Global impacts of abrupt climate change: an initial assessment

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Executive summary

This report describes the potential global-scale implications of three types of abrupt climate – *collapse of the thermohaline circulation*, leading to lower temperatures across Europe and parts of North America, and precipitation changes globally (but with effects depending on the degree of warming at the time of collapse), *accelerated climate change*, leading to very high rates of change in temperature and precipitation, and *regime change*, where the climate shifts into a state with a permanent El Nino, a permanently wet south Asian monsoon, or a permanently dry south Asian monsoon. Quantitative scenarios, with a high degree of uncertainty, are constructed for each of these types of abrupt change, and used to inform the assessment of potential impacts. The assessment combines some numerical simulations (for water scarcity and energy demand) with interpretation of published studies into the impacts of gradual climate change: the literature on impacts of abrupt climate change is extremely limited.

The main implications of the abrupt climate changes are summarised in tables by sector (water, energy, health, agriculture, biodiversity and settlements/infrastructure) and continent, and the concluding section summarises the main implications of each scenario. The most generalised conclusions are:

Both thermohaline circulation collapse and accelerated climate change potentially have global-scale consequences, dependent not just on temperature changes but also the pattern of precipitation change. The effects of regime change are more regional, but each of the regime changes considered have the potential to affect world food markets, and hence risk of hunger even in areas not directly affected.

The large potential impacts, combined with the non-trivial likelihoods of abrupt climate changes occurring, mean that there is an urgent need for more comprehensive quantitative assessments of abrupt climate change at local and global scales, which can inform more generalised integrated assessments of climate policy.

The report does not explicitly consider adaptation, but it is clear that the implications of abrupt climate change for the characteristics of adaptation strategies, and the feasibility of specific adaptation actions, are very large.

1. Introduction: scope and purpose of report

This report provides a summary of the impacts, across the global domain, of a set of defined *abrupt* climate changes. Virtually all climate change impact assessments have assumed that over the next century climate will change gradually – albeit at an historically extremely fast rate – and "smoothly". However, it is known that the climate system has in the last few thousand years undergone a number of rapid or step changes, at regional and global scales, where climate has either changed very rapidly or switched to a different state. Examples of such abrupt climate changes[1] include:

- regional cooling following a shutdown of the thermohaline circulation in the North Atlantic;
- accelerated change due to positive feedbacks in the climate system exaggerating the radiative effects of increased anthropogenic emissions, and
- "regime change", such as a switch to a permanent ENSO state.

Whilst there has been some research into the drivers of such abrupt changes – particularly changes to the thermohaline circulation – there has been very little research into the potential impacts of abrupt change (see Arnell et al, 2005; Higgins & Vellinga, 2004; Higgins & Schneider, 2005). This review of potential impacts is based on these few published studies, on some new model calculations, and on interpretation of results of studies into the impact of gradual climate change. The review is structured around the UN's "WEHAB" sectors (**W**ater, **E**nergy, **H**ealth, **A**griculture and **B**iodiversity), with the addition of settlements and infrastructure. The world is divided into the six continents, with regional differences within continents emphasised where possible. Section 2 describes the scenarios for abrupt climate change used to assess potential impacts.

2. Scenarios for abrupt climate change

2.1 Collapse of the thermohaline circulation

Abrupt shifts in the thermohaline circulation in the North Atlantic have been implicated in many abrupt climate changes in the past (Clark et al., 2002), most significantly during around 12,700 years BP (the Younger Dryas) and at 8,200 years BP (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. A large input 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: temperatures across Europe could fall by around 3°C in little more than a decade (Vellinga & Wood, 2002). Inputs of freshwater have in the past come from catastrophic releases from ice-dammed lakes in North America during deglaciation, and these of course no longer exist. Other possible sources of freshwater include increased rainfall

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[1] Rapid sea level rise due to deglaciation of Greenland or West Antarctica are not considered in this report

over the Arctic and North Atlantic Oceans, increased runoff from rivers draining the Arctic, or accelerated melt of the Greenland ice sheet. The likelihood of the collapse of the thermohaline circulation during the coming century is currently very uncertain: it is not clear how close the circulation is to a threshold of collapse, and how much extra freshwater may become available. A survey of experts revealed subjective probabilities of between 0 and 30% for collapse by 2050, and between 5 and 75% for collapse by 2100 (Arnell et al., 2006); two subsequent model-based studies estimate likelihood of collapse by 2100 at around 45% (Schlesinger et al., 2006) and 30-40% (Challenor et al., 2006).

