this information is perceived by decision makers, and what level of authority such statements possess.

(*c*) *Natural variability?*

One final issue to be raised here concerns the possibility that a sign reversal in regional climate trends may occur in the quite near future for reasons that may or may not be related to human-induced abrupt climate change. It is possible, for example, that over northwest Europe a period of cooling†, perhaps lasting five, ten or even more years, occurs in the next one or two decades. This may well occur due to natural, decadal variability of the climate system (see figure 5; Hall & Stouffer 2001), or indeed it is conceivable according to some commentators that it may occur due to early and more substantial weakening of the THC than is generally supposed.

This raises a number of intriguing questions for the way in which society interacts with climate. Firstly, through what methods would science be able to distinguish between these two possibilities, how quickly could it do so and with what authority would it speak? Trust between society and government and between society and science might be further challenged (Poortinga & Pidgeon 2003). The implications for climate policy in general, and adaptation strategies in particular, of the two different explanations would be quite profound. Secondly, at what stage would adaptive decisions, investments and behaviour alter to take account of this new boundary condition (i.e. a climate reversal interpreted either as permanent or temporary)? One would imagine that different sectors with different constraints and priorities would react quite differently. Thirdly, this scenario suggests that adaptation strategies or incentives should be explored that are robust to such a possibility. In other words, whether regional climate continues to move in the direction conventionally assumed in a relatively smooth fashion, or whether abrupt climate change in the sense of sign reversal is experienced, adaptation strategies might be established by governments, business, resource managers, etc., that are robust to either outcome. In such a scenario, the costing of adaptive decisions and behaviour becomes a crucial factor. In particular an appropriate economic analysis of the value of forecast information would be needed, such as that developed in the context of weather and seasonal climate forecasts where the cost of acting on false positives or false negatives is critical (e.g. Wilks 2001).

6. Conclusions and future research

To date, abrupt climate change, however defined, has generally not been incorporated in analyses of climate-change impacts nor, with a very few exceptions, explicitly been brought into considerations of climate mitigation policies or design of adaptation strategies. How easy this situation is to rectify depends in part on what is meant by abrupt climate change.

† A temperature example is used since this is the primary variable used in discussions of climate change, but just as likely, or more so, at a regional scale would be a sign reversal in precipitation. For example, over northwest Europe such an outcome would involve a period of five, ten or more years when winters became drier and summers became wetter.

If abrupt climate change simply means changes in the occurrence or intensity of extreme weather events within conventional climate-change scenarios, or simply an accelerated unidirectional change in climate (cf. table 1), the design of adaptation strategies, whether structural, regulatory or behavioural, while not necessarily straightforward, can proceed within the existing paradigm. Climate scenario information used in the process may change or become more sophisticated, limits to adaptation in some sectors or regions may be reached, and the costs of appropriate adaptive behaviour may be large. But strategy can develop on the basis of a predicted long-term unidirectional change in climate: the first time in human history that such climate-related long-term anticipatory behaviour has been witnessed.

More challenging, however, would be if abrupt climate change implied a directional change in climate, as for example might well occur in northwest Europe following a collapse of the THC. In such a scenario, cooling would most likely follow warming†, although, even here, temperatures at worst would be likely only to return to some pre-industrial level at least over the next two centuries (figure 4), rather than lead to what some popular commentators have alluded to, namely the onset of a mini Ice Age. There are two fundamental problems presented to society by such an outcome: first, the generally anticipated future changes in climate currently being prepared for might reverse and, second, the probability of such a scenario occurring remains fundamentally unknown. Few, if any, analyses have yet been conducted that have seriously examined what such a sign reversal in climate trends would mean for the region and no analyses have begun to look practically at the implications of such a possibility for the design and implementation of current adaptive decisions. It is premature to argue therefore that abrupt climate change (in the sense referred to here) imposes unacceptable costs on society or the world economy, represents a catastrophic impact of climate change, or constitutes a dangerous change in climate that should therefore be avoided at all reasonable cost.

