Tyndall°Centre
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Vulnerability to abrupt climate change in Europe

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Section 1 Overview of project work and outcomes

Abstract

The most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) projected an increase in global average temperature of between 1.4 and 5.8^{o}C over the period 1990 to 2100, a rate of increase without precedent over at least the last 10,000 years. However, there is mounting evidence that climate, at least regionally, has changed much more rapidly in the past, and there are suspicions that human-induced global warming could trigger rapid and abrupt climate changes in the future. The aim of this project was to explore the implications of rapid or abrupt climate changes – defined here to be either a step change in climate regime or a rate of change outside the IPCC range – for Europe.

There has been a great deal of research into the potential mechanisms of abrupt climate change, but there are no published quantitative scenarios. Three characterisations of abrupt climate change were therefore produced for the current study. The first describes the potential climatic implications of a collapse of the thermohaline circulation in the North Atlantic, resulting in cooling across Europe. The second represents an accelerated climate change, caused by the additional release of greenhouse gases from permafrost and the oceans as climate warms. The final characterisation describes the rapid rise in sea level that would result from disintegration of the West Antarctic Ice Sheet.

Managers adapting to gradual climate change accept that change is happening, and look for information on the magnitude of change. Managers concerned about abrupt climate change, however, are less interested in the magnitude of change – they believe it will by definition be extreme – but are more interested in the likelihood of abrupt change occurring. There are, however, no scientifically robust estimates of the likelihood of thermohaline circulation collapse, accelerated climate change or rapid sea level rise, so a survey of expert opinion was conducted to provide some estimates. Difficulties in identifying a large sample of appropriate experts, and unwillingness of some experts to make subjective estimates of risk, meant that the final sample sizes were small. Estimates of the likelihood of thermohaline circulation collapse or accelerated climate change varied significantly between experts, over several orders of magnitude: most experts believed the risk of either to be very low (well under 1%), but a minority assessed the risk as considerably greater.

A detailed literature review revealed that there have been no published assessments of the implications of future abrupt climate change across Europe (a few palaeoclimatic studies have examined past physical responses to abrupt changes, and a small number of studies have explored how civilisations or communities were affected by past anomalies). An initial assessment of the implications of the three characterisations of abrupt climate change was therefore made using a combination of model simulations (for hydrology, crop potential and energy demand), review of published studies of the effects of gradual climate change and change thresholds, and expert judgement.

The key impacts of both thermohaline circulation collapse and accelerated climate change are likely to be on agriculture and crop production (and hence crop prices and rural economies), mortality and ill health, the ability of physical infrastructure (buildings and networks) to continue to operate effectively, and on ecosystems in both northern and southern Eirope. Accelerated climate change is also likely to significantly affect the availability of water resources as demand increases and supplies reduce. Rapid sea level rise would threaten coastal infrastructure and large parts of many key European cities, and would increase coastal flood losses: this would challenge the viability of insurance against flood hazards, and require very large investment in flood defences. All three abrupt changes would see a change in the economic and cultural centre of gravity of Europe, in different directions: following thermohaline circulation collapse the shift would be southwards, following accelerated change it would be northwards, and it would be inland after rapid sea level rise.

Abrupt climate change challenges the conventional scenario-driven approach to adaptation in two ways. First, it increases substantially the potential range of climate change impacts to be considered, but the likelihood of these extreme impacts occurring is highly uncertain and *probably* very low: unfortunately, it is currently impossible to estimate the likelihood of abrupt climate change. Second, it may be technically or financially difficult to adapt to abrupt change. It is, however, possible that in the face of a recognised abrupt climate change many of the barriers to adaptation, imposed by public attitudes or government policies, would be reduced.

A second approach to adaptation assumes that reducing vulnerability to current climatic variability will make a major contribution to reducing vulnerability to future climate change. Whilst some measures to reduce current vulnerability (such as poverty alleviation, hazard warning and some aspects of land use planning) do also cope with future climatic variability, many others do not. These include measures which are designed to provide some defined standard of services, such as degree of protection against flooding. Abrupt climate change, by definition, involves a step change in climate, and standards-based measures designed to cope with current variability are therefore even less likely to be a reasonable response to abrupt change.

Given the uncertainty associated with abrupt climate change, and the potential major difficulties in actually adapting to change, the most effective adaptation action now is to monitor – in the oceans, atmosphere and ice sheets - for the onset of abrupt change. Despite the impression given in *The Day After Tomorrow*, an abrupt climate change would probably become clear over a decade – although definitive identification of change would likely be highly controversial.

This project has begun to explore the implications of abrupt climate change in Europe, and provides the foundation for more in-depth studies. In particular, it is recommended that further studies seek to quantify the likelihood of defined abrupt changes in climate (this is already under way for some abrupt changes), and that quantitative scenarios for abrupt changes are constructed as the basis for quantitative assessments of the potential impacts of abrupt change. Research is also needed into the levels of likelihood that would be sufficient to trigger adaptive reactions, perhaps building on analogies from other areas exposed to low-probability, high-impact events.

Objectives

The broad aim of this project was to assess the vulnerability of key sectors in Europe to rapid or abrupt climate change, using a combination of desk studies and surveys of expert opinion. The specific objectives were:

i. to characterise and define rapid climate changes which may affect Europe, and collate state-of-the-art assessments of their likelihood and climatic manifestation
ii. to undertake a qualitative assessment of the sectors of the economy and society in Europe likely to be affected by the defined rapid climate changes;
iii. to construct numerical indicators of vulnerability to defined rapid climate changes, across Europe and the UK;
iv. to assess the attitudes of managers in different sectors to the threat of extreme, but rare, challenges, and begin to construct a conceptual model of adaptation to such challenges;
v. to provide the basis for a quantitative assessment of the risk of rapid climate change impacts, combining vulnerability and likelihood.

Results

There have been no formal studies of the implications of abrupt climate change in Europe, or indeed anywhere else, even though there has been much research into the mechanisms of abrupt change. Descriptions of three abrupt climate changes - a rapid cooling due to the collapse of the thermohaline circulation in the North Atlantic, a rapid warming due to the accelerated release of additional greenhouse gases as climate warms, and a rapid sea level rise following collapse of the West Antarctic Ice Sheet – were developed as a basis for an expert assessment. Discussions with those who may need to adapt to abrupt climate change revealed that they were more concerned about the likelihood of it occuring than its magnitude: a survey of experts showed a considerable range in estimates of likelihoods. Impacts of abrupt climate change on Europe are likely to be severe, but cannot yet be quantified. Major implications include significant changes to agriculture, and hence crop prices and the rural economy, and significant impacts on infrastructure reliability, under both cooling and accelerated warming. Rapid sea level rise would increase substantially coastal flood risk and permanently inundate some major cities and infrastructure. In each case, the economic centre of gravity of Europe is likely to change. It is not feasible to begin to adapt now to abrupt climate change, and it reducing vulnerability to current climatic variability or even gradual climate change would not be sufficient to adapt to abrupt climate change, but it is necessary to monitor for the signs of abrupt change.

Relevance to Tyndall Centre research strategy and overall Centre objectives

The project conforms closely to the objectives of the Tyndall Centre, and particularly Theme 3 on Adaptation to Climate Change. Specifically, it contributes towards the first three questions in Theme 3:

1. Who adapts, to what do they adapt, and why should they adapt?
2. What influences the ability of institutions to adapt to climate change?
3. Are there critical thresholds beyond which it is difficult to adapt

Potential for further work

Key areas for future research include:

- Quantitative characterisation of abrupt changes in climate: scenarios that can be used to drive quantitative impacts models need to be constructed using current ocean/climate models. In particular, scenarios combining thermohaline circulation collapse with an increasing concentration of greenhouse gases need to be constructed, and model simulations of accelerated climate change are required. The characterisations used in this preliminary assessment were necessarily based on rather naïve assumptions.
- Quantitative characterisations of the likelihood of defined abrupt changes in climate, under different assumed rates of climate change. This is extremely important, and will involve not only model simulations but also assessment of expert opinion (a major in-depth survey is currently being conducted by the Potsdam Institute for Climate Impact Research).
- Quantitative assessments of the implications of abrupt climate changes for defined sectors and regions: the only model-based assessments so far conducted were done for the current study and concentrated on physical impacts. In principle this is a relatively straightforward task, given scenarios for abrupt climate change and models of impacted sectors.
- Identification of "dangerous" magnitudes of climate change which would pose significant challenges to adaptation: in other words, what are the limits to adaptation?
- What are the specific implications of abrupt climate change for adaptation planning in particular sectors? Is it possible to draw analogies from other areas exposed to low-probability, high-impact events, such as military scenario planning or nuclear power station design.
- What probability of abrupt climate change would alter adaptation planning, and what factors influence this threshold probability?

Communication highlights

One paper has been submitted to a journal, based on a presentation at the conference on "Perspectives on Dangerous Climate Change" held at UEA in June 2004:

Arnell, N.W., Tompkins, E.L. & Adger, W.N. (2005) Eliciting information on the likelihood of rapid climate change. Submitted to *Risk Analysis*

A paper on the potential impacts of rapid climate change is being prepared for publication:

Arnell, N.W., Delaney, E.K., Tompkins, E. & Adger, N. Implications of abrupt climate change for Europe: an initial assessment. To be submitted to *Climatic Change*.

Section 2: Technical Report

1. Introduction and aims

The most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) projected an increase in global average temperature of between 1.4 and 5.8^{o}C over the period 1990 to 2100, a rate of increase without precedent over at least the last 10,000 years (IPCC, 2001a). Many studies – reviewed by the IPCC (2001b) - have assessed the ecological, economic and social impacts of such increases in temperature, in both qualitative and quantitative terms. All such studies, however, have essentially assumed that climate changes gradually (albeit at an historically fast rate under the most extreme projections) and "smoothly". Very few studies have reviewed comprehensively or quantitatively the potential effects of rapid or abrupt climate changes – broadly defined here as a "step change" in climate regime or a rate of change outside the IPCC range – although there has been much more research into the potential processes by which rapid or abrupt climate change might occur (National Research Council, 2002; Alley *et al*., 2003). However, anecdotal evidence suggests that some key sectors are very concerned about rapid climate change – and about the likelihood and impact of unprecedented extreme events - particularly where large and long-lived infrastructure investments are involved, and since late 2003 interest in the threat of rapid or abrupt climate change has increased substantially. Public awareness in the UK has been raised by a BBC Horizon documentary entitled *The Big Chill* first broadcast in November 2003, the leaking of a report commissioned by the US Pentagon (Schwartz & Randall, 2003) and, most recently, by the Hollywood movie *The Day After Tomorrow*, released in the UK in May 2004.

The broad aim of this project, which began in April 2003, was to assess the vulnerability of key sectors in Europe to rapid or abrupt climate change, using a combination of desk studies and surveys of expert opinion. The IPCC's Third Assessment Report (2001b) states that "vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (p995). However, through discussions with policymakers who are considering adapting to climate change – across many sectors – it became clear that perceptions of vulnerability to rapid or abrupt climate change are very much determined by perceptions of *likelihood*: if it happens it will almost by definition be "bad", so what is important is the chance of it happening. Any assessment of vulnerability to and potential adaptation to rapid or abrupt climate change must therefore begin with an assessment of the likelihood of defined rapid changes occurring.

This report is structured as follows. The next section explores in detail the interpretation of "rapid" or "abrupt" climate change, and introduces a classification. Section 3 introduces semi-quantitative characterisations of three abrupt climate changes used as the basis for an assessment of impacts and vulnerability, and Section 4 discusses the assessment of likelihoods for these characterisations. Section 5 summarises the estimated impacts of abrupt climate change in Europe, and Section 6 discusses implications for vulnerability to abrupt climate change. Section 7 describes the implications for developing adaptation strategies. Section 8 explores the implications of abrupt climate change for adaptation.

2. What is abrupt climate change?

2.1 Abrupt forcings and abrupt impacts

Until recently there have been no clear definitions of "rapid" or "abrupt" changes[1]: the glossary of the IPCC's Third Assessment Report, for example, describes some "rapid" climate changes, but does not attempt a formal definition. Essentially, these changes are implicitly assumed to result in a rate of climate change outside the range (increase of 1.5 to 5.8^{o}C in global average temperature and an increase in sea level of 10 to 87cm by 2100, relative to 1961-1990) projected in the Third Assessment Report. A broad distinction can be drawn between two types of rapid or abrupt change. The first can be seen as *abrupt* changes, where the climate system either globally or regionally crosses a threshold and switches to a new state (National Research Council, 2002): these changes include the collapse of the thermohaline circulation and the collapse of ice sheets. The second can be seen as *accelerated* changes, where the rate of climate change increases rapidly: these include changes due to large positive feedbacks, such as the release of methane into the atmosphere following warming at the sea bed or of permafrost. This accelerated change *may* result in an abrupt change in climate, but will not necessarily do so. There is also a scale issue: "abrupt" climate changes are generally implicitly taken to affect large geographic areas. Gradual climate change will mean that some localised marginal areas will experience substantial changes in climate regime which may locally be perceived as rapid and abrupt.

A distinction can also be drawn between abrupt and rapid climate *changes* and abrupt climate change *impacts*. The former represent large changes to the *forcings* applied to a system, whilst the latter arise once a key *response threshold* is crossed (Figure 1). A rapid or abrupt climate change need not cause a major impact; an abrupt climate change impact may result from a gradual change in climate forcings. An important difference between rapid and abrupt climate change forcings and abrupt climate change impacts is that the former can in principle be defined objectively, whilst the latter may be subjectively defined. The next two subsections explain in more detail rapid and abrupt climate change forcings and abrupt climate change impacts. The term "**abrupt climate change**" is used subsequently to cover rapid and abrupt climate change forcings and abrupt climate change impacts.

2.2 Rapid and abrupt forcings

Ecological, social and economic systems are influenced to varying degrees by the state of the physical environment. This includes the underlying soil and rock on the one hand and the processes operating on this underlying material on the other. Whilst some of these processes are geological – such as metamorphosis of rock through heating or uplift through land movement – most are driven by weather and climate. These processes may be effectively constant (but with variation at different time scales around a mean), may change gradually, or may change rapidly and abruptly. An earthquake or volcanic eruption can be seen as a rapid change in process, and climate change has the potential to trigger rapid and abrupt changes in climate processes and regimes.

[1] This is partly because of major differences in time scale between different disciplines involved in climate change science: a change that is rapid for a geologist may be slow for an ecologist

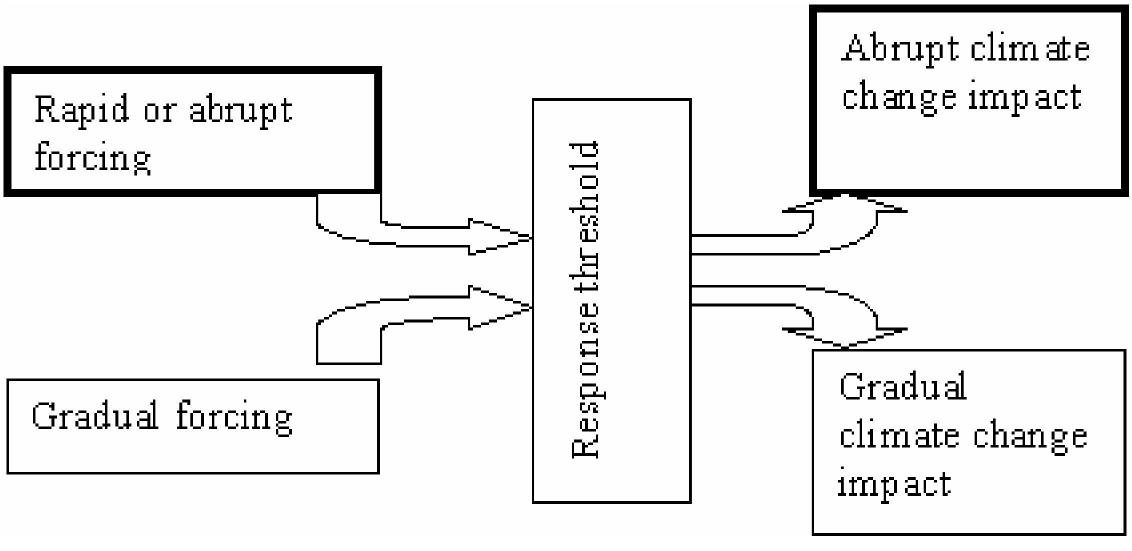

Figure 1: Rapid and abrupt climate change and abrupt climate change impacts

Table 1 proposes a classification of potential rapid and abrupt climate changes due to an increasing concentration of greenhouse gases. Brief descriptions of each follow.

Abrupt shifts in the thermohaline circulation have been implicated in many abrupt climate changes in the past (see Clark *et al*., 2002 for a review), most significantly during the Younger Dryas (12,700 years BP) and 8,200 years BP (known as the 8.2 ka event). The thermohaline circulation can be seen as a pump, bringing warm water across the North Atlantic towards Europe. The pump is driven by this warm salty water cooling, becoming more dense, and then sinking to flow southwards at depth. Large inputs of freshwater into the North Atlantic may reduce surface density, prevent further sinking and essentially switch off the transport of warm water north eastwards across the Atlantic. Model simulations show that temperatures across Europe could fall by up to 3°C in little more than a decade if the transport of warm water were to reduce (Vellinga & Wood, 2002). Inputs of freshwater in the past have come from catastrophic releases from ice-dammed lakes in North America during deglaciation, and these of course no longer exist. Future freshwater could come from extra precipitation over the Arctic Ocean, increased runoff from rivers draining into the Arctic, or accelerated melt of the Greenland ice sheet (see below). The likelihood of the collapse of the thermohaline circulation during the coming century is very uncertain: it is not clear how close the circulation is to a threshold, and it is not clear how much extra freshwater is likely to arrive into the North Atlantic.

It is estimated that over the last century precipitation over the Antarctic ice sheet has exceeded loss by melt or calving, and model projections are for this to continue during the 21st century (Church & Gregory, 2001). However, the West Antarctic Ice Sheet is grounded below sea level, and thus potentially unstable: if the ice shelves surrounding the ice sheet are weakened by melting from above or below, it is possible that discharge of ice would increase substantially. Other mechanisms which may trigger “rapid” deglaciation (over decades or centuries) include rapid acceleration of ice streams within the West Antarctic Ice Sheet. Complete collapse would raise global sea levels by around 5m, but this is likely to take thousands of years: rates of sea level rise during collapse are unlikely to exceed 1 m/century (or 10mm per year: Vaughan & Spouge, 2002).

	Change in ocean circulation	Rapid deglaciation		Major feedbacks			Regime shift		Singular events
	Thermohaline circulation collapse	West Antarctic Ice Sheet (WAIS)	Greenland Ice Sheet	Methane hydrates	Permafrost and methane	Vegetation feedback	Shift in NAO	Permanent ENSO	Unprecedented storm
Description	Reduced salinity of North Atlantic leading to shut-down of thermohaline circulation and large reductions in temperature across western Europe. Defined as sea level rise> 1m/century	Collapse of West Antarctic Ice Sheet, leading to rapid rise in sea level	Collapse of Greenland Ice sheet, leading to rapid rise in sea level (and also THC collapse)	Release of methane stored under sea bed, leading to rapid increase in GHG concentrations	Release of methane stored in permafrost, leading to rapid increase in GHG concentrations	Change in vegetation cover alters land surface processes and hence climate	Circulation patterns in North Atlantic change permanently causing depressions to pass further north. Change in degree, rather than type of regime	Shift in Pacific sea surface temperatures so that El Nino-like regimes become normal	Large event caused by unprecented atmospheric conditions (e.g. hurricane in western Europe – 1703 storm)
Spatial extent of effect	World-wide, but mostly in Europe	World-wide (coastal)	World-wide (coastal)	Global	Global	Regional, with effects declining with scale	Europe, north east America	Around Pacific and Indian Oceans: possibly global	Regional
Effect on temperature and precipitation regimes	Cooling of 1-3°C in Europe, particularly in winter. Reduction in precipitation: -10 to -20%	Effect of flux of cold water into oceans on climate not modelled	Effect of flux of cold water into oceans on climate not modelled: link to THC	Not known	Not known	Removal of forest cover lowers temperatures by 0.7-1.1°C in temperate areas, and raises temperatures locally by up to 1.5°C. Effects on precipitation unclear	Warmer and wetter winters in northern Europe, cooler and drier in the south	Precipitation extremes around Pacific and Indian Oceans become more extreme	Extreme precipitation and windspeed
Effect on sea level	-	Up to 1 m/century	Up to X m/century	?	?		-	-	-
Rate of onset	Within a decade of shutdown	Several hundred years		?	?		Very rapid	Very rapid	Very rapid
Likelihood within 100 years	?	2% (rate > 10mm/year)	"unlikely"	?	?		?	?	?