Most climate model simulations of climate in the 21st century show a slowdown in the thermohaline circulation, but not a collapse. Collapse within climate models can generally only be induced by artificially dumping large volumes of freshwater into the North Atlantic. Wood et al. (2003) used this approach and showed that collapse in 2050, following increasing greenhouse gas concentrations, would lead to temperatures across Europe falling to between 1 and 2°C below present values (after having risen by 1-2°C up to 2050). This scenario is not currently available in digital form. The indicative effects of a collapse of the thermohaline circulation are therefore based on adding the changes in climate with collapse but no climate change (available from Vellinga & Wood's (2002) simulation) to the changes in climate simulated by the same climate model (HadCM3) assuming the SRES A2 emissions scenario, assuming collapse in 2015, 2035 and 2055. This is inevitably an approximation, for three reasons. First, the effects of the two drivers of change are unlikely to be additive (although the patterns of change are similar to those reported in Wood et al., 2003). Second, the approach does not take into account the continuing increase in greenhouse gases after collapse. Third, the collapse scenario is based on an instantaneous influx of freshwater, rather than a gradual but prolonged increase. Also, different climate models would give a different spatial pattern of change.

Figure 1 shows the change in average annual temperature and average annual precipitation by the 2050s, under A2 emissions ("gradual" climate change), and A2 plus thermohaline circulation collapse in 2015 and 2035; Figure 2 shows the same for the 2080s, together with thermohaline circulation collapse in 2055. Figure 3 shows the change in annual temperature for six locations under each scenario, plus the average global land surface temperature change.

2.2 Accelerated climate change

The climate system is characterised by a large number of feedbacks, both positive and negative. Some are included within current climate simulation models, but others are only poorly understood. For example, higher temperatures may lead to increased emissions of methane from thawing permafrost or warmer sea beds (Ehhalt & Prather, 2001); higher temperatures could also increase the rate at which carbon is released from the soil (Knorr et al., 2005).