Whatever view of abrupt climate change is adopted, this assessment has suggested the following recommendations and priorities for research.

Greater care needs to be taken in the use of terms such as 'abrupt' and 'rapid' climate change. This applies as much to communication between natural and social scientists as it does to communication between science and policy or science and the public.

For studies to explore the significance of abrupt climate change for society, a number of credible scenarios of transient climate change, at appropriate geographic resolution, should be constructed, based on one or more modelling experiments which combine plausible greenhouse-gas forcing with nonlinear climate system behaviour over a 50–200 yr time-scale.

Significant effort should be placed into developing methods for estimating the probability of abrupt climate-change outcomes. A diversity of methods should be explored and this should be done in close association with decision-makers who have responsible for policy advice or implementation. Assumptions underlying outcome probabilities should be transparent.

A study should be undertaken of how policy, business and public communities would respond to a series of years (say five or ten) in which regional climate trends

† It is less obvious whether all other dimensions of climate change would also follow a sign reversal in such an eventuality; for the UK, for example, would winters become drier and summers wetter, would growing seasons shorten and would snowfall increase? Sea-level would definitely continue to rise.

reversed, *whether or not* this sign reversal was related to natural climate variability or abrupt climate change triggered by anthropogenic forcing. This study should focus on the credibility and authority for society of scientific statements interpreting such an outcome.

Can we characterize or identify no-regrets adaptation investments? For example, can we develop adaptive capacities across society, irrespective of the direction and magnitude of future climate change? What differences does the prospect of abrupt climate change make for structural adaptation (largely anticipatory adaptation), for institutional adaptation (both anticipatory and reactive) and for behavioural adaptation (mostly reactive)? What are the costs of adaptive investments, including transaction costs, made on the basis of misplaced foresight?

Discussions with colleagues in the Tyndall Centre (Neil Adger, Nigel Arnell, Emma Tompkins) and with Stefan Rahmstorf are acknowledged. The paper has drawn upon work completed for Tyndall Centre project IT1.16 by Clare Goodess & Tim Osborn, especially their literature review. The principal investigators of four new ESRC projects investigating rapid climate change and human behaviour are also thanked for sharing their research ideas and plans: Nigel Arnell (*Exploring vulnerability to rapid climate change in Europe*), Clare Johnson (*Crises as catalysts for adaptation: human response to major floods*), Judith Petts (*Predicting thresholds of social behavioural responses to rapid climate change*) and Mark Pelling (*Rapid climate change in the UK: towards an institutional theory of adaptation*). Clare Johnson and Simon Niemeyer in particular are thanked for their comments on an early draft of this paper. The views expressed here are, however, my own interpretation of these conversations. Andrey Ganopolski provided data for figures 2 and 4 and John Turnpenny is thanked for assistance with diagrams.

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Discussion

R. R. Dickson (*Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK*). You cannot appropriate the use of the word 'rapid' to your purposes. If our title (Dickson *et al*. 2002) had been 'Rapid *effects* of freshening . . . ', then you might have had a point. But it wasn't. The fact that the freshening of the overflows led in four decades to the greatest change in oceanography means by definition that it was rapid and we were right to use the word.

M. Hulme. I accept that no community has exclusive rights over a word or term. My point is that the word 'rapid' means quite different things, however, to a palaeoclimatologist or oceanographer compared with a social or political scientist. Your question just confirms this. When you say 'by definition' you mean according to the accepted norms of oceanography. But a change over four decades for a political scientist would not 'by definition' be rapid at all. In fact, 40 years in politics is almost a geological age in your terminology.

H. Stevenson (*Cambridge, UK*). Do you have any working definitions of successful adaptation and successful mediation? If so, what are they and why have you chosen them?