Table 1: A classification of rapid and abrupt climate changes

Complete disintegration of the Greenland Ice Sheet would raise sea levels by 7m. This ice sheet is much more stable than the West Antarctic Ice Sheet because it is entirely grounded above sea level, and under most of the scenarios reviewed in the Third Assessment Report melting of the Greenland Ice Sheet would lead to only a small increase in global sea level (Church & Gregory, 2001). However, subsequent research has suggested that the Greenland Ice Sheet is less stable than previously suspected, and is likely to be eliminated once temperatures rise by more than around 3^{o}C above 1990 temperatures (Gregory *et al.*, 2004). Whilst this is unlikely to have an effect during the 21st century, over the next 1000 years sea level would rise by 7m (and, of course, this freshwater would contribute to weakening of the thermohaline circulation).

The climate system is characterised by a large number of feedbacks, both positive and negative. Most of these feedbacks are incorporated into climate models and therefore influence projections of future climate change. However, many of the feedbacks are not well understood or adequately modelled, and there are some additional feedbacks which have the potential to produce substantially larger increases in temperature than currently projected. The US National Research Council identifies three groups of climate feedback (NRC, 2003). The first affect the *magnitude* of climate change, and are divided into feedbacks which affect climate sensitivity (change in climate for a given change in forcing) and feedbacks which affect the rate of forcing. Whilst there are many unknowns in the first of these two sub-groups, and the NRC recommends further research as a high priority, it is not anticipated that these feedbacks would result in substantially more rapid rates of climate change than currently projected. The second sub-group – affecting rates of forcing - however, have greater potential for generating rapid climate change. Higher temperatures may lead to increased release of methane from high latitude wetlands, particularly where permafrost thaws, and higher temperatures at the sea bed may lead to the release of methane currently stored as methane hydrates (Ehhalt & Prather, 2001). Recent research also suggests that higher temperatures would increase further the rate at which carbon is released from the soil (Knorr *et al.*, 2005). The magnitude of effect is unknown, and potential effects on forcings and hence climate have not yet been simulated.

The second group of climate feedbacks identified by the NRC influence the rate of response to climate change, and primarily relate to rates of heat uptake in the ocean. Whilst these feedbacks are important, they are unlikely to lead to rapid climate change. The third group of feedbacks, however, may result in large and abrupt changes in climate at the regional scale. These feedbacks include the effect of changes in land surface on climate, and shifts in the natural modes of climatic variability. The potential effects of changes in land surface on climate (through changes in albedo and evaporation) have been suspected for several decades, although it is only in the last few years that model studies have shown substantial regional impacts on climate of changes in land cover (e.g. Chase *et al.*, 2000; Pitman & Zhao, 2000; Higgins *et al.*, 2002)). However, there is considerable uncertainty over the extent of change, largely due to uncertainties in the modelling of land surface processes. Also, the effects of future land cover change on climate (current generation climate models assume no change in land cover) depend on projections of future land cover.

The climate system is characterised by a number of consistent patterns, known as modes of climatic variability. The most well-known is the El Nino/Southern Oscillation (ENSO), which influences spatial and temporal patterns of temperature and rainfall around the Pacific Ocean and into the Indian Ocean: during an ENSO event rainfall is anomalously high in the eastern Pacific and low in the west, and the south and east Asian monsoons are weaker. The

North Atlantic Oscillation (NAO) affects variability in weather across Europe from year to year. In years when the pressure gradient across the North Atlantic is high depressions are more vigorous, and when the pressure gradient is low depressions are weaker and pass further to the south. Some climate models project shifts in modes of variability so that, for example, the the climate switches to a “permanent-ENSO” or the pressure gradient across the North Atlantic is consistently high (Cubasch & Meehl, 2001). Whilst this may not have large effects on indicators of global climate, it may have very rapid and abrupt effects on regional climate. A particular concern is that a shift to a more persistent ENSO would lead to reductions in the south Asian and east Asian monsoons. However, computer simulations show that increased moisture availability would more than offset reduced circulation, and rainfall is projected to increase in both the south and east Asian monsoons (May, 2004; Bueh *et al*., 2003).

Any change in climate has the potential to alter mean climate and the frequency of occurrence of extremes. A rapid or abrupt climate change will (by definition) alter mean climates substantially, and have large effects on the frequency with which extremes occur. A relatively small “non-abrupt” change in climate which has relatively little effect on regional mean climate, however, may produce very large changes not only in the frequency of extreme events in the region, but also their characteristics. For example, an increase in sea surface temperatures has the potential to generate more vigorous tropical cyclones, which may begin to affect areas currently not exposed to them (although current model projections suggest little change in areas affected by tropical cyclones: Cubasch & Meehl, 2001). The occurrence of an unprecedented event – a hurricane, for example, or an exceptionally prolonged drought – in an area may trigger significant impacts and major changes in the management of extreme events, which may be different in character to the changes that would result from an altered frequency of “normal” extreme events. In practice, of course, it may be difficult to distinguish an extremely rare but “normal” event from one that is qualitatively different: was, for example, the 1703 “hurricane” that affected southern England really just an extreme storm, or was it in a class of its own, and were the 2002 floods in central Europe really caused by unprecedented combinations of climatic conditions?

2.3 Rapid and abrupt impacts

In the most general terms, climate change is likely to have three broad types of impact on an ecological, social or economic system. First, a changing climate may have no identifiable impact, either because the climate change is small (perhaps relative to other relevant forcings) or because the system can adapt to the changing climate with little or no cost or effort. Second, a changing climate may require either a more substantial adaptive response or create greater impacts if adaptation does not take place, but even so does impose an unduly excessive burden. Adaptation is in principle feasible, and the impacts are not intolerable (at least at some scales). Third, a changing climate may generate unacceptable impacts or be extremely difficult to adapt to: this last category can be termed a “rapid”, “abrupt” or “dangerous”[2] climate change impact.

The boundaries between the three types of impact are fuzzy, but broadly can be seen as critical thresholds: as thresholds are crossed, climate change impacts move from being trivial, through broadly tolerable, to unacceptable. There are two types of threshold. A biophysical threshold (a “force threshold”: Arnell, 2000) exists when the system performs differently

[2] there is an increasing literature on the interpretation of “dangerous” climate change (Dessai *et al*., 2004)

when the climate-driven forcing passes a certain point. There are many examples from geomorphology and ecology (e.g. for thermal bleaching of corals: Berkelmans, 2002), and Kenny *et al*. (2000) give examples of biophysical thresholds in some sectors in New Zealand agriculture.

A “response” threshold (Arnell, 2000) is imposed by the operators or managers of a particular system, and may be expressed in terms of standards of service. In this case, transition from one impact state to another occurs not because the system is behaving differently, but because its performance is outside specified boundaries. These boundaries may be objectively defined – they may be based on cost-benefit criteria, for example – but the key point is that they are human inventions, and may be entirely subjective. Climate change may be believed to be “too rapid”, or impacts to be “unacceptable”.

Whilst rapid and abrupt changes to climate forcings can in principle be identified and characterised objectively and scientifically, rapid and abrupt impacts of climate change may largely be either subjectively defined or at the very least based on human rules and procedures. These types of impacts cannot therefore necessarily be identified “top-down”, but must be determined from the bottom-up (Dessai *et al*., 2004).

3. Characterising abrupt climate changes

3.1 Types of abrupt climate change

Unlike “gradual” climate change, rapid climate changes are most easily visualised as notable singular events, such as collapse of the thermohaline circulation or collapse of the West Antarctic Ice Sheet, or as the results of step changes in forcing. Discussion of the implications of rapid climate change can therefore be based around narrative characterisations of potential changes. The Pentagon report (Schwartz & Randall, 2003), for example, used the climate changes during the Younger Dryas (12700 years ago) as an analogue for the future climatic impacts of a collapse of the thermohaline circulation. This section describe the characterisations of three abrupt climate change scenarios developed in the current study. Two of the scenarios are based on climate changes simulated under the IPCC’s A2 emissions scenario using the HadCM3 climate model (Johns *et al*., 2003).

3.2 Collapse of the thermohaline circulation

There have so far been no published simulations of the combined effect of climate change and thermohaline circulation collapse. The indicative effects of a collapse of the thermohaline circulation are therefore here based on combining changes in climate presented by Vellinga & Wood (2002) assuming no climate change with simulations made using the same HadCM3 climate model and the A2 emissions scenario. Scenarios for change in climate by the 2020s and 2050s are here constructed by adding the simulated effects of thermohaline circulation collapse to the seasonal climates as simulated using the HadCM3 model and the A2 emissions scenario, assuming thermohaline circulation collapse in 2015 and 2035. Specifically, Vellinga & Wood’s changes in climate in the first decade are added to the HadCM3 A2 ensemble mean climate change for the 2020s (collapse in 2015) and 2040s (collapse in 2035), and changes for the 2050s are estimated by appying the relevant decadal change from Vellinga & Wood to the climate at the time of collapse. This is inevitably an approximation, for three reasons: first, it is not necessarily the case that the effects of thermohaline circulation collapse and increasing concentrations of greenhouse gases will be additive; second, the approach does not take into account the continuing increase in greenhouse gases after thermohaline circulation collapse, and third, Vellinga & Wood's (2002) simulation involved an instantaneous influx of freshwater rather than a gradual but prolonged increase. Also, different climate models would of course give a different spatial pattern of change.

Figure 2 shows the change in average annual temperature, winter precipitation and summer precipitation across Europe by the 2020s and 2050s, assuming collapse in 2015, and Figure 3 shows the same assuming collapse in 2035 (note that here the 2020s changes represent just the effect of increasing concentrations of greenhouse gases). Figure 4 shows the change in annual temperature in England and Wales with climate change as projected in the UKCIP02 scenarios (Hulme *et al*., 2002) and assuming collapse of the thermohaline circulation in 2015 and 2035.

3.3 Accelerated climate change

Accelerated climate change is characterised by rescaling the spatial pattern of change simulated by the HadCM3 climate model under the A2 emissions scenario to represent faster rates of change. Specifically, it is assumed that accelerated feedbacks would lead to climate change twice as fast as that under the A2 emissions scenario, resulting in increases in global mean temperature, relative to the 1961-1990 mean, of 2^{o}C by 2020s, 4.2^{o}C by 2050s, and 7.2^{o}C by 2080s. Figure 5 shows changes in mean annual temperature, together with winter and summer precipitation, across Europe by the 2020s and 2050s. It is implicitly assumed that the rate of increase in forcing does not affect the spatial pattern of change (on physical grounds it could be expected that land would warm up more rapidly than sea). It is also important to note that different climate models would give different patterns of change in climate. Figure 4 shows the change in average annual temperature across England and Wales under the scenario for accelerated climate change, compared to the projections under the UKCIP02 scenarios.

3.4 Collapse of the West Antarctic Ice Sheet

Rapid sea level rise is characterised by an increase in sea level of 2.2m by 2100, relative to 1990 mean, with the increase continuing unabated after 2100. This increase of 20mm per year represents the maximum IPCC rate (8.8mm per year) plus a contribution of 10 mm per year from the West Antarctic Ice Sheet, plus a bit more to allow for decline of the Greenland Ice Sheet.

Figure 6 shows the change in global sea level from the IPCC's Third Assessment Report together with the assumed rapid sea level rise scenario. Sea level rise due to thermal expansion varies geographically, but variations would be relatively small if a large proportion of the increase was due to ice sheet collapse.

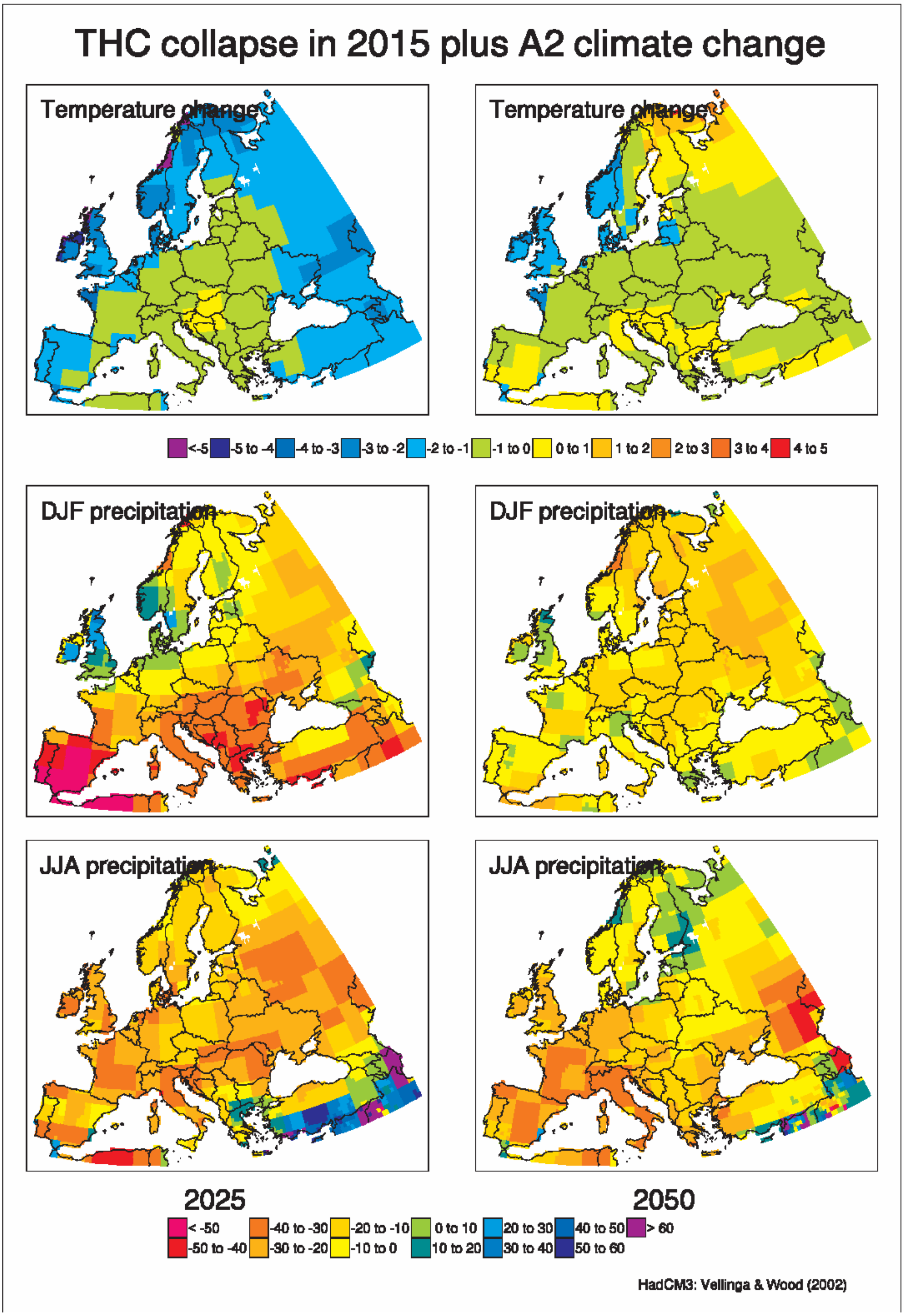

Figure 2: Change in temperature and precipitation by 2025 and 2050, with thermohaline circulation collapse in 2015 and global warming following A2 emissions

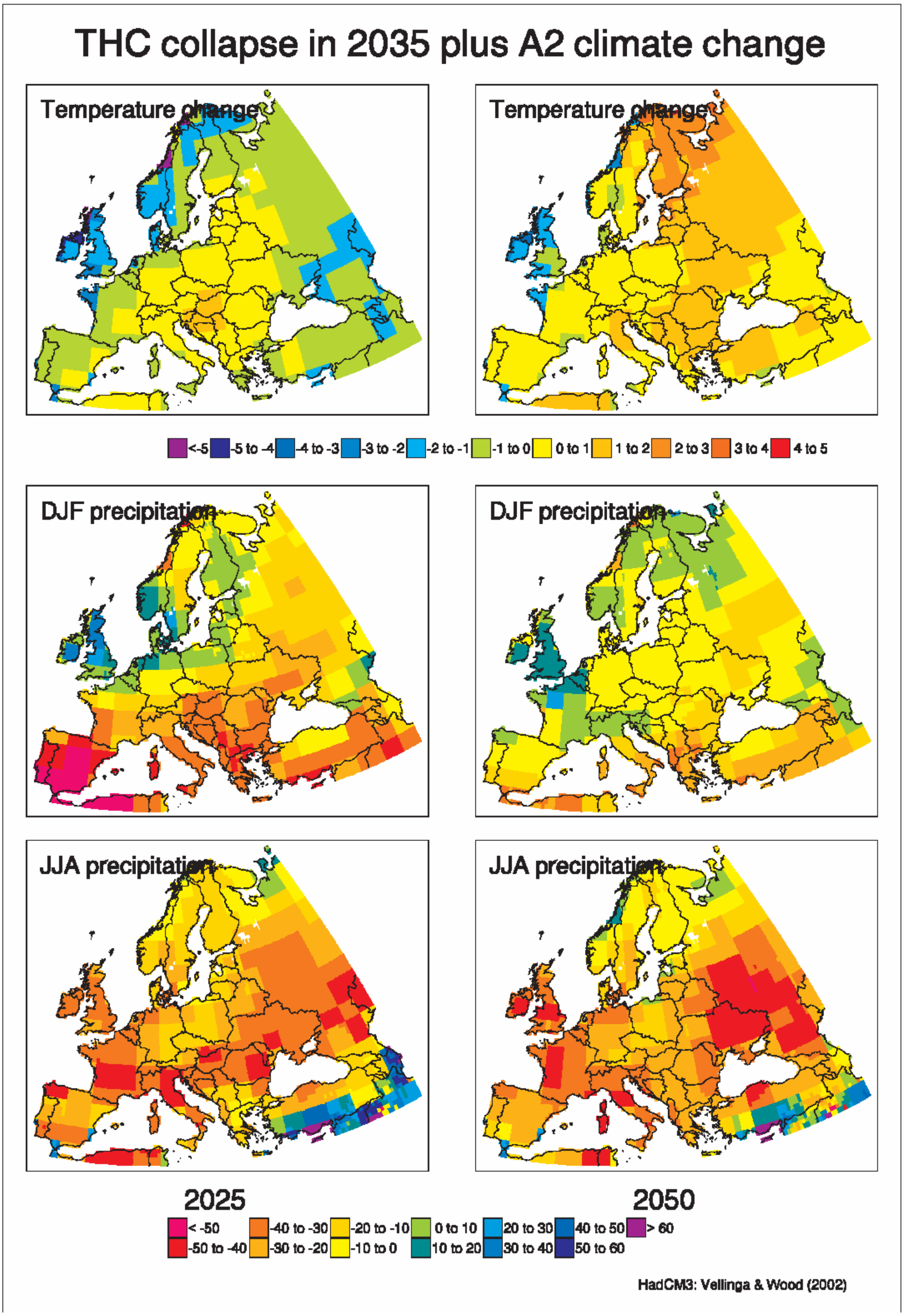

Figure 3: Change in temperature and precipitation by 2025 and 2050, with thermohaline circulation collapse in 2035 and global warming following A2 emissions