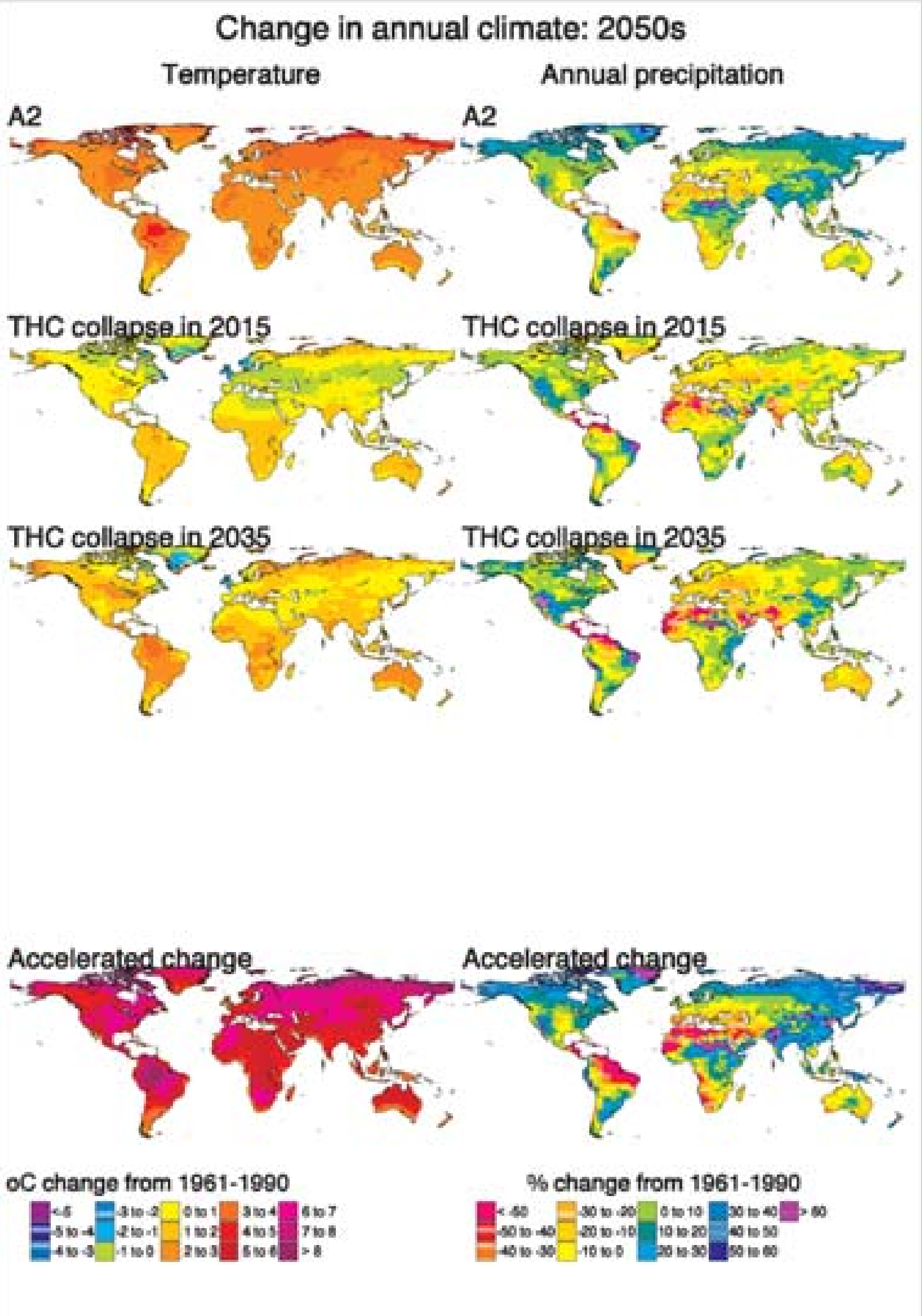

Figure 1: Change in average annual temperature and precipitation by the 2050s, under A2 emissions, thermohaline circulation collapse in 2015 and 2035, and accelerated climate change (based on HadCM3 climate model scenarios)