M. Hulme. No I do not. These are very much questions that have to be explored and answered. It is not obvious how one should go about defining or, further, measuring successful adaptation. But given that increasingly large sums of money are likely to be attached to adaptation interventions, both here in the UK and worldwide, I regard it as important that we introduce some frameworks for measuring the success of adaptation investments.

A. Troccoli (*European Centre for Medium-Range Weather Forecasts, Reading, UK*). Why can society not cope with climate change? What are the factors that determine the range of tolerability for society?

M. Hulme. Many studies are currently looking at definitions of adaptive capacity and social and ecological tolerances. I doubt however, that it is meaningful to talk about a single threshold or definition for a society, let alone the world. The level of climate variability and climate change that is tolerable will vary enormously from sector to sector and from community to community. Attitudes to risk and risk management will be central here.

B. J. Hoskins (*Department of Meteorology, University of Reading, UK*). There seems often to be an assumption that a THC impact on temperature near us would counteract global warming and would mean no change in climate. In fact the resulting climate, as the ensemble of weather, *would* be very different even if the average temperature changed little. Much of the discussion equates abrupt climate change with a switch-off of the THC. We should not lose sight of the fact that an anthropogenic-enhanced CO_2 forcing of climate change is likely to trigger all sorts of changes, such as to the El Niño/Southern Oscillation or to the North Atlantic Oscillation, and these would give rapid and important changes in climate in many regions affected by them.

J. T. Houghton (*Hadley Centre, Bracknell, UK*). In addressing policymakers, we talk of two kinds of climate change: that based on a wide range of observations and models that will almost certainly occur within the next few decades and that which may be abrupt and more damaging, but about which we are much less certain. Do you think that by emphasizing the latter we are in danger of detracting from policymakers' focus on the former?

M. Hulme. Yes, I think there is this danger. It is important that the former kind is used to firmly implant in the minds of political, business and community leaders the fact that future climate will not be like past climate and therefore requires a more sophisticated and visionary approach to strategic planning, investment and management with respect to climate. Only once this is achieved can one move on sensibly to debate the way in which very low probability, but high outcome events (of the latter kind to which you refer), might alter these strategies. But we should learn to walk before we try to run.

S. J. Niemeyer (*Department of Geography, Earth and Environmental Sciences, University of Birmingham, UK*). With respect to the representation of 'adaptive space' and the role of scientific information in increasing this space: is the 'space' a function of social or political adaptation? And if social, should there be a greater attempt by scientific communities to better communicate extreme scenarios (e.g. a collapse of the THC)?

M. Hulme. Adaptive space is a function of social *and* political constraints and heavily influenced by prevailing views of risk, opportunity and views of the natural world. Political attempts to enhance adaptation can only be successful in so far as they appreciate the social and cultural context within which business decisions and individual behaviour takes place. Communicating extreme (low probability) scenarios is a delicate business for scientists (see my answer to Houghton above), yet it is important that we explore matters of risk perception and communication with our public.

J. Venables (*Crane Environmental Ltd, Surbiton, UK*). Speaking as the Chair of the Regional Flood Defence Committee in the Thames Region, I would like to comment that within the Thames catchment:

(i) January 2003 experienced the third highest fluvial flow since records began;

(ii) the 1953 floods led to the erection of the Thames Flood Barrier and associated defences;

(iii) the barrier first operated in 1983.

Thus, the planning-to-execution time was 30 years. We have therefore set up a project group to study the need for flood risk management in the Thames estuary for the 100 years from 2030.

I agree with your comments on the need for research, but would like to make the point that decision makers need advice about climate change sooner rather than later.

M. Hulme. I agree, and that is why we produced the UKCIPO2 scenarios for the Government in April 2002, to provide a coherent assessment of the range of possible future climates for the UK. But advancements in scientific knowledge always make such scenarios provisional. Future work may eventually allow us to estimate the probability of climate change occurring outside the range of conventional scenarios such as UKCIPO2.