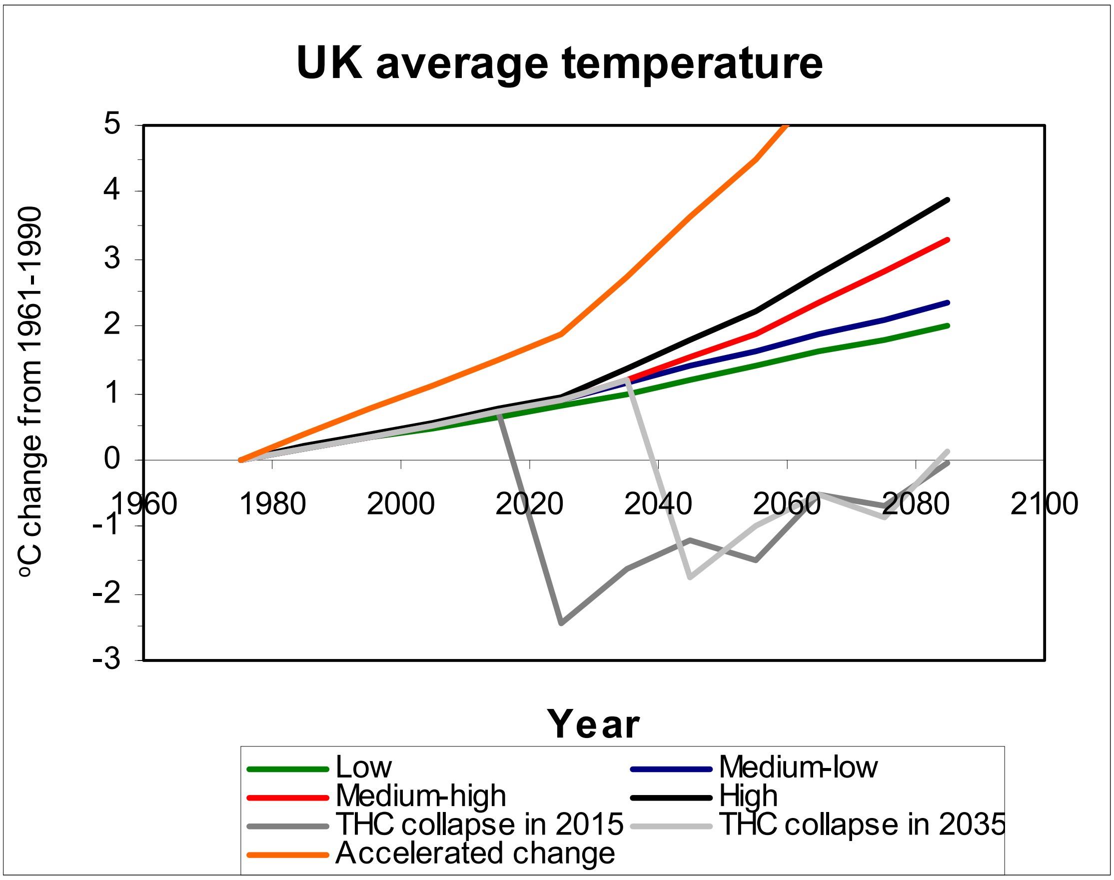

Figure 4: Change in UK temperature under the UKCIP02 scenarios, together with thermohaline circulation collapse in 2015 and 2035, and accelerated climate change

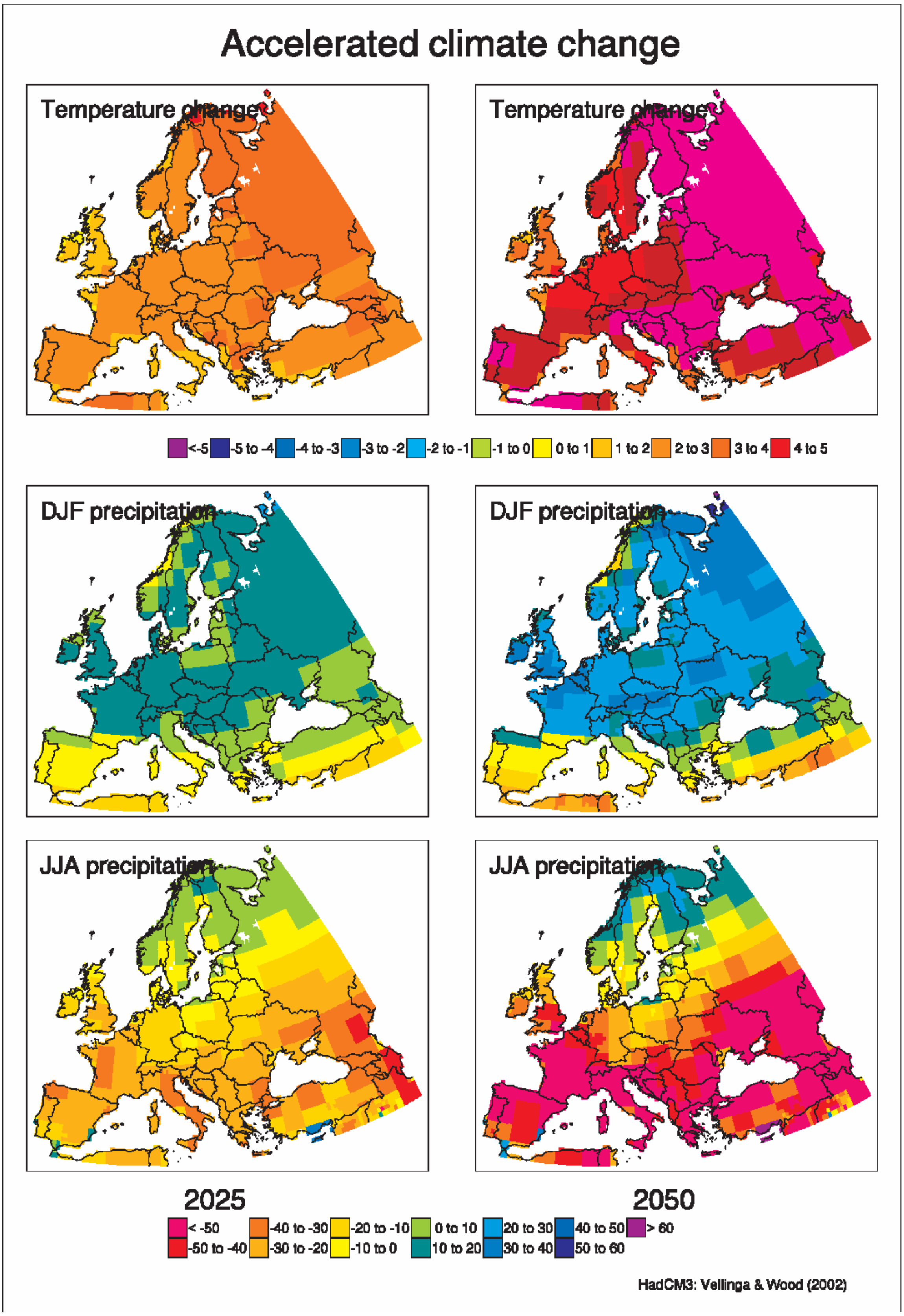

Figure 5: Change in temperature and precipitation by 2025 and 2050, under accelerated climate change

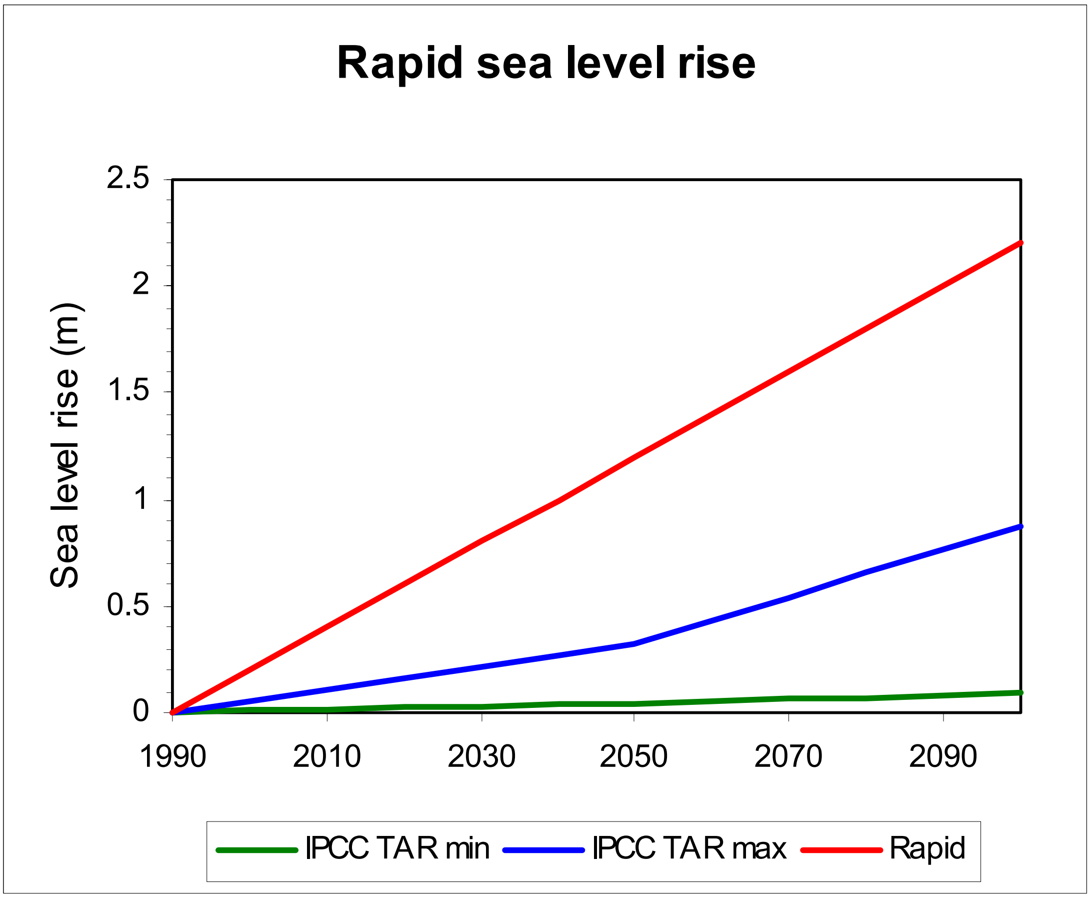

Figure 6: Sea level rise under the IPCC and rapid sea level rise scenarios

4. Estimating likelihoods of abrupt climate change[3]

4.1 Introduction: the role of likelihoods

The IPCC's Third Assessment Report (TAR) has been criticised (Reilly *et al*., 2001; Schneider, 2001;2002) for not assigning probability levels to projected rates of climate change, and a number of arguments have been put forward as to why probabilities were not estimated. These essentially fall into two categories. Firstly, the physical climate system is not well enough known to be able to construct objective probability distributions for model parameters or responses to a given forcing, and secondly it is inherently impossible to assign probabilities to narrative storylines describing possible future emissions scenarios (Grubler & Nakicenovic, 2001). Nevertheless, since the TAR there have been several attempts to construct probability distributions for measures such as change in global temperature (Wigley & Raper, 2001; Webster *et al*., 2003) and also to construct probability distributions for potential changes in some indicator of impact (e.g. Jones, 2000). There has, however, been far less work on assessing the likelihood of rapid or abrupt climate changes – and these probabilities are increasingly being demanded by those seeking to mitigate or adapt.

Dessai & Hulme (2004) noted that the extent to which probabilities were useful or not for climate policy depends on context, and in particular on the policy question being asked. Most of the controversy over the *value* of probabilities (rather than how to estimate them) in climate policy relates to the use of probababilities in making adaptation or mitigation decisions. First, it is argued (Lempert & Schlesinger, 2000; Lempert *et al*., 2004) that where uncertainty is "deep" – as in climate change assessments – it is more appropriate to rely on robust strategies that can cope with climate change uncertainty than to use a more formal risk-based strategy such as designing to a specified probability standard (designing a reservoir, for example, so that there was only a 5% chance that in the future it would be insufficiently large to maintain yields). Following this argument, it is therefore unnecessary and misleading to attempt to assess probabilities of climate change outcomes: efficient and effective adaptation does not rely on probabilities. However, whilst some adaptation strategies may be robust to any possible future outcome, it will often not be feasible to design strategies that can cope with everything: in practice some potential outcomes would be screened out as being "too unlikely".

Second, some approaches to developing adaptation strategies focus on understanding and reducing social vulnerability to the impact of change. Again, probabilities – and indeed climate scenarios - are believed not to be relevant here because such measures are insensitive to the amount of future change. However, in practice again such assessments need to define some boundaries on ranges of possible future climates.

4.2 Estimating likelihoods

All of the potential rapid and abrupt climate changes that have been identified are either physically plausible, have occurred in the past or have been simulated with computer simulation models. In principle there are three ways of estimating likelihoods of occurrence:

[3] Section 4 is based on Arnell *et al*. (2005)

through analysis of past records, through computer simulation using multiple drivers and process representations, or through expert judgement.

4.2.1 Analysis of past records

The traditional way of estimating the frequency of occurrence of an event is to use information on its occurrence in the past. However, it is very difficult to apply this approach to estimate the likelihood of future rapid changes, either because analogue events have not occurred in the past or, more problematically, when they did occur the climatic and environmental conditions were very different.

For example, there is considerable evidence that the thermohaline circulation in the North Atlantic has switched off on several occasions over the last few hundred thousand years (Rahmstorf, 2002). In each case, however, shutdowns have been triggered by the release of water from very large ice-dammed lakes in North America: these lakes no longer exist.

4.2.2 Computer simulation

The second approach is to use computer simulation models to construct probability distributions of defined events from large numbers of simulations making different assumptions about, for example, rates of change in driving forces, model formulations and parameter values. Several studies have sought to construct probability distributions of future global temperature change with this approach, using either simplified climate models run several hundreds of times (e.g. Wigley & Raper, 2001; Webster *et al*., 2003) or smaller ensembles of more complicated climate models (e.g. Raisanen & Palmer, 2001; Knutti *et al*., 2003; Murphy *et al*., 2004). Wigley & Raper (2001) and Webster *et al*. (2003) estimated the 90% confidence interval for change in global mean temperature by 2100 at 1.7-4.9^{o}C and 1-4.9^{o}C respectively, using slightly different approaches. Raisanen & Palmer (2001) used an ensemble of seventeen different climate models to estimate that the probability of a global temperature increase greater than 1^{o}C was 14% after forty years of increasing greenhouse gas concentrations, and 82% after eighty years. Murphy *et al*. (2004) used a 53-member ensemble of different versions of the HadAM3 climate model to estimate, amongst other things, a 5-95% confidence interval of 2.4 to 5.4^{o}C for the equilibrium effect of a doubling of CO_2 concentrations.

Whilst several studies have sought to identify critical thresholds for the collapse of the thermohaline circulation in the North Atlantic (e.g. Rahmstorf & Ganopowlski, 1999), no published studies have so far attempted to estimate the likelihood of collapse. Schaeffer *et al*. (2002) ran ten member ensemble simulations under different emissions scenarios to estimate the likelihood of abrupt *regional* cooling due to disruption of ocean circulations patterns in part of the Arctic Ocean, showing a virtually 100% likelihood by the end of the 21st century under high emissions, a 33% chance under moderate emissions, and a 10% chance under stabilised emissions (they noted that the regional disruptions to ocean circulation did not necessarily affect the North Atlantic). Gregory *et al*. (2004) estimated the likelihood that the Greenland Ice Sheet would go into terminal decline, using an ensemble of different climate models run with different emissions scenarios.

Estimates of likelihood based on computer simulation models, however, are only as robust as the simulation model itself and the assumed probability distributions of input drivers. Weaver & Hillaire-Marcel (2004), for example, emphasise how different types of ocean-climate model imply different sensitivities of the ocean circulation in the North Atlantic to perturbation. Distributions of some input drivers, such as key model parameters, can be based on calibrations with observed experience, but there may often be either no or conflicting empirical evidence on which to construct probability distributions: in these cases, some form of expert judgement is necessary.

4.2.3 By expert judgement

In one sense, all “scientific” assessments are based on some form of expert judgement: the judgement of the individual or group responsible for collating “relevant” past experience or constructing “accurate and reliable” simulation models. However, a third approach to estimating the likelihood of rapid or abrupt climate change is to elicit formally the opinions of a number of experts. Formal approaches to use expert opinion have been used for many years in many areas of decision making (see Ayuub, 2000 and Morgan & Henrion, 1990). Formalised procedures are essential to ensure reliability and credibility (Cooke & Goossens, 2004), and these may involve two stages.

The first is the *elicitation* of information from a group of identified experts. Cooke & Goossens (2004) suggest that the selection criteria for experts include reputation, experience and published track record in the field of interest, diversity of background, balance of views and, of course, interest and availability. Information can be elicited using a variety of methods, ranging from unstructured in-depth interviews through focus groups to the use of structured questionnaires. One variant is the Delphi approach, which essentially involves iteration around the group of experts, giving individuals the opportunity to revise their estimates or comment on the estimates of others. Acknowledged pitfalls of expert elicitation include different interpretations of the questions posed and a widely-reported observation that experts tend to be overconfident in their assessments (Morgan *et al*., 2001).

A second stage involves the *aggregation* of the information elicited from the experts to produce a consensus (Cooke & Goossens (2004) state that the goal of formal expert elicitation methods “is to achieve rational consensus in the resulting assessments” (p644)). This aggregation could produce, for example, a probability distribution of the magnitude of some state parameter reflecting different possible futures or various sources of uncertainty (Keith, 1996). There are several ways of constructing aggregated expert assessments (see Cooke & Goossens, 2004), all based on different ways of weighting the views of individual experts.

Surveys of expert judgement do not necessarily need to aggregate information from individual experts. Whilst in some cases it may be appropriate to aggregate in order to construct a single probability distribution, in many others the range of expert opinion may be much more important (Keith, 1996): information on the diversity of opinion may be extremely valuable to policy-makers. Lempert *et al*. (2004) claim that the attempt to construct consensus probability distributions for key climate parameters is fundamentally flawed, due to the deep uncertainty over many of the drivers and proceses of global change.

Expert elicitation has been used in a number of climate change assessments. Morgan & Keith (1995) interviewed sixteen experts to assess possible future changes in temperature and precipitation: each expert gave a “best estimate” and a range, and these were represented individually without aggregation. Morgan *et al.* (2001) surveyed eleven ecologists to obtain individual qualitative and quantitative estimates of the impact of climate change on minimally-disturbed forest ecosystems, finding a greater diversity of opinion than apparent in consensus summaries, such as those of the IPCC. Again, the results were not aggregated. Vaughan & Spouge (2002) conducted a more formal Delphi survey of the likelihood of rapid sea level rise following collapse of the West Antarctic Ice Sheet, and aggregated individual expert assessments to produce a single probability distribution function describing likelihood of collapse. Murphy *et al*. (2004) based the upper and lower limits for the changing parameters of their climate model on expert opinion, although did not use a formal elicitation approach. Mastrandrea & Schneider (2004) and Webster *et al.* (2003), however, used formal expert elicitation processes to, respectively, construct probability distributions of climate sensitivity and estimate the likelihood of different rates of future emissions of greenhouse gases. These two studies both used aggregate constructions from the individual experts.