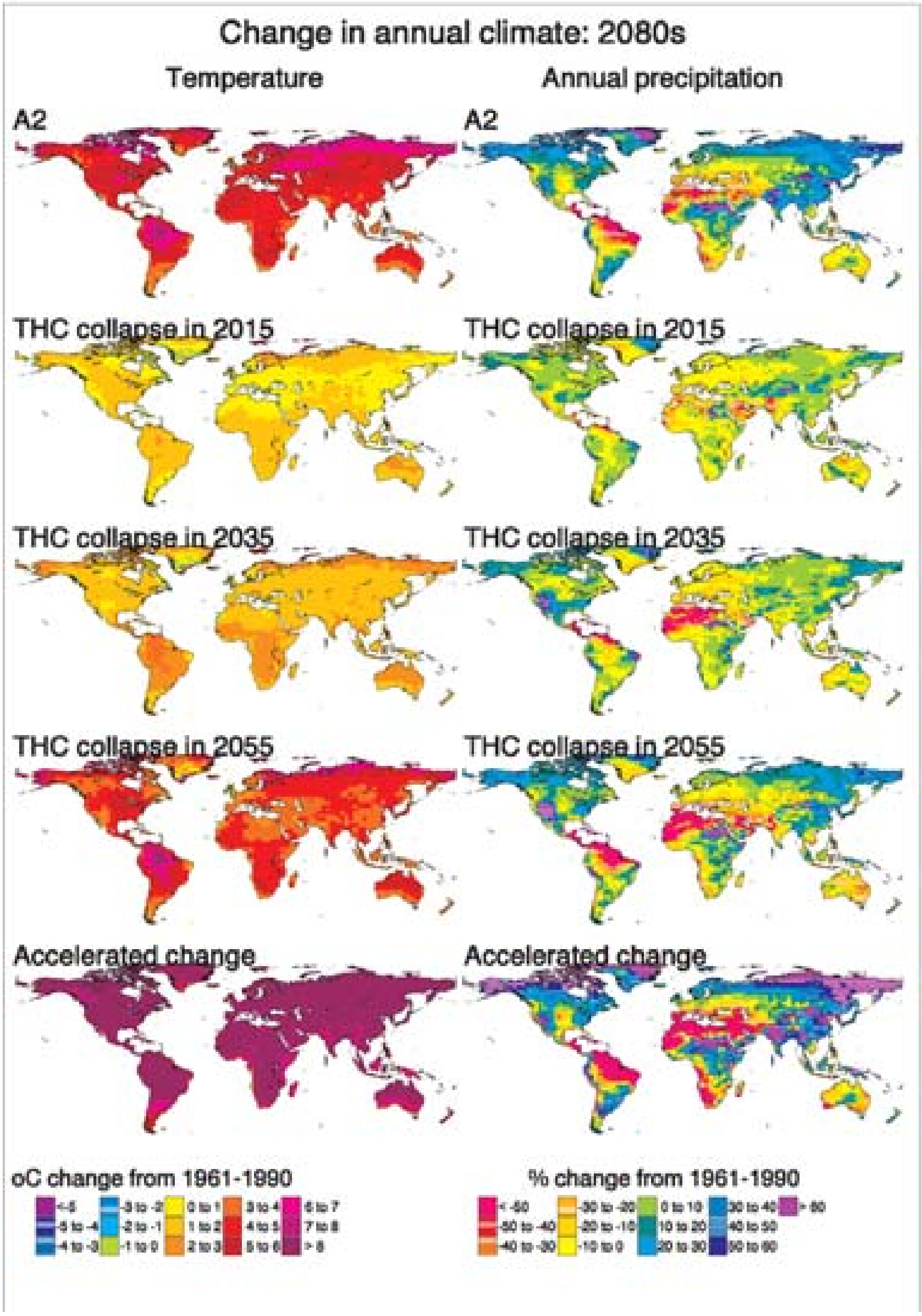

Figure 2: Change in average annual temperature and precipitation by the 2080s, under A2 emissions, thermohaline circulation collapse in 2015, 2035 and 2085, and accelerated climate change (based on HadCM3 climate model scenarios)