4.3 Assessing likelihoods: results

4.3.1 The approach

An expert survey approach was adopted in the current study to assess the likelihood of thermohaline circulation collapse and accelerated climate change (Vaughan & Spouge's (2002) results were used to characterise the likelihood of rapid sea level rise). The approach involved the identification of relevant experts and the circulation via email of a standardised questionnaire for each of the two abrupt climate changes. The survey involved two iterations: the second iteration presented the results and sought both revisions to original estimates and comments on the estimates. No attempt was made to aggregate the individual expert assessments to produce consensus probability distributions: from the comments of the experts (below) it is very unlikely that a consensus could in any case have been reached.

4.3.2 Identifying experts

Central to any survey of expert opinion is the definition of the experts to be surveyed. "Experts" on rapid and abrupt climate change can fall into several different categories:

- Scientists actively studying the physical processes of rapid and abrupt climate change
- Scientists reviewing the work of other scientists (through the IPCC, for example)
- Scientists involved in assessing the implications of rapid and abrupt climate change scenarios
- Policymakers concerned about the implications of rapid and abrupt climate change for adaptation or mitigation policies
- Lobbyists

Any of these may have opinions on the likelihood of rapid and abrupt climate change, but the basis for these opinions and agendas will be different. In order to reduce potential bias the decision was made to restrict the survey to scientists involved in studying physical processes and reviewing abrupt change science. Experts identified included those who lead major research programmes into rapid and abrupt climate change, those who had published on the processes of change, and those who had participated in the IPCC's Third Assessment Report reviews of rapid and abrupt change. A total of 21 experts on thermohaline circulation collapse was identified, together with 17 experts on accelerated climate change. Experts were based in the UK, Europe and the United States. Some of the experts were common to both changes.

One of the surveyed experts declined to take part in the survey precisely because he declined to identify himself as an expert:

> "I doubt if there are more than 5 or 6 people in the UK[4]…who could express an independent expert view on this. The rest would all be second hand (and hence distort the statistics) or, worse, second hand plus a bit of their own subjective biases. Unless you limit your canvassing to the handful of hands-on experts, your result could be misleading…"

4.3.3 Participation rates

The actual response rate to the two surveys was low – thirteen and nine for the thermohaline and accelerated surveys respectively, despite reminders. Four of the thermohaline survey respondents declined to participate, as did five of the accelerated change survey: their reasons are summarised in Table 2. Two declined because of conceptual problems with the allocation of subjective probabilities, and two preferred the use of output from simulation models: one declined because the likelihood of change was believed to be very small. Six of the nine thermohaline circulation survey respondents participated in the second round, as did four of the five accelerated change survey respondents.

Table 2: Reasons for declining to participate

Collapse of thermohaline circulation
• I don't consider abrupt cooling of Europe due to a collapse of the thermohaline circulation during the next century to be a serious risk • I don't believe that any statement I make without reference to models would be more than a guess, with no reliable information content, whereas if I refer to models you should get the same, more accurately, by analysing their output yourself. • The approach adopted is not sufficiently sophisticated and the results are therefore potentially misleading • I'm not an expert
Accelerated climate change
• I participated in an earlier assessment. On reflection I found the process unsatisfactory and therefore decline to take part in another. • I believe there are serious drawbacks to expert elicitations and the subsequent use of their subjective probability distributions. • Why you can't obtain results from modelling groups worldwide and do some sort of probabilistic analysis of the likelihood of suitably-defined abrupt changes? In any case, I don't really think there is much usefulinformation I can give to such a survey. • I find it difficult to answer and therefore will abstain • I'm not an expert

4.3.4 Likelihood of thermohaline circulation collapse

Table 3 summarises the expert assessments of the likelihood of thermohaline circulation collapse by three dates: 2020, 2050 and 2100. There are clear orders of magnitude difference between the eight experts who provided an assessment, although with one exception estimated likelihoods are very low (and, with this exception, considerably lower than the subjective assessment of 50% quoted in the BBC's Horizon programme *The Big Chill*). Each respondent based assessments not directly on model simulations, but on a combination of

[4] The survey was not in fact limited to the UK

analysis of model output with general knowledge of the ocean/climate system: one based the assessment partially on interpretation of recent ocean behaviour. Three experts explicitly stated that they believed that current models underestimated the sensitivity to collapse and hence likelihood of change. The expert with the highly anomalous assessment was particularly sceptical about the ability of climate models to simulate perturbations ("…GCMs are probably unrealistically well-behaved…"). Three of the experts stated that it should be possible within "a few years" to attempt to estimate likelihoods using either individual climate/ocean models or ensembles of models. Three of the respondents provided estimates of likelihood for different rates of change, but six could not: one explicitly stated that the uncertainty was too high to allow the first estimate to be broken down further. In contrast, one of the second round respondents expressed surprise that estimates were independent of emissions scenario.

Table 3: Expert estimates of the likelihood (%) of collapse of the thermohaline circulation

Collapse by..	THC1	THC8	THC9	THC11	THC17	THC18*	THC20	THC6	THC15
2020	1	10	0.1	0	1	0.05-0.2	1	0	very low
2050	15	30	1	0	10	0.5-7	2	0	low
2100	30	75	10	5	25	5-40	5	possible	possible

* varies with emisssions scenario

None of the seven respondents who participated in the second round changed their estimates. One commented that some of the reasons given for refusal to participation showed an over-reliance on the potential use of climate models, and another noted that the some of the comments in Table 2 suggested that modellers were being a "little coy" in the interpretation of their models. One was surprised at the high probabilities estimated by some respondents – but "would need to know who these experts are to assess whether to believe these estimates". One respondent expressed increased skepticism over the approach and hence the reliability of any conclusions, and another was surprised by the low response rate ("I do not consider myself an expert in this field to the extent as to justify being one of only nine experts worldwide to play a role in this assessment").

4.3.5 Likelihood of accelerated climate change

Expert assessments of the likelihood of climate change exceeding different high rates of change per decade are summarised in Table 4. Note that the top of the IPCC TAR range is approximately 0.5^{o}C/decade: Wigley & Raper (2001) estimated that the likelihood of change by 2100 greater than 5.8^{o}C (approximately 0.53^{o}C/decade) was 0.6%, and Webster *et al.* (2003) estimated a 2.5% chance that the increase would be greater than 4.9^{o}C (0.45^{o}C/decade). Again, there is a considerable range of assessments, with one particularly anomalous assessment. A range of methods were used to construct these likelihoods. Two experts used directly model simulations. A third started from an explicit assumption about the likelihood of change occurring at the top IPCC TAR rate, assumed an order of magnitude likelihood for the highest rate and then interpolated. A fourth expert adopted a similar approach, but using much higher estimates of likelihood because of a belief that the TAR "very likely underestimates sensitivity". The remaining expert explicitly adopted a subjective approach. None of the four respondents who participated in the second round wished to change their estimates (one noted that if an estimate were revised, it would no longer be independent). Three of the respondents expressed surprise at AC4's estimates.

Table 4: Expert estimates of the likelihood (%) of accelerated climate change

Global temperature change exceeds…	AC1	AC4	AC6	AC12	AC13
0.5°C/decade	1	90	20	3	2
0.6 °C /decade	0.1	80	10	0.5	0.5
0.7 °C /decade	0	70	5	0.1	0.1
0.8 °C /decade	0	60	2	0	0.01
>0.9 °C /decade	0	50	1	0	0.001

4.3.6 Likelihood of rapid sea level rise

Vaughan & Spouge (2002) conducted a Delphi survy of expert opinion of the likelihood of the West Antarctic Ice Sheet collapsing and raising sea levels. As with the surveys conducted for this project, there was a range of estimates of likelihood, but from the evidence presented Vaughan & Spouge (2002) came up with an assessment that there is a less than 5% chance that sea level rise due to the collapse of the West Antarctic Ice Sheet would be greater than 10 mm per year.

The Vaughan & Spouge (2002) survey focused on the West Antarctic Ice Sheet, and did not consider explicitly any increase in sea level from melt of the Greenland Ice Sheet. Gregory *et al.* (2004) concluded from a model simulation that prolonged melt of the Greenland Ice Sheet was likely once temperatures increased by more than 3°C, but this would be most noticeable late in the 21st century and probably[5] would not affect expert assessments of the likelihood of rapid sea level rise over the next 100 years.

5. Impacts of abrupt climate change

5.1 Assessing impacts

5.1.1 Potential approaches

Whilst there have been many quantitative or at least structured assessments of the implications of “gradual” climate change, there have been virtually no rigorous assessments of the implications of rapid or abrupt climate change. As Hulme (2003) notes, none of the frequently published claims that abrupt climate change would have severe consequences are based on substantive environmental, economic, or social research. The few studies which have attempted to make an integrated assessment of the global scale implications of abrupt climate change for the costs of mitigation and adaptation have, admittedly, simply assumed values for impacts (e.g. Keller *et al*. (2000) and Mastrandrea & Schneider (2001).

In principle, there are three ways of estimating the impacts of abrupt climate change. The first is to use simulation models with quantitative scenarios of the potential changes in climate. Only one quantitative studies of possible future abrupt change have been published, largely

[5] A subjective assessment…

because there are no quantitative abrupt climate change scenarios[6]: the exception (Higgins & Vellinga, 2004) explores the effect of thermohaline circulation collapse on ecosystem structure and function, but assumes no global warming.

The second approach is to use analogues from past abrupt climate change events. There is a large literature on changes in the physical environment following past abrupt changes, including for example land cover (e.g. Van Geel *et al*., 1996; Tinner & Lotter, 2001) and fluvial systems (e.g. van Huissteden & Kasse, 2001). There is also an increasingly large literature on the effect of past abrupt climate changes on previous civilisations and societies. In a very early study, Parry (1974) showed how agricultural patterns in southern Scotland were affected by the Little Ice Age, and more recent studies have examined changes in other parts of the world associated with abrupt climate shifts, such as rapid cooling or changes in ENSO patterns (e.g. van Geel *et al*., 1996; Berglund, 2003; Sandweiss *et al*., 2001; Fagan, 2004, Xoplaki *et al*., 2001). However, whilst there is some evidence that abrupt climate shifts have led to collapses of some civilisations and economies, the use of such analogues to assess impacts in the future is problematic. The impacts of a given change in climate (or indeed hazard event) depend very much on the characteristics and dynamics of the economy and society being impacted, including aspects such as distribution of income, governance and equity. It may be extremely difficult to separate out all the interacting causes of an identified impact (Messerli *et al*., 2000).

The final approach uses expert judgement to assess the implications of defined abrupt climate changes. This approach was used in the ACACIA project (Parry, 2000) and is also the basis of the IPCC's assessment of the impacts of climate change (Kundzewicz & Parry, 2001). Expert judgement of the impacts of abrupt climate change could be informed by studies of the impact of gradual climate change or assessments of vulnerability. The Pentagon survey was in effect an expert judgement review of the implications of thermohaline circulation collapse.

5.1.2 Approach used in the current study

The approach used in the current study was based on expert interpretation of published and "grey" literature on the implications of gradual climate change, in the context of the characterisations described in Section 3, supplemented by a number of computer simulations. These simulations, conducted for the current study, looked at changes in river runoff, changes crop suitability and energy requirements across Europe under the thermohaline circulation collapse and accelerated feedback scenarios, and are described below.

The expert judgement was provided by the project team (who were involved in the ACACIA study of the impacts of gradual climate change in Europe), with input from some sectoral experts and climate change impact researchers involved in the EU-funded ATEAM project (ATEAM meeting, May 2004) and at a workshop on research into adaptation to climate change in Europe hosted by CICERO in Norway (May 2004). The assessment of the impacts of the three characterisations of abrupt climate change was made by major European region and by the UN's "WEHAB" sectors (WEHAB stands for **w**ater, **e**nergy, **h**ealth, **a**griculture and **b**iodiversity) plus settlements. Changes in the WEHAB+ sectors will impact upon the

[6] although numerical models have been used to simulate response to past abrupt changes: e.g. Veldkamp & Tebbens (2001)

pattern of economic and social activity within a region, including conflict between groups, sectors and regions. The five regions are:

Southern Europe	(Spain, Portugal, Italy, Greece and southern France)
Northern Europe	(Norway, Sweden and Finland)
Western Europe	(UK, Ireland, northern France, Germany, Belgium, Netherlands, Luxembourg, Switzerland and Denmark)
Eastern Europe	(Poland, Latvia, Lithuania, Estonia, Czech Republic, Slovakia, Hungary, Slovenia, Austria)
South-eastern Europe	(Serbia, Croatia, Bosnia, Albania, Rumania, Bulgaria, Macedonia)

Whilst there is inevitably a degree of variability within the five regions, each country in a region has *broadly* the same climate regime and a *broadly* similar economic and political structure.

Tables 5a to 5e show the potential impacts of the three abrupt climate change scenarios by region and sector, together with the implications of "gradual" climate change. Table 6 summarises the key implications of the three abrupt climate change characterisations for Europe, based on the information in Tables 5a to 5e. The implications are shown in order of significance. The relative significance of each implication is, however, extremely uncertain, largely because there are no common metrics of impact on which to base a comparison (this is true not only for abrupt climate change, but also for "gradual" climate change).

The quantitative impacts of climate change also depend on the state of the economy and society which is being impacted (Arnell *et al*., 2004), including population totals, total wealth and its distribution, distribution of economic activities, and governance. The IPCC's SRES (IPCC, 2000) report describes four "storylines" for future development, broadly distinguished according to regional orientation and style of economic development. In terms of European population, the scenarios are not very different (and are less different than they are in other regions), but in terms of wealth and value of assets exposed to climate change are very different.

The following sections provide greater description of the potential implications of abrupt climate change by sector, together with the supporting references.

Table 5: Impacts of abrupt climate change:
(a) Southern Europe (Spain, Portugal, Italy, Greece, southern France)

	"Conventinal" climate change	THC collapse	Accelerated climate change	Rapid sea level rise
Water				
Public supply and demand *- river flows and recharge*	• Decrease in runoff and recharge	• Reduction in total runoff of at least 50% for at least 30 years	• Reduction in runoff of 50% by 2050	
- demand	• Incease in peak demands	• Reductions in peak demands	• Large increase in peak demands	
Irrigation	• Increase in demand	• Reduction in demand	• Large increase in demand	• Lowlying irrigated land inundated
Floods	• Increase in risk of winter flooding	• Shift from winter to spring snowmelt flooding	• Increase in risk of winter flooding	• Large rise in risk to coastal zones
Navigation	• Small change in opportunities due to increasing flow range	• Increase in ice cover: reduced opportunities	• Large reductions in opportunities due to higher winter and lower summer flows	• Navigability in lower reaches affected by tides
Energy				
Demand	• Increase in summer cooling requirements	• Large increase in heating requirements	• Large increase in summer cooling requirements	• -
Renewable generation	• Lower hydropower potential throughout year	• Reduced hydropower potential and shift to spring • Reduced wind potential	• Lower hydropower potential throughout year • Increased wind potential in winter	• Altered feasibility of tidal power schemes
Non-renewable generation	• Reduced availability of summer cooling water		• Reduced availability of summer cooling water	• Coastal facilities threatened
Distribution	• Increased storminess affects winter network	• Network susceptible to freeze events	• Increased storminess affects winter network	• -
Health				
Thermal effects	• Increased heat-related deaths in summer	• Increased cold-related deaths in winter	• Increased heat-related deaths in summer	• -
Disease	• Increased potential for disease transmission	• Reduced potential for disease transmission	• Increased potential for disease transmission	• -
Agriculture				
Crop productivity	• Decrease in productivity	• Decrease in productivity	• Major decrease in productivity	• -
Food production	• Decrease	• Decrease	• Decrease	• -
Forestry	• Increased fire risk	• Major adverse effects on broadleaved forest • Increased fire risk	• Fire risk severe • Summer droughts adversely affect all species	• -
Fisheries	• increased risk of failure of coastal fisheries	•	• increased risk of failure of coastal fisheries	•
Biodiversity				
Natural areas	• Northward shift in natural ecosystems	• Major changes across region	• Northward shift in natural ecosystems	• Coastal wetlands lost
Settlement and infrastructure				
Urban areas	• Increased urban heat island • Reduced summer comfort • Increased building damage	• Reduced winter comfort	• Increased urban heat island • Large reductions in summer comfort • Large increase in damage	• Inundation
Transportation	•	• Increased winter disruption	• Summer heat-related problems on railways	• Coastal-zone infrastructure threatened
Security				
Conflict	•	• Global scale disruption	• North-south conflict in Europe	• Coastal/inland conflict
Population movement	• -	• Immigration from the north	• In-migration from outside Europe	• Movement away from coastal zone

(b) Northern Europe (Norway, Sweden, Finland)

	"Conventional" climate change	THC collapse	Accelerated climate change	Rapid sea level rise
Water				
Public supply and demand *- river flows and recharge*	• Increase in runoff and recharge	• Reduction in total runoff of at least 50% for at least 30 years	• Reduction in runoff of up to 20% by 2050	
- demand	• Incease in peak demands	• Reductions in peak demands	• Large increase in peak demands	
Irrigation	• Some increase in demand	• Reduction in demand	• Large increase in demand	• Lowlying irrigated land inundated
Floods	• Increase in risk of winter flooding: shift from winter to spring flooding	• Shift from winter to spring snowmelt flooding	• Increase in risk of winter flooding	• Large rise in risk to coastal zones
Navigation	• -	• -	• -	• -
Energy				
Demand	• Increase in summer cooling requirements	• Large increase in heating requirements	• Large increase in summer cooling requirements	• -
Renewable generation	• Lower hydropower potential throughout year	• Reduced hydropower potential and shift to spring • Reduced wind potential	• Lower hydropower potential throughout year • Increased wind potential in winter	• Altered feasibility of tidal power schemes
Non-renewable generation	• Reduced availability of summer cooling water		• Reduced availability of summer cooling water	• Coastal facilities threatened
Distribution	• Increased storminess affects winter network	• Network susceptible to freeze events	• Increased storminess affects winter network	• -
Health				
Thermal effects	• Increased heat-related deaths in summer	• Increased cold-related deaths in winter	• Increased heat-related deaths in summer	• -
Disease	• Increased potential for disease transmission	• Reduced potential for disease transmission	• Increased potential for disease transmission	• -
Agriculture				
Crop productivity	• Decrease in productivity	• Decrease in productivity	• Major decrease in productivity	• -
Food production	• Decrease	• Decrease	• Decrease	• -
Forestry	• Increased fire risk	• Major adverse effects on broadleaved forest • Increased fire risk	• Fire risk severe • Summer droughts adversely affect all species	• -
Fisheries	• Reduced potential for established fisheries; possible new species	• Reduced potential for established fisheries	• Reduced potential for established fisheries; possible new species	•
Biodiversity				
Natural areas	• Northward shift in natural ecosystems	• Major changes across region	• Northward shift in natural ecosystems	• Coastal wetlands lost
Settlement and infrastructure				
Urban areas	• Increased urban heat island • Reduced summer comfort • Incrtease in damage	• Reduced winter comfort • Increase in damage due to ice/snow	• Increased urban heat island • Large reductions in summer comfort • Large increase in damage	• Inundation
Transportation	•	• Increased winter disruption	• Summer heat-related problems on railways • Reduced ice cover at ports	• Coastal-zone infrastructure threatened
Security				
Conflict	•	• Global scale disruption	• North-south conflict in Europe	• Coastal/inland conflict
Population movement	• -	• Immigration from the north	• In-migration from outside Europe	• Movement away from coastal zone

(c) Western Europe (UK, Ireland, northern France, Germany, Belgium, Netherlands, Luxembourg, Switzerland, Denmark)

	"Conventional" climate change	THC collapse	Accelerated climate change	Rapid sea level rise
Water				
Public supply and demand *- river flows and recharge*	• Increase in winter runoff, decrease in summer	• Reduction in total runoff of at least 30% for at least 30 years • Shift to snow-dominated regimes: lower flows in winter	• Reduction in total runoff of at least 40% by 2050 • Increased range in flows through the year, with lower summer flows	
- demand	• Incease in peak demands	• Reductions in peak demands	• Large increase in peak demands	
Irrigation	• Increase in demand	• Reduction in demand	• Large increase in demand	• Lowlying irrigated land inundated
Floods	• Increase in risk of winter flooding	• Shift from winter to spring snowmelt flooding	• Increase in risk of winter flooding	• Large rise in risk to coastal zones
Navigation	• Small change in opportunities due to increasing flow range	• Increase in ice cover: reduced opportunities	• Large reductions in opportunities due to higher winter and lower summer flows	• Navigability in lower reaches affected by tides
Energy				
Demand	• Increase in summer cooling requirements	• Large increase in heating requirements	• Large increase in summer cooling requirements	• -
Renewable generation	• Increase winter hydropower potential, lower summer potential	• Reduced hydropower potential and shift to spring • Reduced wind potential	• Increased winter hydropower, but reduced generation in summer • Increased wind potential in winter	• Altered feasibility of tidal power schemes
Non-renewable generation	• Reduced availability of summer cooling water		• Reduced availability of summer cooling water	• Coastal facilities threatened
Distribution	• Increased storminess affects winter network	• Network susceptible to freeze events	• Increased storminess affects winter network	• -
Health				
Thermal effects	• Increased heat-related deaths in summer	• Increased cold-related deaths in winter	• Increased heat-related deaths in summer	• -
Disease	• Increased potential for disease transmission	• Reduced potential for disease transmission	• Increased potential for disease transmission	• -
Agriculture				
Crop productivity	• Increase in productivity	• Decrease in productivity	• Increase in productivity	• -
Food production	• Increase	• Decrease	• Increase	• -
Forestry	• Faster growth in conifere	• Reduction in growth and yield	• Much faster growth in conifers • Summer droughts adversely affect all species	• -
Fisheries	• Reduced fisheries production	• Reduced fisheries production	• Reduced fisheries production	•
Biodiversity				
Natural areas	• Northward shift in natural ecosystems	• Major changes across region	• Northward shift in natural ecosystems	• Coastal wetlands lost
Settlements and infrastructure				
Urban areas	• Increased urban heat island • Reduced summer comfort • Incrtease in damage	• Reduced winter comfort • Increase in snow/ice damage	• Increased urban heat island • Large reductions in summer comfort • Large increase in damage	• Inundation
Transportation	•	• Increased winter disruption and blockage of ports by ice	• Summer heat-related problems on railways • Reduced ice cover	• Coastal-zone infrastructure threatened
Security				
Conflict	•	• Global scale disruption	• North-south conflict in Europe	• Coastal/inland conflict
Population movement	• -	• Depopulation	• In-migration from outside Europe	• Movement away from coastal zone

(d) Eastern Europe (Poland, Baltic states, Czech Republic, Slovakia, Hungary, Slovenia, Austria)

	"Conventional" climate change	THC collapse	Accelerated climate change	Rapid sea level rise
Water				
Public supply and demand *- river flows and recharge*	• Decrease in runoff and recharge • Shift to winter maxima from spring	• Reduction in total runoff of at least 50% for at least 30 years	• Reduction in runoff of >50% by 2050 • Elimination of snowmelt peak	
- demand	• Incease in peak demands	• Reductions in peak demands	• Large increase in peak demands	
Irrigation	• Increase in demand	• Reduction in demand	• Large increase in demand	• Lowlying irrigated land inundated
Floods	• Increase in risk of winter flooding	• Shift from winter to spring snowmelt flooding	• Increase in risk of winter flooding	• Large rise in risk to coastal zones
Navigation	• Small change in opportunities due to increasing flow range	• Increase in ice cover: reduced opportunities	• Large reductions in opportunities due to higher winter and lower summer flows	• Navigability in lower reaches affected by tides
Energy				
Demand	• Increase in summer cooling requirements	• Large increase in heating requirements	• Large increase in summer cooling requirements	• -
Renewable generation	• Lower hydropower potential throughout year	• Reduced hydropower potential and shift to spring • Reduced wind potential	• Lower hydropower potential throughout year • Increased wind potential in winter	•
Non-renewable generation	• Reduced availability of summer cooling water		• Reduced availability of summer cooling water	• Coastal facilities threatened
Distribution	• Increased storminess affects winter network	• Network susceptible to freeze events	• Increased storminess affects winter network	• -
Health				
Thermal effects	• Increased heat-related deaths in summer	• Increased cold-related deaths in winter	• Increased heat-related deaths in summer	• -
Disease	• Increased potential for disease transmission	• Reduced potential for disease transmission	• Increased potential for disease transmission	• -
Agriculture				
Crop productivity	• Decrease in productivity	• Decrease in productivity	• Major decrease in productivity	• -
Food production	• Decrease	• Decrease	• Decrease	• -
Forestry	• Increased fire risk	• Major adverse effects on broadleaved forest • Increased fire risk	• Fire risk severe • Summer droughts adversely affect all species	• -
Fisheries	• -	• -	• -	• -
Biodiversity				
Natural areas	• Northward shift in natural ecosystems	• Major changes across region	• Northward shift in natural ecosystems	• Coastal wetlands lost
Settlements and infrastructure				
Urban areas	• Increased urban heat island • Reduced summer comfort • Increase in damage	• Reduced winter comfort • Increase in snow/ice damage	• Increased urban heat island • Large reductions in summer comfort • Large increase in damage	• Inundation
Transportation	•	• Increased winter disruption • Increased ice cover at ports	• Summer heat-related problems on railways • Reduced ice cover	• Coastal-zone infrastructure threatened
Security				
Conflict	•	• Global scale disruption	• North-south conflict in Europe	• Coastal/inland conflict
Population movement	• -	• Immigration from the north	• In-migration from outside Europe	• Movement away from coastal zone

(e) South-eastern Europe (Serbia, Croatia, Bosnia, Albania, Bulgaria, Romania, Macedonia)

	"Conventionaly" climate change	THC collapse	Accelerated climate change	Rapid sea level rise
Water				
Public supply and demand *- river flows and recharge*	• Decrease in runoff and recharge	• Reduction in total runoff of at least 50% for at least 30 years	• Reduction in runoff of >50% by 2050	
- demand	• Incease in peak demands	• Reductions in peak demands	• Large increase in peak demands	
Irrigation	• Increase in demand	• Reduction in demand	• Large increase in demand	• Lowlying irrigated land inundated
Floods	• Increase in risk of winter flooding	• Shift from winter to spring snowmelt flooding	• Increase in risk of winter flooding	• Large rise in risk to coastal zones
Navigation	• Small change in opportunities due to increasing flow range	• Increase in ice cover: reduced opportunities	• Large reductions in opportunities due to higher winter and lower summer flows	• Navigability in lower reaches affected by tides
Energy				
Demand	• Increase in summer cooling requirements	• Large increase in heating requirements	• Large increase in summer cooling requirements	• -
Renewable generation	• Lower hydropower potential throughout year	• Reduced hydropower potential and shift to spring • Reduced wind potential	• Lower hydropower potential throughout year • Increased wind potential in winter	• Altered feasibility of tidal power schemes
Non-renewable generation	• Reduced availability of summer cooling water		• Reduced availability of summer cooling water	• Coastal facilities threatened
Distribution	• Increased storminess affects winter network	• Network susceptible to freeze events	• Increased storminess affects winter network	• -
Health				
Thermal effects	• Increased heat-related deaths in summer	• Increased cold-related deaths in winter	• Increased heat-related deaths in summer	• -
Disease	• Increased potential for disease transmission	• Reduced potential for disease transmission	• Increased potential for disease transmission	• -
Agriculture				
Crop productivity	• Decrease in productivity	• Small decrease in productivity	• Major decrease in productivity	• -
Food production	• Decrease	• Decrease	• Decrease	• -
Forestry	• Increased fire risk	• Major adverse effects on broadleaved forest • Increased fire risk	• Fire risk severe • Summer droughts adversely affect all species	• -
Fisheries	•	•	•	•
Biodiversity				
Natural areas	• Northward shift in natural ecosystems	• Major changes across region	• Northward shift in natural ecosystems	• Coastal wetlands lost
Settlements and infrastructure				
Urban areas	• Increased urban heat island • Reduced summer comfort • Increase in damage	• Reduced winter comfort	• Increased urban heat island • Large reductions in summer comfort • Large increase in damage	• Inundation
Transportation	•	• Increased winter disruption	• Summer heat-related problems on railways	• Coastal-zone infrastructure threatened
Security				
Conflict	•	• Global scale disruption	• North-south conflict in Europe	• Coastal/inland conflict
Population movement	• -	• Immigration from the north	• In-migration from outside Europe	• Movement away from coastal zone

Table 6: Major implications of abrupt climate change in Europe

Collapse of the thermohaline circulation
• Major reductions in crop production, with consequent impacts on food prices, access to food, and rural economies • Increases in cold-related deaths and ill-health • Movement of populations to southern Europe, and shift in centre of economic gravity • Major changes in temperate and Mediterranean ecosystems and the services they provide (food, biodiversity, forest products, recreation) • Disruption to winter travel opportunities and increased icing of northern ports and seas • Requirement to refurbish infrastructure, especially in western Europe, towards Scandinavian standards • Reductions in runoff and water availability in southern Europe, and major increase in snowmelt flooding in western Europe
Accelerated climate change
• Major reductions in crop production, with consequent impacts on food prices, access to food, and rural economies • Increase in summer heat-related mortality and ill-health, and increased risk of transmission of disease • Major reductions in water availability in southern and western Europe, coupled with large increases in demand for water, particularly for irrigation • Major changes in boreal and Mediterranean ecosystems and the services they provide • Requirement to refurbish infrastructure, especially in western and northern Europe • Reduction in ice cover in northern ports and seas
Rapid sea level rise
• Inundation of parts of coastal cities (including London, Hamburg, Venice, Amsterdam and Rotterdam), coastal wetlands and deltas • Inundation of coastal facilities, including ports and power stations • Very substantial increase in coastal flooding damages and requirement for major investment in coastal flood defences • Major threat to viability of the financial services industry, particularly insurance • Relocation of economic activity away from coastal cities

5.2 Water

5.2.1 Water supply and demand

The reliability of water supply systems – for public supplies, industrial use or irrigation – is a function of the relationship between the ability to supply water and demand for that water. In any given catchment, the ability to supply water depends on its volume and timing through the year and the infrastructure available to store and distribute water. Changes in the amount of water available through the year are potentially extremely important, although their effects depend on supply infrastructure. For reservoir-supported or groundwater supply systems changes in wet season rainfall are most important, whilst for unsupported direct river abstractions from small to medium-sized rivers changes in runoff at any time of the year may be critical.

A macro-scale hydrological model previously used in hydrological impact assessments (Arnell, 2003; 2004) was used to assess the implications of the thermohaline circulation collapse and accelerated climate change scenarios (Figures 7 and 8). Under the "gradual" climate change scenario used here (based on the HadCM3 climate model) annual runoff decreases across most of Europe, with the exception of northern and western areas[7]. Accelerated climate change essentially produces larger percentage reductions and reduces the area with an increase in runoff. Although precipitation is increased across much of Europe, this is more than offset by the higher evaporation associated with higher temperatures. Thermohaline circulation collapse also results in a reduction in runoff across most of Europe (but an increase in northern and western Britain). This is largely due to a reduction in precipitation across Europe: the lower temperatures mean lower evaporation.

Changes in the distribution of runoff through the year are perhaps as significant as changes in the total volume of runoff. Figure 9 shows mean monthly runoff in a number of catchments under current conditions and in the 2050s, following gradual climate change, accelerated change and the collapse of the thermohaline circulation in 2015. "Gradual" climate change tends to increase the seasonality of flows in temperate western Europe and produce a shift in flows from spring to winter in central Europe as precipitation falls as rain rather than snow. Accelerated climate change exaggerates this tendency, and over a larger part of Europe there is a shift from spring snowmelt peaks to winter maxima. Collapse of the thermohaline circulation, however, leads to a shift in peak flows from winter to spring across much of western Europe (where more precipitation falls as snow), but has relatively little affect on flow regimes in central and eastern Europe which are already snow-dominated.

There have been very few published assessments of the implications of "conventional" climate change for the reliability of public water supplies. Studies in England suggest possible reductions in reliable yields by the 2020s of between 6 and 13% in some catchment areas (Arnell & Delaney, 2005), which would severely challenge the provision of supplies to customers during drought years. Both thermohaline circulation collapse and accelerated climate change are likely to make this situation even more challenging, as both imply a reduction in available runoff.

Climate change is also likely to impact upon the infrastructure used to treat and distribute both potable water and sewage effluent. Thermohaline circulation collapse would increase the risk of frost damage to pipe networks in maritime parts of Europe, whilst accelerated climate change would increase the risk of damage due to the drying and shrinking of soils.

[7] scenarios based on other climate models produce broadly similar spatial patterns of change, although in some the area with an increase in runoff is more extensive (Arnell, 2003)

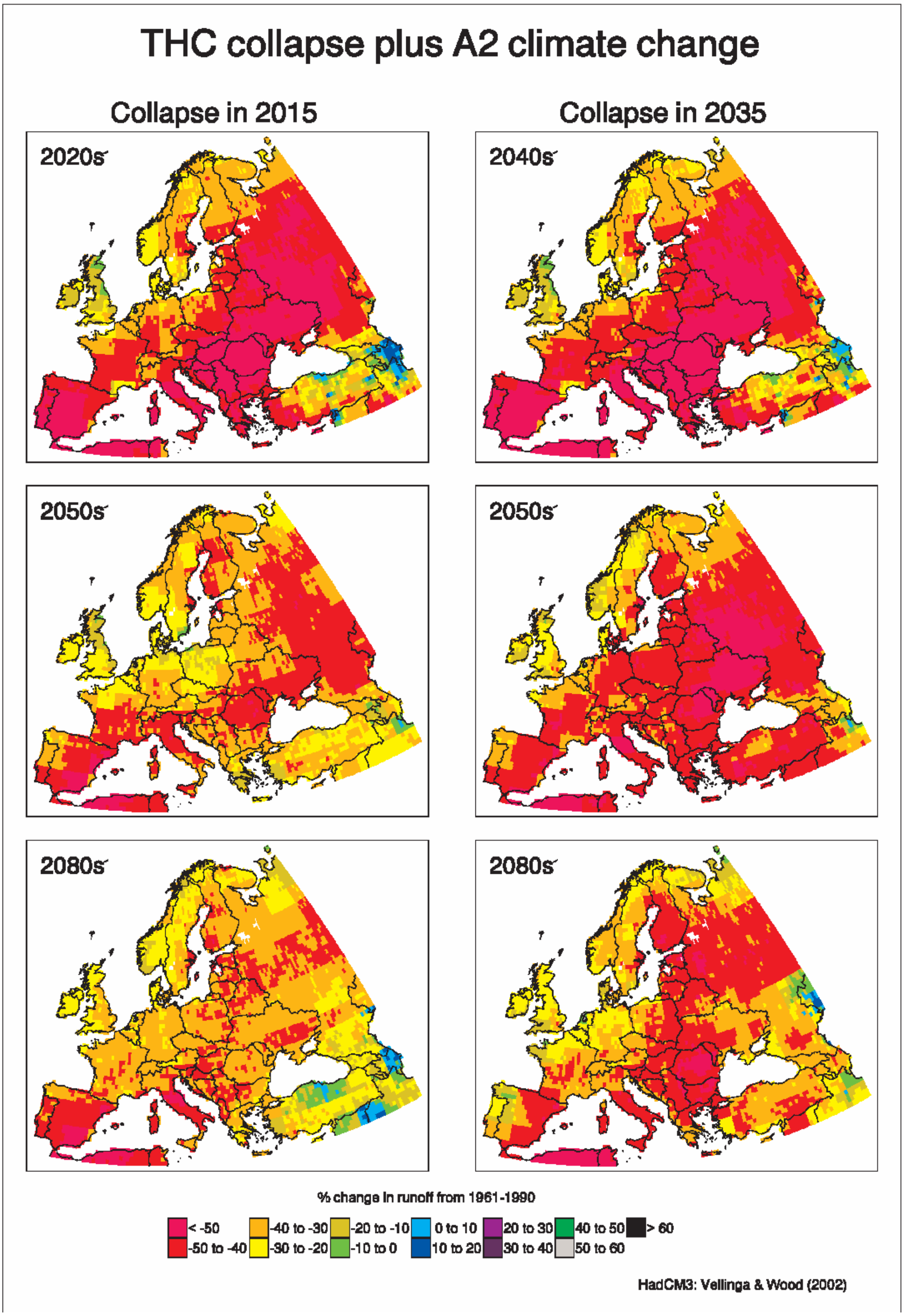

Figure 7: Change in average annual runoff, assuming thermohaline circulation collapse in 2015 and 2035, with A2 emissions

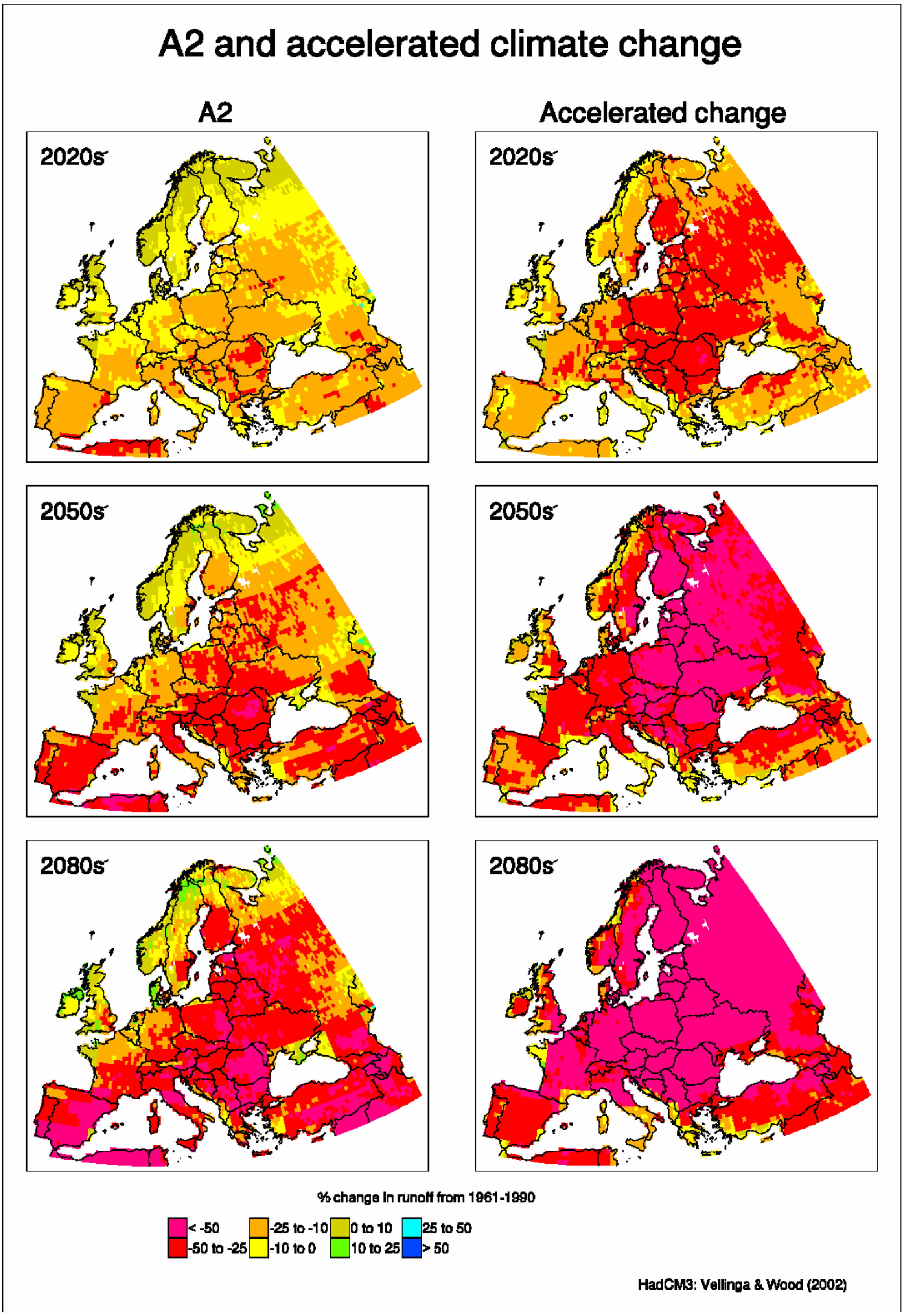

Figure 8: Change in average annual runoff, assuming A2 emissions and accelerated climate change