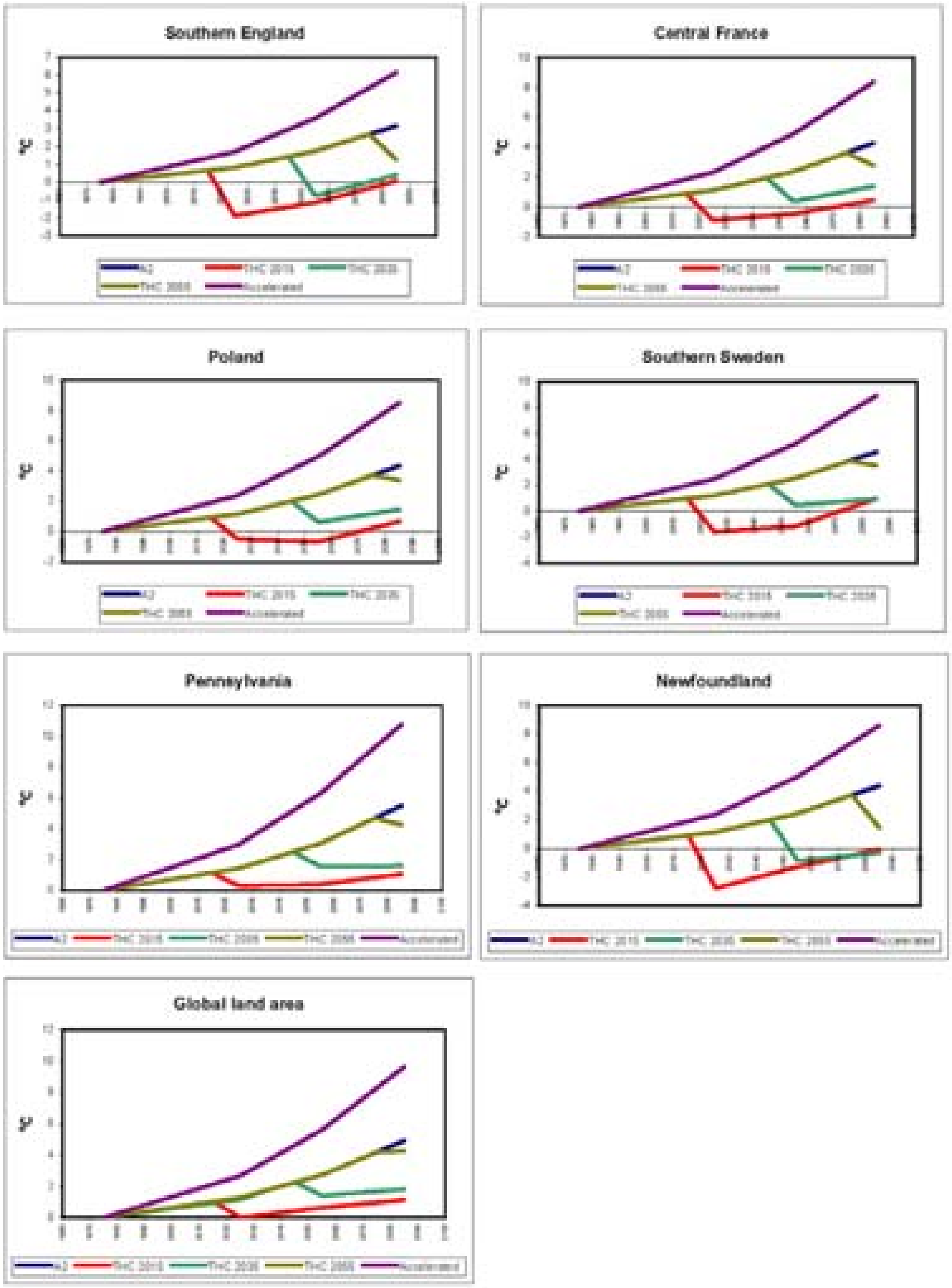

Figure 3: Change in average annual temperature under A2 emissions, thermohaline circulation collapse in 2015, 2035 and 2085, and accelerated climate change for six sample locations

An expert survey revealed subjective likelihoods between 1 and 20% that the rate of climate change would exceed 0.5°C/decade, with one outlier at 90% (Arnell et al., 2006). Simulations using simple models which incorporate some of the uncertainties suggest low likelihoods of high rates of change (Wigley & Raper, 2001; Webster et al., 2003); simulations using more complex models incorporating more uncertainties suggest higher likelihoods (a 4% chance that the warming following a doubling of CO_2 would exceed 8°C, for example (Stainforth et al. (2005)).

Accelerated climate change in the current study is characterised by simply rescaling the pattern of change simulated by the HadCM3 climate model with A2 emissions to represent a doubled rate of change. Specifically, this results in increases in global mean temperature, relative to the 1961-1990 mean, of 2°C by the 2020s, 4.2°C by the 2050s, and 7.2°C by the 2080s. The spatial patterns of change in temperature and precipitation under this accelerated change scenario are shown in Figures 1 and 2, and the rate of change at six locations summarised in Figure 3.

2.3 Regime change

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; the south and east Asian monsoons are weaker. Some climate models project shifts in modes of variability so that the climate switches to a "permanent El Nino" mode.

There are currently no numerical climate scenarios demonstrating "regime change". The approach adopted in this assessment was to calculate the composite precipitation anomaly from a number of years with anomalous behaviour, apply this anomaly to the 1961-1990 mean monthly precipitation, and assume that this altered precipitation pattern represented the long-term mean. Composite precipitation anomalies were extracted from the NCEP/NCAR global reanalysis output (http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl) for El Nino years (1958, 1966, 1969, 1973, 1983, 1987, 1992 and 1998, November to March only), wet South Asian monsoon (1956, 1970, 1973, 1978, 1990 and 1994, June to August only) and dry South Asian monsoon (1951, 1965, 1966, 1972, 1987 and 1999, June to August only) years.

Figure 4 shows the difference in annual precipitation from the 1961-1990 mean during a composite El Nino event (between 40°S and 40°N only), a permanent wet South Asian monsoon and a permanent dry South Asian monsoon. The South Asian monsoon maps show only the South Asian window, for the same reason: there is very little correlation between anomalous South Asian monsoon rainfall and rainfall in other parts of the world. *The scenarios describing regime changes are therefore to be treated with extreme caution.*