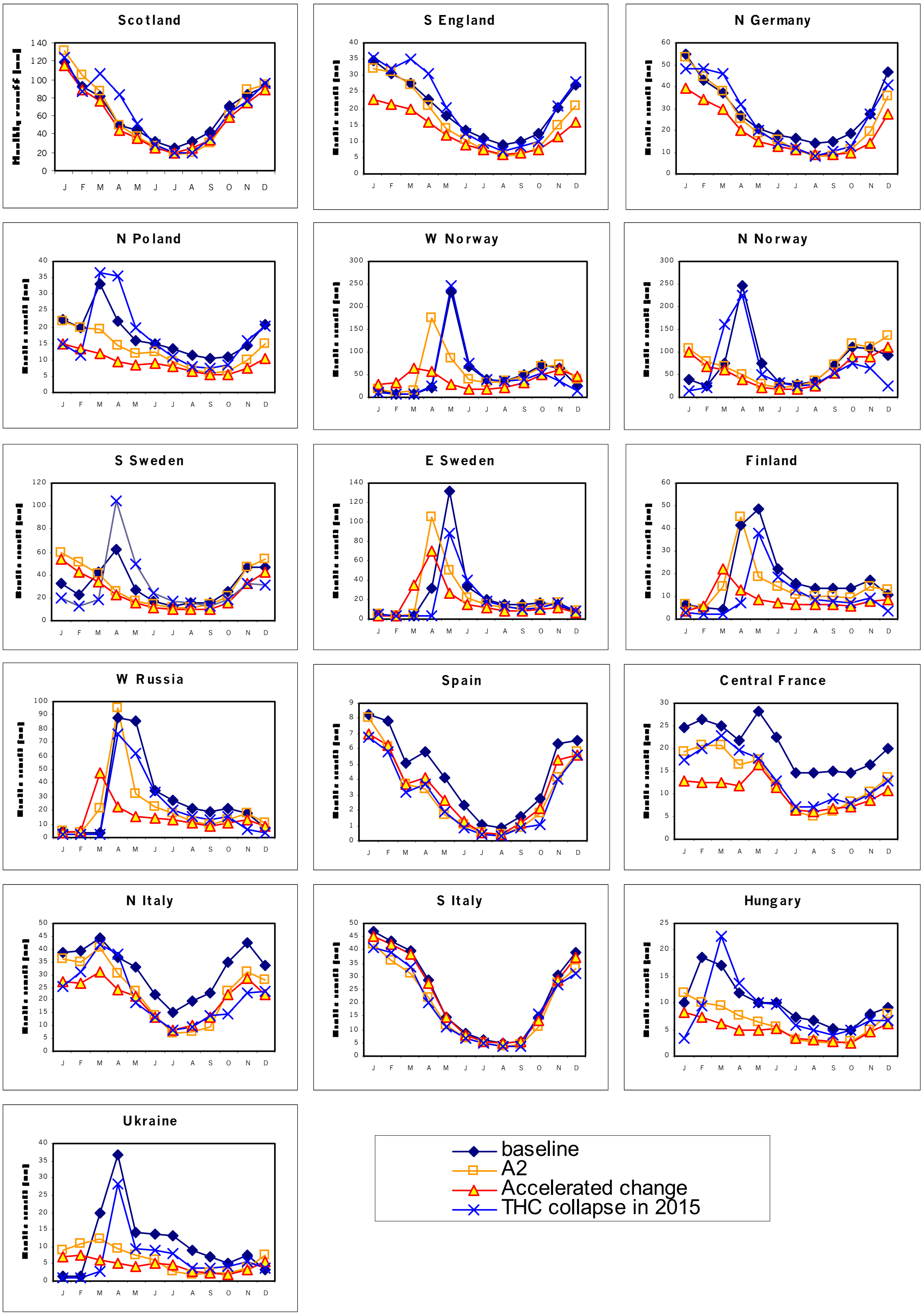

Figure 9: Mean monthly runoff in different parts of Europe, under current conditions and in the 2050s under A2 emissions, accelerated climate change and thermohaline circulation collapse in 2015

The primary effect of climate change on demand for water is through changes in growing season soil moisture deficits: these affect both domestic demand and, most importantly, demand for irrigation water. Soil moisture deficits are a function of spring and summer rainfall and temperature (or, more precisely, evaporation). Actual demands for irrigation water, however, are also determined by the crop types grown and irrigation efficiency. Whilst thermohaline circulation collapse, for example, might appear to lead to an increased demand for irrigation because available water decreases, the lower temperatures might mean that cultivation of crops which require irrigation is less feasible. Similarly, accelerated climate change might mean temperatures become too high for crops currently grown with irrigation.

Rapid sea level rise has much less impact on water supply reliability than accelerated climate change or thermohaline circulation collapse. The primary impacts are through the reduced reliability of river water abstraction points that are close to the tidal limit, and increased saline intrusion up major rivers and aquifers. This is likely to be particularly important in the Netherlands, where higher sea levels would increase the salinity not only of the Rhine but also the shallow groundwaters which provide a large proportion of agricultural and public supplies.

5.2.2 Floods and their management

There are currently three types of fluvial floods in Europe: floods following prolonged saturation during the “wet” season (in winter in western Europe, summer in parts of eastern and central Europe), floods following snowmelt in spring, and floods following short-duration intense rainfall events (typically in summer). The frequency of coastal flooding depends on sea level and the frequency of occurrence of storm surges (Nicholls, 2004). The economic and social impacts of both fluvial and coastal flooding in the future will depend on the numbers of people living in flood-prone areas and the value of their assets, together with the degree of protection against flooding.

Thermohaline circulation collapse would lessen the risk of winter flooding in western Europe because precipitation would be more likely to fall as snow, but shift the peak flood season to spring snowmelt period. Whether these peaks would be higher or lower than the current winter peaks depends on both the volume of snowfall during winter and the rate at which that snow would melt, but in any case the characteristics of the flood regime would change substantially. It is possible that reliable flood forecasting would become easier, as it would be based on information on accumulated snowfall. In central and eastern Europe thermohaline circulation collapse is likely to delay the snowmelt season (see Figure 9), perhaps leading to larger snowmelt floods as the snow accumulation season is lengthened.

Accelerated climate change would increase the risk of winter flooding in western Europe and summer flooding in central and eastern Europe, as the intensity of the hydrological cycle increases. Reductions in snowfall would lead to a shift in the peak flood season from spring to winter in parts of upland, central and eastern Europe: the effect on the magnitude of peaks depends on changes in the volume of peak winter rainfalls.

An increasing risk of coastal flooding is one of the most widely cited impacts of sea level rise. Nicholls (2004) estimates that by the 2080s an additional 0.2-1.6 million people in Europe would be affected by coastal flooding each year, depending largely on assumed rates of change in coastal populations. This is based on a sea level rise of up to 34cm, but rapid sea level rise due to collapse of the West Antarctic Ice Sheet could lead to a rise of 2.2m by the 2080s. This is likely to increase very substantially the numbers of people affected by coastal flooding, and it is clearly not possible to extrapolate from studies of the impacts of conventional climate change. Major European cities including London, Amsterdam, Rotterdam, Copenhagen, Hamburg, Stockholm, Helsinki, Barcelona and Venice would be extremely seriously affected by rapid sea level rise.

5.2.3 Navigation

Most of the major rivers in Europe are used for commerical navigation (e.g. the Rhine, Rhone, Elbe, Danube). Navigability is primarily influenced by the depth of water and, in eastern Europe, by the duration of ice-free conditions (Middelkoop *et al*., 2001). Conventional climate change would reduce the impact of ice, but by increasing low flows and possibly increasing high flows potentially shorten the navigation season (Middelkoop *et al*., 2001).

Collapse of the thermohaline circulation would increase the duration of ice cover on navigable rivers, and hence reduce navigation opportunities. Accelerated climate change would reduce ice cover, but increase still further the variability in river flows through the year and hence probably reduce the navigation season. Rapid sea level rise would primarily affect inland navigation through saline intrusion into the lower reaches of major rivers and the inundation of riverside infrastructure such as docks.

5.3 Energy

5.3.1 Demand for energy

The vast bulk of the literature on future energy demand is concerned with effects of different growth rates, extent of innovation and changing patterns of energy use: there is relatively little quantitative information on the implications of climate change for demand. The main effects of climatic variability are on the demand for space heating fuels and the amount of electricity used for air conditioning and refrigeration.

The extent of the change in the requirement for heating and cooling can be inferred from changes in the number of heating (HDD) and cooling (CDD) degree days per year. Figure 10 shows the change in HDD and CDD by the 2050s, under the A2 emissions scenario, thermohaline circulation collapse in 2015, and accelerated climate change. HDD is calculated from daily mean temperature T_i simply as:

$$HDD = \Sigma\,(15.5 - T_i) \qquad \text{where } T_i \text{ is less than } 15.5^{o}C$$

CDD is calculated from:

$$CDD = \Sigma\,(T_i - 22) \qquad \text{where } T_i \text{ is greater than } 22\,^{o}C$$

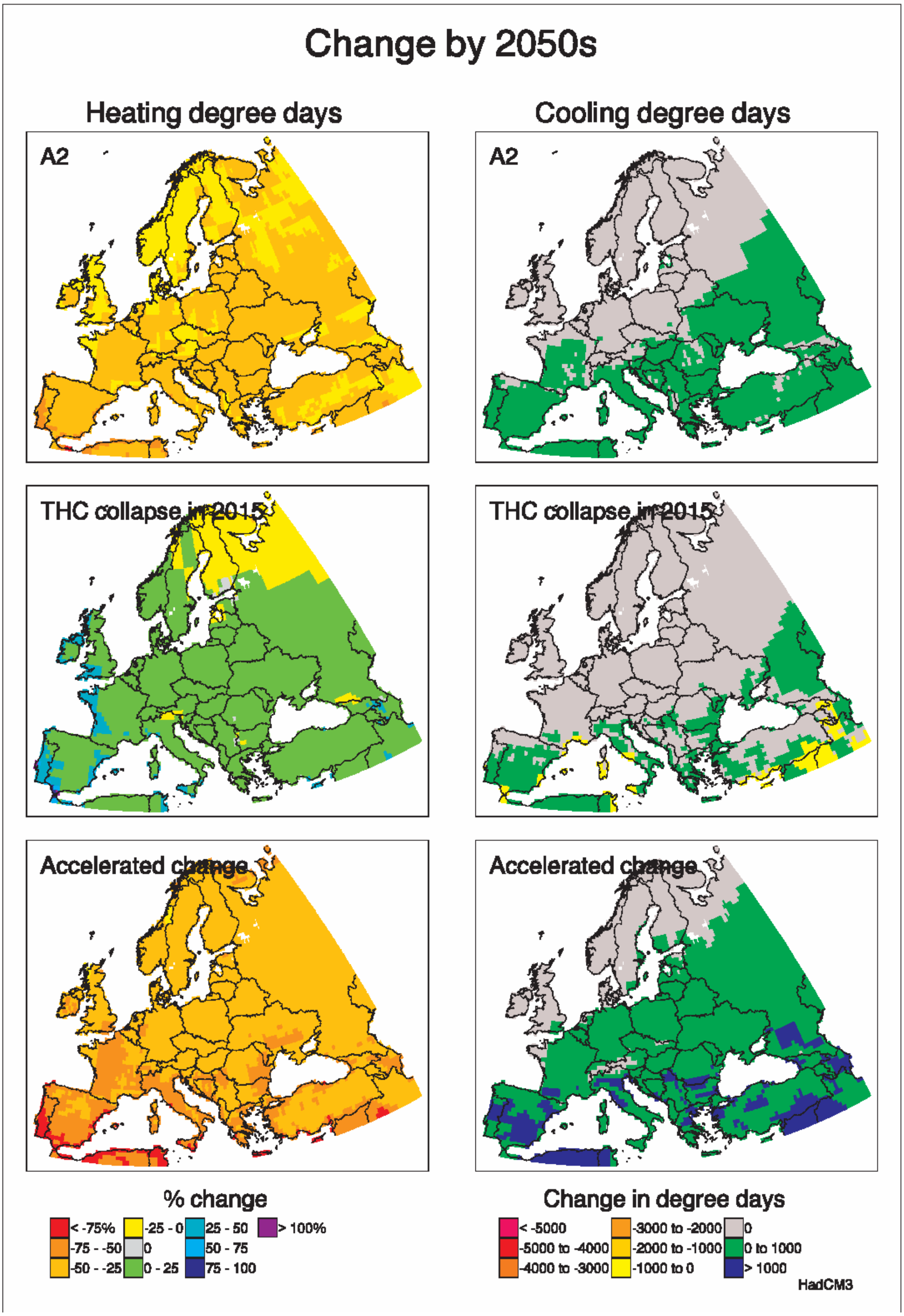

Figure 10: Change in heating and cooling requirements by 2050, under A2 emissions, thermohaline circulation collapse in 2015, and accelerated climate change

Daily mean temperature T_i is estimated from the monthly mean temperature by fitting a sine function through the monthly series, and Figure 10 can therefore be regarded as being indicative only.

Under gradual climate change, heating requirement falls by the 2050s by up to 25% (relative to 1961-1990) across most of Europe, and cooling requirement increases everywhere except for Scotland, Ireland, Norway and northern Sweden. Thermohaline circulation collapse in 2015 leads to increases in heating requirement by the 2050s by up to 25% across most of Europe, with relatively little effect in the far north east. It also still leads to increases in cooling requirements in parts of southern Europe (in decades closer to thermohaline circulation collapse heating requirements increase further and cooling requirements decrease). Accelerated climate change produces very large percentage reductions in heating requirements, and increases in cooling requirements across virtually the whole of Europe.

Translating these changes to energy demand, however, is complicated by secular changes in demand (air conditioning in Europe is becoming much more widespread) and technological innovations. In the UK, the Climate Change Impacts Review Group (CCIRG, 1996) estimated that higher temperatures under an A2-type emissions scenario would lead to a 5% fall in energy demand by the 2050s, relative to the demand without climate change. Levermore *et al*. (2004) simulated a reduction in heating requirements in a hypothetical office building by 2050 of between 6 and 12%, depending on construction type, under the A2 emissions scenario,and an increase in cooling requirements of 10-20%: heating demands remained higher than cooling demands. The ACACIA report (Parry, 2000) cites a study showing a doubling of demand for energy for cooling in Europe with a 4.5°C rise in temperature: this is close to the rise by the 2050s under accelerated change.

Climate change, whether gradual or abrupt, will change not only the gross magnitude of energy demands, but also its timing. Both gradual and accelerated change will lead to a shift in demand from winter heating to summer cooling; thermohaline circulation collapse will lead to an increasing concentration of demand in winter.

5.3.2 Energy generation

Climate change has five broad implications for energy generation: it affects the viability of renewable sources, energy-from-biomass schemes, availability of cooling water, extraction of offshore oil and gas, and physical infrastructure.

The key renewable energy sources in Europe at present are hydropower (large-scale and micro) and wind, with tidal and wave turbines likely to become more significant during the 21st century. The viability of hydropower generation depends on changes in the volume and timing of streamflow: Lehner *et al*. (2005) show that even moderate climate change would lead to reductions in hydropower potentials of 25% and more in parts of southern and southeastern Europe. Wind generation potential is rather obviously determined by windspeeds and their consistencies. Climate models do not simulate windspeeds very accurately so scenarios are difficult to construct, but indications are that climate change has relatively little effect on windspeeds across Europe (Hansen *et al*., 2004).

The viability of energy from biomass depends of course on biomass productivity. The species most widely used in Europe include willow and miscanthus, whose productivity is largely determined by the length of the growing season (Olesen & Bindi, 2002).

Thermal power stations require cooling water, taken in practice either from rivers or the sea. Lower summer river flows have in recent drought years led to reductions in output from French nuclear power stations, and have the potential to cause more widespread problems in the future (see Section 5.2). Thermohaline circulation collapse would lead to lower flows in winter across much of western Europe (because precipitation falls as snow rather than rain), possibly reducing the amount of cooling water available during what would be the peak demand season.

The extraction of offshore oil and gas is potentially sensitive to climate change if the frequency of extreme weather conditions increases. The impacts of thermohaline circulation are likely to be most significant, as lower temperatures and icing would cause increased production difficulties even in the absence of changed storm frequency.

Finally, much energy generation infrastructure is vulnerable to climate change, particularly that located around the coast: many thermal power stations are located at the coast for access to cooling water, and most would be threatened by rapid sea level rise.

5.3.3 Energy distribution

Energy distribution, particularly the transmission of electricity, is vulnerable to extreme climate events, and the transmission efficiency of power lines falls as temperature rises. Energy distribution is likely to be most severely challenged by thermohaline circulation collapse, because the frequency of icing of power lines would increase substantially. The precise impact, however, will depend on how interconnected the European energy distribution network is in the future. A move towards the use of more local micro-grids, for example, would reduce sensitivity of energy distribution to disruption.

5.4 Health

5.4.1 Thermal effects on health

Cold winters and hot summers in Europe both tend to lead to an increase in mortality (Parry, 2000). In northern Europe excess mortality is greater in winter than summer, whilst in southern Europe most heat-related deaths are during summer (particularly during very hot summers). Low temperatures in winter and high temperatures in summer both exacerbate respiratory and circulatory problems, particularly amongst the elderly and frail, and effects are greatest in urban areas. The precise effects of a given temperature anomaly, however, depend on acclimatisation and social and behavioural adaptations to weather conditions (including such measures as quality of housing stock). Mortality during a cold winter, for example, increases most in countries with normally mild winters.

Several studies have developed and applied empirical statistical relationships between temperature and mortality in order to estimate the effects of future climate change. In the UK, for example, gradual climate change has the potential to increase the average annual number of summer heat deaths by the 2050s from around 800 to approximately 2800 (Department of Health, 2001), but to decrease the number of winter cold deaths from around 80,000 to 60,000. Dessai (2003) estimated a smaller percentage increase in heat-related deaths in Lisbon, amongst a population already well acclimatised to warm conditions.

Accelerated climate change would exaggerate these trends even more, potentially leading to extremely large increases in the numbers of summer heat-related deaths and reducing winter mortality in northern Europe. Thermohaline circulation collapse would lead to very substantial increases in winter mortality, particularly in western Europe where winters are currently relatively mild, and probably little change in summer mortality.

5.4.2 Disease and ill-health

Climate change has the potential to alter patterns of disease and ill-health by changing the distribution of disease vectors and altering the frequency of extreme events such as floods.

Most research attention has been directed towards potential changes in the risk of malaria transmission (e.g. van Lieshout *et al*., 2004). Warmer temperatures in general would lead to an expansion in the potential habitat of the mosquitoes which carry the parasites which bear malaria, although this may be offset by reductions in the amount of rainfall and hence available water bodies. Impacts on malaria, however, will be dependent on the state of public health: if current standards in Europe are maintained, it is unlikely that malaria would become re-established (Parry, 2000). Other vector-borne diseases potentially susceptible to climate change include leishmaniasis (vectors present in southern Europe) and tick-borne diseases such as tick-borne encephalitus and Lyme's disease (present across much of Europe). In each case, higher temperatures are likely to lengthen the transmission period and extend the areas affected northwards.

Accelerated climate change would increase still further potential for transmission of all these vector-borne diseases, whilst thermohaline circulation collapse would reduce transmission potential.

Floods, both inland and coastal, have a number of potential effects on health and disease, ranging from death and injury, through infection from water-borne diseases to stress (Hagat *et al*., 2003). Increasing flood frequency across Europe (see Section 5.2) may increase disaster-related ill-health. Rapid sea level rise would have a particularly large effect on flood frequency.

5.5 Agriculture

5.5.1 Agricultural productivity in Europe

Over the last decade there have been many studies into the potential effect of future climate change on productivity of a wide range of crops in Europe (see Olesen & Bindi (2002) and Fuhrer (2003) for reviews). In general, the effects of climate change on productivity depend on the interactions between changes in CO_2 concentration, the length of the growing season, water availability, and pests and diseases. Under a scenario of gradual warming, productivity in general is likely to increase in northern Europe as growing seasons lengthen and areas with suitable climates move northwards, and decrease in southern Europe as heat stress and water shortages become more significant (Olesen & Bindi, 2002). The precise quantitative effects of climate change vary between crop types and individual cultivars (Olesen & Bindi, 2002), and also with assumed changes in agricultural efficiency and use of technology.

There have been no published quantitative studies of the effect of accelerated climate change or thermohaline circulation collapse on agricultural productivity (although Engvild (2003) showed how sensitive productivity was to cooling caused by any change). Figure 11 shows changes in crop suitability across Europe under gradual climate change, thermohaline circulation collapse and accelerated climate change. Crop suitability is a function of an index of growing degree days (similar to HDD above, but with a temperature threshold of $5^{o}C$) and the ratio of actual to potential evaporation (Ramankutty *et al*., 2002). Under gradual change suitability increases in northern Europe and decreases in parts of southern Europe. Accelerated climate change enhances this pattern. Thermohaline circulation collapse leads to reductions in suitability across large parts of western Europe, as well as in southern Europe.

5.5.2 Implications of changes in global food production

Whilst changes in productivity in Europe will affect farm incomes and the rural economy, changes in food prices and therefore risk of hunger are much more affected by changes in the global food market (Parry *et al*., 2004). Gradual climate change results in a general shift in world food production to higher latitudes, with increases in production of cereals in developed countries compensating, to a large extent, for reductions in developing countries (Parry *et al*., 2004). Food prices would increase, and the risk of hunger – particularly in Africa – would also rise, with the precise effects depending, once again, on the characteristics of the future global economy and society.

Accelerated climate change would have the result of increasing this polarisation, and would probably therefore increase food prices. Thermohaline circulation collapse, however, would probably have a much larger effect on food prices and hence risk of hunger, because it would reduce substantially cereal production in the high latitude, developed country regions which currently produce the bulk of the world’s traded cereals.

5.5.3 Forestry

As with agriculture, there has been a large amount of research in Europe over the last decade examining the potential effects of gradual climate change on forest resources. Much has been funded by the European Union. The general conclusion (e.g. Parry, 2000; Nabuurs *et al*., 2002) is that productivity will increase in northern Europe, and the boreal forest zone will expand northwards. However, the rate of northwards displacement of climatic suitability will be greater than the estimated potential of many species of migrate (Parry, 2000), so the boreal forest zone may in practice be squeezed by declining suitability in the south and a slow rate of migration northwards. Fire risk is likely to increase (Stocks *et al*., 1998), but increased productivity would probably offset increased disturbances (Schelhaus *et al*., 2003), at least in northern, western and central areas. In western and central European temperate forests higher temperatures would lead to an increasing dominance of deciduous broad-leaved species over coniferous species, but summer droughts could threaten some forests. Changes in the forests of southern Europe would be more affected by changes in water availability than temperature (Parry, 2000). Increased timber productivity in northern Europe could mean a reduction in the import of timber products from Russia and eastern Europe (Solberg *et al*., 2003).

Accelerated climate change will increase these trends, with the difference between the rate of change in climatic suitability and the rate of migration even greater than with gradual climate change. It will also increase the risk of both summer drought and fire.

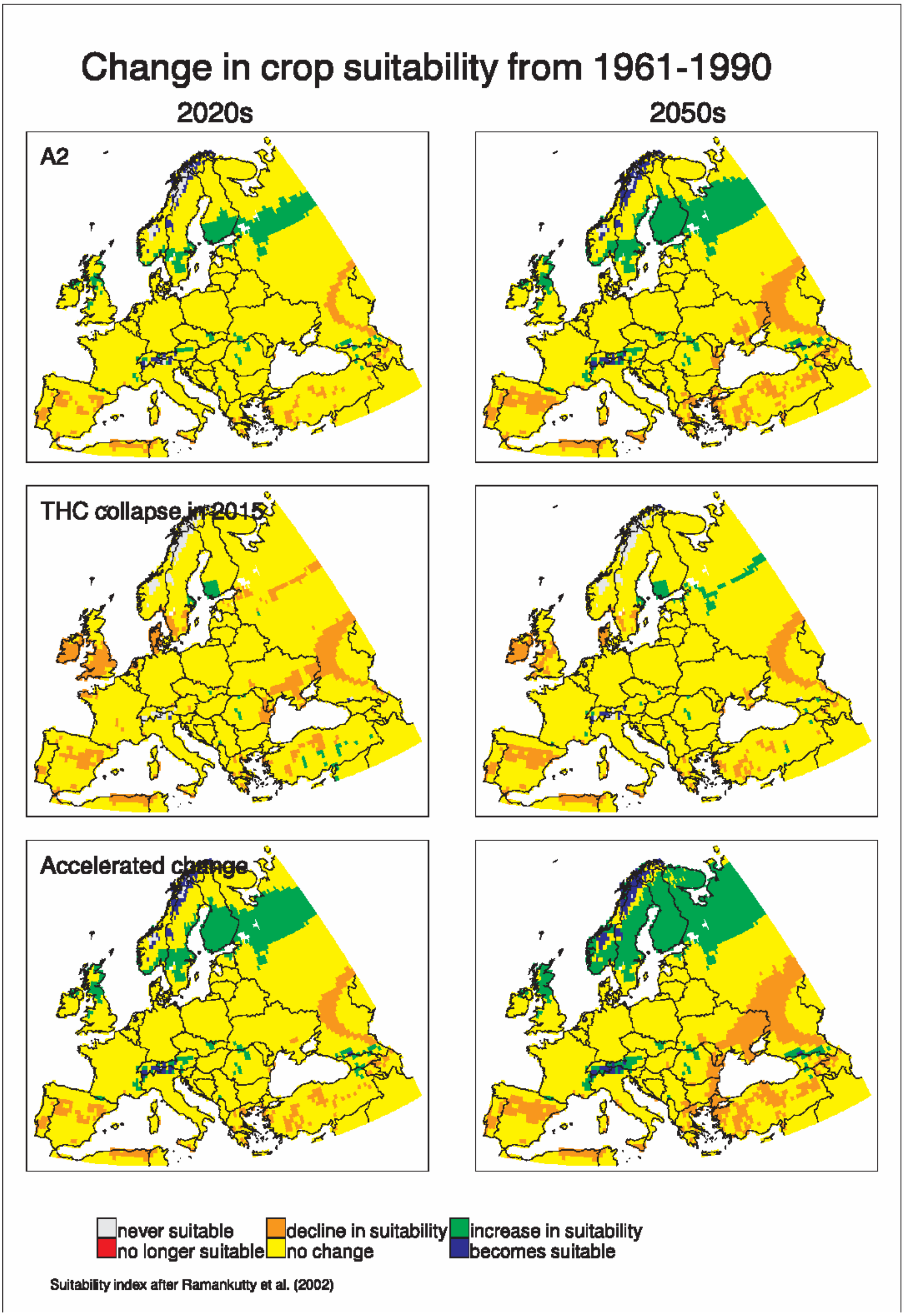

Figure 11: Change in crop suitability by 2020 and 2050, under A2 emissions, thermohaline circulation collapse in 2015, and accelerated climate change

Thermohaline circulation collapse would reduce forest growth and timber yield, and be particularly challenging to broadleaved species at their northern or altitudinal limits. “Exotic” non-hardy species, such as sweet chestnut and eucalyptus, will be most threatened. Lower temperatures would increase the risk of many damaging fungi, but lower the risk posed by insect pests.

5.5.4 Fisheries

The diversity and productivity of marine fisheries around Europe is a function not only of ocean and climatic conditions, but also of the past history of overfishing. Empirical evidence from past climatic anomalies (spanning single years or decades) shows that marine fisheries populations are sensitive to climatic variability and hence potentially sensitive to future change. The warming in the North Sea between 1920 and 1940, for example, led to a northward expansion of cod. However, it can be very difficult to separate out effects of sea surface temperatures and effects of change in ocean circulation, which may themselves be a result of changes in sea surface temperatures elsewhere. Also, empirical evidence shows that different populations of the same species can respond differently to the same environmental forcing (Genner *et al*., 2004). Simulation of the response of marine fish populations to future climate change is therefore difficult, and has been rarely attempted (see Clark *et al*. (2003) for an example).

There is virtually no information on potential changes in groundfish fisheries, and most evidence relates to North Sea cod. This is at its southerly limit in the North Sea (Parry, 2000), and simulation studies with a simple model suggest higher temperatures would lead to a northward movement in the cod fishery (Clark *et al*., 2003). Accelerated change would therefore be likely to result in the elimination of cod from the North Sea, whilst thermohaline circulation collapse could see expansion into the English Channel. However, precise changes in cod fisheries will depend also on changes in ocean circulation. Higher water temperatures are already being blamed for an observed decline in salmon abundance in northern Europe: evidence from physiological studies suggests that warmer temperatures would lead to a northward move in the geographic distribution of Atlantic salmon in Europe, with extinction at the southerly edge of the current range (McCarthy & Houlihan, 1997). The sardine fishery is economically important off the Iberian peninsula, and emprical evidence shows that sardine abundance is related to the intensity of upwelling in the previous summer (Guisande *et al*., 2004). Global warming is likely to increase the intensity of upwelling, and whilst this may benefit sardines, has the potential to significantly degrade marine ecosystems generally (Bakun & Weeks, 2004).

Freshwater fisheries are commercially much less important in Europe than marine fisheries, but are extremely important not only for biodiversity reasons but also for recreation. Freshwater fisheries are affected not only by climatic variability and change but also by changes in water quality and the volume and timing of river flows. Species close to their current thermal limits (such as the Arctic Charr in English and Scottish lakes) are obviously most affected by climate change, and the impacts on population numbers will depend on ability to migrate. Rapid changes in climatic conditions, particularly water temperature, are therefore likely to have the greatest effect on small lakes, rivers and isolated water bodies (Parry, 2000).

5.6 Biodiversity and its management

Biodiversity in Europe is challenged not only by climate change, but also by other pressures including land cover change and pollution. To a large extent the effects of climate change will be dependent on how these other pressures change too in the future.

Climate change affects different plant and animal species differently, and therefore has the potential to affect species composition and biodiversity in a given area. The more specialised the species, the more vulnerable it is to change (Julliard *et al*., 2004), and the more important these species are to a particular location the more sensitive biodiversity at that site is to climate change. Biodiversity in Europe will also be affected by climate changes elsewhere, as these may affect migrant species: changes in the Arctic are likely to be particularly important for European bird populations, for example.

"Natural" biodiversity in Europe is largely maintained through nature reserves, typically covering a specified ecological niche. Climate change affects the viability of these reserves by changing climatic conditions. Reserves at greatest risk of change are those in marginal climate zones, such as alpine areas.

Whilst there has been a great deal of research into the sensitivity of species and ecosystems to climatic variability, there has been less into how future climate change may affect ecosystems and biodiversity. Leemans & Eickhout (2004) simulated the distribution of major plant types (e.g. evergreen coniferous trees, drought deciduous trees, and so on) and ecosystems composed of these plant types across the globe with different rates of climate change. They showed that with temperature increases between 1 and 2^{o}C above pre-industrial levels (0.25-1.25^{o}C above the 1961-1990 mean), most species, ecosystems and hence landscapes would be impacted. In the most general terms, global warming leads to a poleward or upward shift in many ecosystems. Boreal forest replace large parts of the southern edges of the tundra, and temperate forests replace boreal forest. Bakkenes *et al*.'s (2002) simulations in Europe (using empirical relationships between climate and species distribution) showed that, under gradual climate change, approximately a third of the plant species present in an grid cell in 1990 would disappear from that cell by 2050: across approximately 40% of Europe, more than 50% of the species present in 2050 would be different from those present in 1990. Thomas *et al*. (2004), using a similar approach, examined risk of extinction. With mid-range warming, they estimated that between 3 and 16% of plant species in Europe would become extinct, depending on assumed rates of dispersal. Taken together, these studies suggest that even where there is relatively little change in ecosystem or major plant type, there may be much larger changes in the abundance of individual species.

At a more local scale, Lasch *et al.* (2002) simulated changes in forest characteristics in a part of Germany under climate change, showing a decrease in species diversity (numbers of different tree species) despite an increase in habitat diversity, due to a mismatch between the rate of climate change and the rate at which species can adjust to changed climates. A study of potential changes in species composition in nature reserves in the UK (Dockerty *et al*., 2003) showed that biodiversity would be little affected in most UK reserves, but that key species in some important "climatically-marginal" reserves would be affected. Lemoine & Bohning-Goese, 2003) estimated that higher temperatures would lead to a reduction in bird migration to northern Europe, as warmer conditions would increase competition from resident species.

Accelerated climate change would increase these tendencies still further, leading to even larger changes in local biodiversity and reductions in the viability of nature reserves (note that Leemans & Eickhout (2004) only considered temperature increases up to 3^{o}C by the end of the 21st century). Palaeoecological evidence shows large and rapid changes in vegetation composition in response to earlier cooling events. Cooling after the 8.2ka event, for example, led to rapid increases in pine, birch and fir across northern Europe at the expense of less cold-tolerant broad-leaved species such as hazel (Tinner & Lotter, 2001; Williams *et al*., 2002). Higgins & Vellinga (2004) simulated the effects of thermohaline circulation collapse (with no global warming) on ecosystem type and productivity, showing changes not just around the North Atlantic region. The distribution of ecosystem change was found to be largely determined by changes in rainfall, rather than temperature. In Europe lower precipitation and temperatures produced a shift from temperate deciduous forest to boreal evergreen forest.

Rapid sea level rises poses a serious threat to coastal ecosystems, including wetlands and tidal flats. "Coastal squeeze" prevents many of these habitats from moving inland as sea level rises. Large areas of wetland around the Mediterranean and the Baltic are at risk from sea level rise (Nicholls et al., 1999; Nicholls, 2004), and rapid sea level rise would effectively eliminate them.

5.7 Settlements and infrastructure

5.7.1 The urban environment

The design and construction styles of buildings in European cities and towns, and to a lesser extent the layout of the urban environment itself, are influenced by climate regime. Buildings in northern areas are designed for cold winters, whilst buildings in southern Europe are designed to keep cool during hot summers. Climate change will affect the "performance" of the building fabric in European cities, in terms of thermal comfort, use of energy for heating and/or cooling and risk of damage during extreme wind or rain events (Liso *et al*., 2003).

There has been very little research into building performance under changed climatic conditions (but see Camilleri *et al*., 2001). Levermore *et al.* (2000;2004) simulated performance of a typical naturally-ventilated office in southern England, showing that the percentage of time indoor temperatures exceeded 25^{o}C more than doubled to 7-8% with a temperature rise of 2^{o}C, and increased by between 5 and 6 times to 15-18% with a rise of 5^{o}C, with the increase depending on construction type. Current design standards in the UK require temperatures to be above 25^{o}C for less than 5% of occupied time. Higher temperatures, then, can be expected to lead to increased discomfort in buildings, with the greatest effect likely in areas not accustomed to hot summers. The effects of a *reduction* in temperature will be felt through increases in the duration of "unacceptably" low temperatures during winter and increased energy expenditure on heating (Section 5.3).

Many European cities have large stocks of old and historically significant buildings. The structural integrity and performance of these buildings are likely to be significantly impacted by a changing climate, and they will be particularly difficult to alter. Rather more speculatively, urban design and the use of open spaces would change as climate changed.

Climate change also changes the risk of damage to buildings in the urban environment from extreme weather events, such as wind and ice storms (flooding is discussed in Section 5.2). Across much of Europe such damage is covered by insurance: whilst a reduced risk of damage would lessen burdens on the insurance industry, and increase in risk could seriously challenge the ability of the insurance market to continue to provide cover. There is, however, little information on potential changes in extreme windspeeds or ice loadings under climate change. There are some indications that whilst the frequency of wind storm events across the UK would not change under gradual climate change, the maximum gust intensity and hence risk of damage could increase (Hanson *et al*., 2004). Accelerated climate change could increase further windstorm intensity across Europe. Thermohaline circulation collapse could increase the frequency of extreme ice and snow loading in western Europe.

5.7.2 Transportation networks and infrastructure

Transport networks are clearly sensitive to climatic variability, and any change in the frequency of disruptive events (including high winds, icings and fog) would obviously affect the reliability of a transport network. More significantly, however, such a change would affect maintenance expenditure and may alter the physical reliability of transport infrastructure.

In northern Europe the main maintenance expenditure is on de-icing for roads, railways and runways, and unanticipated freezing events tend to be the events causing the greatest disruption. This is particularly the case where temperatures during winter can fluctuate around 0^{o}C. With higher temperatures this marginal temperature zone will move eastwards into Europe, shifting the disruption potential from the UK and France eastwards into Germany (Parry, 2000), although because these areas are used to low temperatures, impacts may be relatively small. With lower temperatures, the risk of disruption increases significantly in milder western Europe – areas with less experience of dealing with low temperatures.

The physical infrastructure associated with transport networks is designed to cope with current climatic variability, and standards therefore vary across Europe. Roads and railways in northern countries are designed to cope with low temperatures, for example, whilst in southern Europe they are designed for high summer temperatures. Drainage design is based on local rainfall characteristics.

Port infrastructure is particularly sensitive to changes in sea level, as much is by necessity close to sea level. Accessibility may also be affected by changes in offshore sediment transport, themselves affected partly by sea level rise and partly by changes in storm characteristics. Higher temperatures would increase the ice-free season for ports in northern Europe – such as those on the shores of the Baltic – and increase the potential for sea transport. Conversely, lower temperatures would increase ice cover and perhaps close British ports to winter shipping: this would severely disrupt trade.

5.8 Economic implications of the impacts of climate change

The impacts of climate change on water, energy, health, agriculture, biodiversity and settlements will alter the pattern of economic activity within a region and change the distribution of activities across Europe. In particular, changes to resource-based sectors – agriculture, fisheries, forestry and tourism – will affect the pattern of economic activity under most scenarios. Under the extreme climate change scenarios the changes in climate may be sufficient to challenge the viability of activities that are currently not seen as climate-sensitive.

Gradual climate change in Europe is likely to exaggerate the economic gradient between northern and southern Europe. The centre of gravity of agricultural production would move northwards, and tourism would be oriented towards the north rather than the south and around the Mediterranean. Accelerated climate change would exaggerate these trends even more, and may also threaten the economic viability of industry in parts of southern and eastern Europe which become particularly warm. Air conditioning or cooling costs, for example, may make indoor factory work prohibitively expensive. Thermohaline circulation collapse, however, would result in a shift *southwards* in the economic centre of gravity of Europe, as agriculture and industry moves south to escape the colder and less disruptive winter conditions. Again, increases in space heating costs and disruption to transport networks during winter may make some industrial activities in northern and western Europe uneconomic. Rapid sea level rise would threaten a number of the most economically important cities in Europe, including London, Hamburg and Amsterdam, leading to a shift inland. Each of these changes would affect power relations within the European Union in different ways, but exactly how these effects are manifest is very difficult to judge.

5.9 Security, population movements and conflict

Stories in the media frequently raise the possibility that climate change would lead to major political disruption and conflict, either between states or following the breakdown of social order. Indeed, fictional representations of climate change (e.g. *The Day After Tomorrow* and Christopher's *The World In Winter*) tend to be based on this premise. Archaeological and historical evidence (e.g. Fagan, 2004; van Geel *et al*., 1996) shows that past abrupt climate changes have led to major population movements and societal collapse.

However, there has been very little academic work on the link between future climate change and conflict (Barnett, 2003). The only published study is that of Edwards (1999), who explored the security implications of sea level rise inundating several island states in the south west Pacific. He showed that climate change, in this case leading to loss of inhabitable area, had the potential to exacerbate existing issues associated with economic, social, political and military security.

Climate change will also impact differentially within a society, and the more extreme the climate change the greater the differentiation. A robust conclusion from hazard research is that ability to recover from loss and adapt to change is strongly dependent on wealth. The poorest in society are least able to relocate or be able to afford increased cooling or heating costs, for example.

Europe may also be affected by climate change elsewhere in the world. The threat of environmental refugees driven towards Europe by deteriorating conditions in Africa particularly has been discussed in the media, but there are no academic studies of the potential for this to occur. Similarly, climate change may exacerbate resource conflicts (e.g. over oil) that affect European and American interests.

5.10 Overview: estimating the impacts of abrupt climate change

This review has been very speculative, and is based on no published studies of the implications of abrupt climate change: the calculations undertaken specifically for this study must be seen as indicative only. Moreover, there have actually been very few comprehensive assessments of the implications of gradual climate change in Europe. Virtually all quantitative studies have so far concentrated on particular sectors and regions, and many sectors – such as transportation – have not been studied at all. Most studies have focused on biophysical impacts of climate change, rather than social and economic consequences. There are, however, a number of ongoing projects, such as cCASHh (www.who.dk/ccashh) looking at health implications and ATEAM examining ecosystem services (www.pik-potsdam.de/ateam), although these are not looking at scenarios of abrupt climate change.

It is, in fact, rather dangerous to seek to extrapolate from studies of gradual climate change in order to assess the implications of abrupt climate change. The translation of climate change into social and economic impact is characterised by the presence of both physical and human critical thresholds, and the greater the rate of climate change the greater the likelihood that a threshold is reached. Unfortunately, these thresholds vary with location and the current and future state of economy and society.

Lessons from the past are of value in assessing the biophysical effects of abrupt climate change, but are of limited use in assessing social and economic impacts because impacts of are so dependent on economic and social conditions.

6. Vulnerability in Europe to abrupt climate change

Vulnerability, as defined by the Intergovernmental Panel on Climate Change (2001), depends not only on the magnitude of impact or sensitivity to change, but also on the ability to adapt to change ("adaptive capacity"). The previous section has considered in qualitative terms the potential magnitude of the impact of abrupt climate change in Europe, but assessing vulnerability to abrupt climate change is extremely problematic, for two reasons. First, it is difficult to characterise capacity to adapt to abrupt climate change, and second assessments of vulnerability must be based on assessments of risk of occurrence.

One hypothesis would be that capacity to adapt to abrupt climate change is related to the capacity to adapt to conventional climate change. Several studies have explored the factors which potentially affect the variability in adaptive capacity between regions or countries, and hence vulnerability. Intuitively, regional or national wealth is a major driver of vulnerability and ability to respond to events, but Brooks *et al.* (2005) suggest that variability in adaptive capacity varies with measures associated with governance and access to resources, rather than simply the gross wealth of a nation. Klein *et al.* (pers comm.) attempted to characterise the variability of adaptive capacity across Europe using indicators of wealth, governance, and other social measures, suggesting lower adaptive capacity in southern Europe. Under this hypothesis, the poorer parts of Europe – in the south and east – would be most vulnerable to abrupt climate change, not because the changes are greater but because ability to cope is lower than further west.

A second hypothesis would be that the implications of abrupt climate change are so large that ability to cope with relatively small changes becomes irrelevant. In this case, vulnerability would therefore largely be function of the potential impacts of climate change, which are (as indicated in Section 5) likely to be greatest in western and southern Europe.

It is, of course, extremely difficult to evaluate these two hypotheses, primarily because it is actually very difficult to derive an index of capacity to adapt to conventional or, even more problematically, abrupt climate change. Brooks *et al.*'s (2005) index of capacity to adapt to conventional climate change is calibrated on numbers of people affected by climate-related natural disasters, which is arguably an unrealistic proxy for adaptability to climate change. One approach would be to conduct an expert elicitation survey amongst experts experienced in assessing vulnerability to change.

The second difficulty with conducting a vulnerability assessment relates to the actual or perceived likelihood of the event occurring. As noted above, it is widely accepted that conventional climate change is occurring, and to a large extent the scientific uncertainty revolves around the precise rate of change and exactly what would happen with a given rate of change. Abrupt climate change is, largely, characterised as some form of step change which has a discrete, but unknown probability of occurrence. Perceptions of vulnerability are therefore based not on magnitude of change, but on likelihood of the step change. If this likelihood is believed to be "too low", then Europe will not be perceived to be vulnerable to abrupt climate change. This threshold will vary from sector to sector and, probably, region to region, and contrasts with thresholds of danger from other step changes – such as asteroid impact – would be illuminating. Unfortunately, as also noted above, estimates of the likelihood of abrupt climate change are uncertain and contested.

7. Implications for adaptation strategies

7.1 Introduction: adaptation to climate change

Adaptation can be broadly defined as an adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts. Adaptation involves changes in processes, practices and structures to moderate potential damages or to benefit from new opportunities.

Two basic approaches to adaptation to climate change are emerging. The first is scenario driven, and essentially includes the following stages:

- identify exposure to climate change
- identify impacts under a range of change scenarios
- determine adaptation strategy
- identify and evaluate adaptation options
- select an adaptation option

Given that there is a large degree of uncertainty, the "ideal" adaptation option is one that is robust to uncertainty or sufficiently flexible to be able to cope with different futures.

The other approach derives from the development agenda, and seeks to adapt to climate change by reducing vulnerability to current and future climatic extremes. This approach is less concerned with the development and use of climate change scenarios, and focuses more on the characteristics of economic and social systems that are exposed to change. However, in practice climate change scenarios must provide some limiting conditions.

Virtually all research into adaptation to future climate change has focused on "conventional" gradual climate change, although even here there is considerable evidence that the rates of change will be too rapid for efficient adaptation: many of the large infrastructure investments potentially sensitive to climate change have lead times of several decades. The threat of *abrupt* climate change challenges the scenario-driven approach by introducing additional, more extreme, climate and impact scenarios, and in a similar way expands the potential boundary conditions in the vulnerability-based approach. It challenges both approaches by affecting the feasibility of adaptation options.

Managers considering adaptation are already used to the concept of a changing climate and, in the UK at least, have access to a set of scenarios describing a range of possible futures. Whilst there is some discussion about the likelihood of different rates of change (see for example Dessai & Hulme, 2004; Schneider, 2001; 2002), in practice organisations in the UK seeking to adapt are likely to be content – at the strategic level – with exploring the implications of a finite set of "reasonable" climate change scenarios. Indeed, this is increasingly becoming standard business practice in general. Scenarios of abrupt change, however, have a highly uncertain, but probably very low (but see Section 4.2), likelihood of realisation. They will only be taken seriously in strategic scenario-based adaptation planning if their perceived likelihood is sufficiently high, but the definition of "sufficiently high" will vary between organisations. It can be hypothesised that the threshold will be a function of the potential consequences of abrupt climate change for the organisation, the ability of the organisation to adapt to changing conditions (itself a function of technical considerations and organisational capacity: see next section), and organisational risk aversion.

The second key implication of abrupt climate change is for the feasibility of adaptation options. In the most general terms, there are four limits to adaptation: physical, financial, social and political, and those relating to organisational capacity. The physical limits are likely to be the broadest, given that human societies have already adapted to an extremely wide range of climates and there is thus, in principle, a wide range of experience (although this may be outside existing organisational experience or awareness). The other three limits will be more challenging. Whilst a particular response may be technically feasible – adapting UK housing standards to those found in continental Russia, for example, under a scenario of thermohaline circulation collapse – it may be extremely difficult and costly to implement in practice, even for new developments. It is likely, however, that many of the current social and political constraints on adaptation options would change in the face of an abrupt climate change. It is quite possible that concerns for the physical environment would reduce as climate change becomes more extreme: it would, for example, be increasingly difficult for water managers to justify maintaining river flows for environmental reasons when farmers, households and industry are seriously affected by shortage. Finally, the threat of abrupt climate change over very short time scales is highly likely to seriously challenge the organisational capabilities of an organisation exposed to climate change, even one aware of and responding to gradual climate change.

Central to the vulnerability-oriented approach to adaptation is the idea that adapting better to current climatic variability would go a long way towards adapting to future climate change. Whilst some measures to adapt to current variability would also cope with changing circumstances (Adger *et al*., 2005), many would not: their performance is based on providing some defined standard of service, which would obviously change as climate changes. Abrupt climate change, by definition, involves a step change in climate in an area, and measures designed to cope with current climatic variability are therefore even less likely to be a reasonable response to abrupt climate change.

Abrupt climate change, therefore, affects the potential range of climate impacts and the feasibility of adaptation options, but given the (uncertain) low probability of abrupt change and uncertainty over its direction (cooling or rapid warming?) it is difficult to see how organisations can plan now to adapt to abrupt climate change. However, whilst it may not be necessary for organisations to prepare for abrupt climate change, it is extremely important to *monitor* for the onset of abrupt climate change. Despite the impression given in *The Day After Tomorrow*, an abrupt climate change would probably take place over at least a decade (Vellinga & Wood's (2002) simulation showed that it took a decade for the thermohaline circulation to completely switch off after a large input of freshwater and up to 20 years for the development of persistent reductions in temperature across the Northern Hemisphere). Whilst this is very short in terms of many adaptation options, it is highly likely that awareness of impending dramatic change would focus the mind. Monitoring for the onset of abrupt climate change is therefore the most appropriate short-term adaptive action.

7.2 The adaptation process

Figure 12 below presents a simple three-stage conceptual model of the process of adopting an adaptation to climate change. Each stage – awareness, intention and action – is influenced by the internal characteristics of the adapting organisation, sensitivity to change and external drivers, although different aspects of these influences are relevant at each stage.

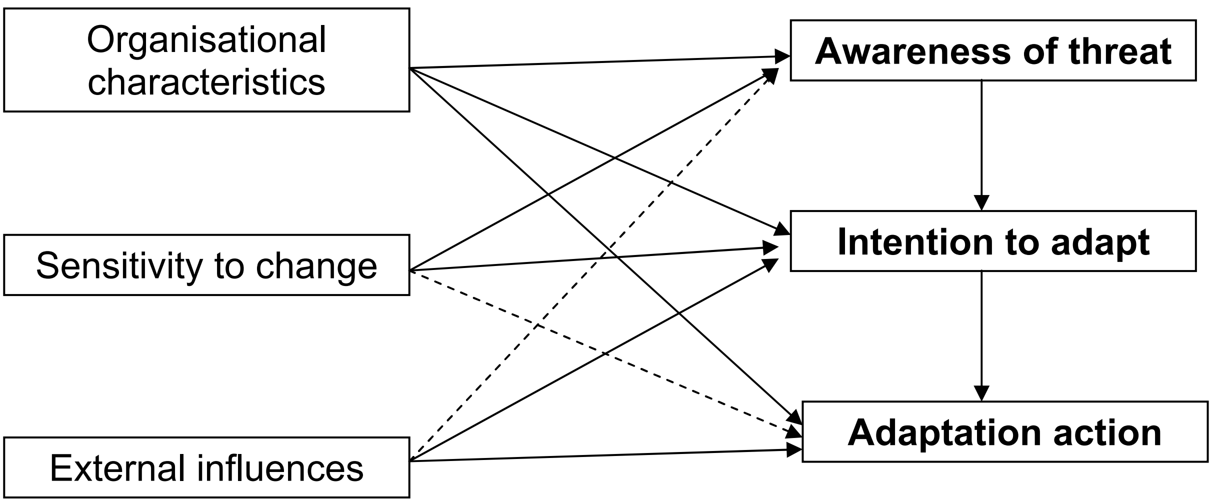

Figure 12: The adaptation process: the dashed lines show weaker connections

The first stage is the awareness of the potential threat. This is determined by access to information on climate change, experience of past extreme events or changing conditions, and the sensitivity of the activity to climate change. The first two factors are essentially internal characteristics of the organisation, and are in turn dependent on organisational culture, the extent to which the organisation is internally- or externally-oriented, and organisational history. Information on climate change may be provided by the government or media, but its effect on awareness will be mediated by organisational characteristics, so the link between external influences and awareness is shown as a dashed line in Figure 12.

Sensitivity to change affects not only awareness, but also the development of an intention to adapt: in the simplest terms, the greater the potential impact of climate change, the greater the likely intention to adapt. Organisational characteristics that affect the intention to adapt include perception of the significance of the threat, degree of risk aversion and the ability to identify opportunities through adaptation. External influences include directives from government or regulators and economic signals from the market.

The translation of an intention into an action is primarily determined by organisational characteristics – primarily wealth or ability to mobilise resources – and by external drivers. These drivers may require action to be taken, through the issuance of new regulations, for example, but may make it more difficult to translate intention into action. For example, legal or regulatory constraints may preclude some adaptation actions.

Empirical evidence from the UK water industry suggests that the ability of different water supply companies to adapt to “gradual” climate change is largely determined by geographical variations in the susceptibility to climate change across the UK: each company is subject to the same regulatory constraints, and the resources, capabilities and objectives of each supply company are broadly similar (Arnell & Delaney, 2005). The ability of house-building companies to adapt, however, is much more determined by the characteristics of the company (Berkhout *et al*., 2003).

The ability to adapt to *abrupt* climate change will be affected by the same three sets of influences, but their relative importance will be different. First, it is likely that the susceptibility to climate change will become much more important, even in those sectors where susceptibility is already the key determinant of adaptive capacity. In most cases, gradual climate change does not produce radically or conceptually different climatic conditions. Whilst adaptation may be challenging, it is relatively straightforward to learn from either past extreme events or other geographic environments. Abrupt climate change brings quite different and much more challenging climatic conditions. Second, it is likely that the role of government will be much more significant – regardless of future development pathways – in the face of abrupt climate change. Fictional accounts of rapid climate change (e.g. *The Day After Tomorrow* and John Christopher’s 1963 novel *The World in Winter*) tend to portray the breakdown of government authority, but these usually assume a very rapid climatic breakdown. In the face of an inevitable, but slightly slower-onset, abrupt climate change it is more likely that government authority and degree of attempted control over climate-sensitive sectors would increase.

8. Conclusions and further research

8.1 Summary of conclusions

The aim of this project was to explore the implications of rapid or abrupt climate changes – defined here to be either a step change in climate regime or a rate of change outside the IPCC range – for Europe. Whilst there has been a great deal of research into the potential mechanisms of abrupt climate change, but there are no published quantitative scenarios on which to base assessments of impacts or vulnerability. Three characterisations of abrupt climate change were therefore produced for the current study, representing a collapse of the thermohaline circulation in the North Atlantic, accelerated climate change caused by the additional release of greenhouse gases, and the rapid rise in sea level that would result from disintegration of the West Antarctic Ice Sheet.

Managers adapting to gradual climate change accept that change is happening, and look for information on the magnitude of change. Managers concerned about abrupt climate change, however, are less interested in the magnitude of change – they believe it will by definition be extreme – but are more interested in the *likelihood* of abrupt change occurring. There are as yet no scientifically robust estimates of such likelihoods, so an expert survey was conducted focusing on assessments of the likelihood of thermohaline circulation collapse and accelerated climate change. Estimates of the likelihood of thermohaline circulation collapse or accelerated climate change varied significantly between experts, over several orders of magnitude: most experts believed the risk of either to be very low (well under 1%), but a minority assessed the risk as considerably greater.

An initial assessment of the implications of the three characterisations of abrupt climate change was made using a combination of model simulations (for hydrology and crop potential), review of published studies of the effects of gradual climate change and change thresholds, and expert judgement.

The key impacts of both thermohaline circulation collapse and accelerated climate change are likely to be on agriculture and crop production (and hence crop prices and rural economies), mortality and ill health, the ability of physical infrastructure (buildings and networks) to continue to operate effectively, and on ecosystems in both northern and southern Eirope. Accelerated climate change is also likely to significantly affect the availability of water resources as demand increases and supplies reduce. Rapid sea level rise would threaten coastal infrastructure and large parts of many key European cities, and would increase coastal flood losses: this would challenge the viability of insurance against flood hazards, and require very large investment in flood defences. All three abrupt changes would see a change in the economic and cultural centre of gravity of Europe, in different directions: following thermohaline circulation collapse the shift would be southwards, following accelerated change it would be northwards, and it would be inland after rapid sea level rise.

Abrupt climate change influences adaptation strategies by affecting the potential range of climate impacts and the feasibility of adaptation options, but given the (uncertain) low probability of abrupt change and uncertainty over its direction (cooling or rapid warming?) it is difficult to see how organisations can plan now to adapt to abrupt climate change. However, it is extremely important that measures are implemented to monitor for the onset of abrupt climate change.

Several recent papers have suggested that analogues from the past can provide useful information about the vulnerability of economies and societies to abrupt climate change (e.g. Fagan, 2004; van Geel *et al*., 1996). However, in each case the societies that were impacted and adapted are quite different to those of the 21st century: they were largely agrarian, frequently governed by despots and not part of a globalising economy.

8.2 Future research

This study has shown that whilst there has been considerable research into the potential mechanisms of abrupt climate change, there has been much less research into their potential impacts or possible responses.

Key areas for future research include:

- Quantitative characterisations of abrupt changes in climate: scenarios that can be used to drive quantitative impacts models need to be constructed using current ocean/climate models. In particular, scenarios combining thermohaline circulation collapse with an increasing concentration of greenhouse gases need to be constructed, and model simulations of accelerated climate change are required. The characterisations used in this preliminary assessment were necessarily based on rather naïve assumptions.
- Quantitative characterisations of the likelihood of defined abrupt changes in climate, under different assumed rates of climate change. This is extremely important, and should involve not only model simulations but also assessment of expert opinion (a major in-depth survey is currently being conducted by the Potsdam Institute for Climate Impact Research).
- Quantitative assessments of the implications of abrupt climate changes for defined sectors and regions: the only model-based assessments so far conducted were done for the current study and concentrated on physical impacts. In principle this is a relatively straightforward task, given scenarios for abrupt climate change and models of impacted sectors.
- Identification of "dangerous" magnitudes of climate change which would pose significant challenges to adaptation (see Dessai *et al*., 2004): in other words, what are the limits to adaptation? These will vary between sectors.
- Assessment of the vulnerability of different regions of Europe to abrupt climate change, in contrast to vulnerability to "conventional" climate change, based on expert elicitation.
- What are the specific implications of abrupt climate change for adaptation planning in particular sectors? Is it possible to draw analogies from other areas exposed to low-probability, high-impact events, such as military scenario planning or nuclear power station design?
- What probability of abrupt climate change would alter adaptation planning, and what factors influence this threshold probability?

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