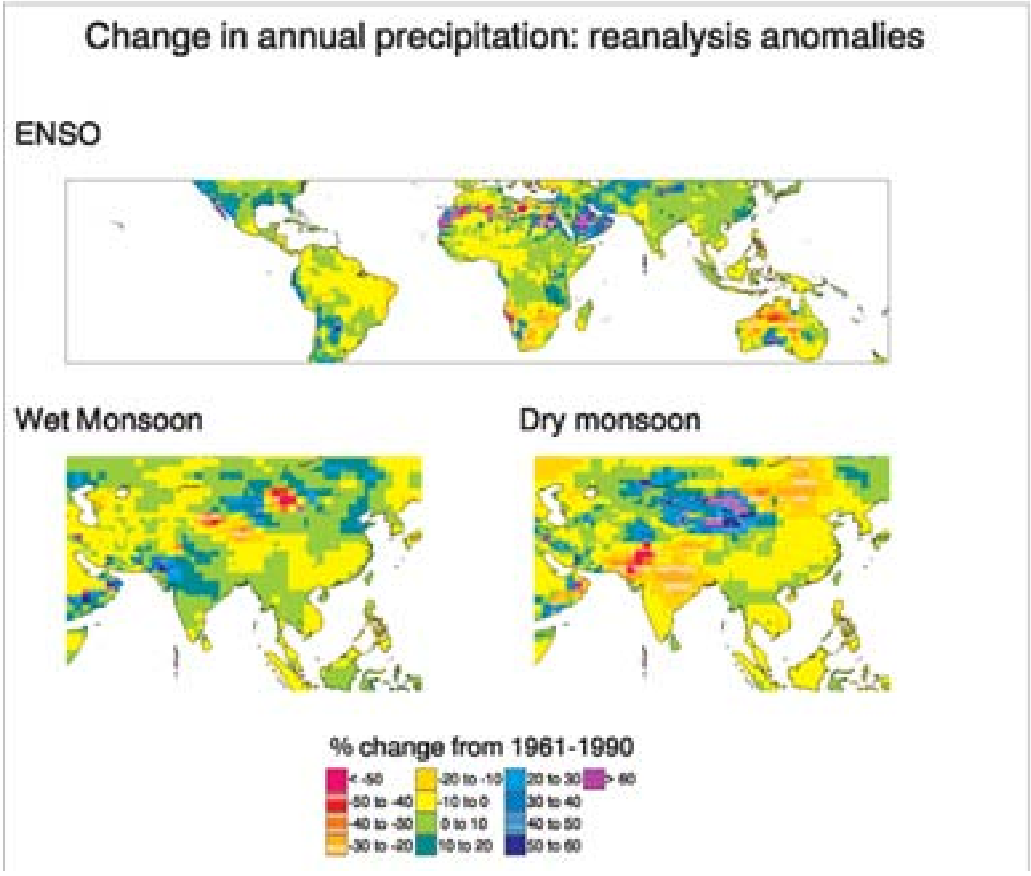

Figure 4: Change in average annual precipitation assuming permanent El Nino, a wet South Asian monsoon, and a dry South Asian monsoon.

3. Impacts of abrupt climate change

3.1 Introduction

The potential impacts of abrupt climate change are summarised by table for the WEHAB+ sectors in the following sections. Most of the analysis is qualitative – and necessarily speculative - based on interpretation of impact studies which have in most cases not considered explicitly the effects of abrupt climate change. In three sectors – water, energy and agriculture – some of the analysis is based on quantitative assessments carried out for the current study.

3.2 Water

The implications of the abrupt climate change scenarios for water resource availability were assessed for the current study using a macro-scale hydrological model to simulate runoff and by calculating indicators of water resources stress at the watershed scale (Arnell, 2004). A watershed is assumed to be exposed to water stress if it has less than $1000m^3$/capita/year (Falkenmark et al., 1989). The numbers of people living in watersheds exposed to an increase in water stress due to climate change is the sum of people living in watersheds that become stressed (availability falls below $1000m^3$/capita/year) due to climate change, and those living in already-stressed watersheds where climate change produces a significant decrease in runoff (greater than the standard deviation of long-term average annual runoff, which typically varies between 5 and 10% of average annual runoff). Climate change also increases runoff in some watersheds: in some stressed watersheds runoff increases significantly, and in some of these availability rises above $1000m^3$/capita/year. People living in these watersheds have an apparent decrease in water resources stress, but in practice the extra water may not alleviate water stress because it may occur largely during increased flood flows. It is therefore not appropriate to calculate the net numbers of people affected by changes in water stress. The indicator is not a perfect measure of actual climate change impact, as the ability of countries to cope with water stress varies.

Figure 5 shows the change in average annual runoff by 2055 and 2085 under A2 emissions, thermohaline circulation collapse, and accelerated climate change. A2 emissions (with the HadCM3 climate model) result in increased runoff in high latitudes, parts of the tropics, and south and east Asia; runoff decreases in many mid-latitude and dry regions. Thermohaline circulation collapse leads to further reductions in runoff across much of Europe, and smaller increases in runoff in high latitudes. It also appears to lead to reduced runoff across south and east Asia, although it is currently not clear whether this is an artefact of the way the scenarios were constructed (changes in rainfall in south and east Asia vary considerably between model runs, and the differences here may be due to model noise rather than climate change signal).

Table 1 summarises the numbers of people with an increase or decrease in water resources stress by 2055 and 2085, under the A2, thermohaline circulation and accelerated climate change scenarios. In the couple of decades after collapse, water resources stresses increase in Europe, East Asia and, particularly, South Asia (following the change in runoff), but relative increases in runoff in North America lead to smaller increases in stress. The numbers of people with a decrease in water stress appears to reduce significantly following thermohaline circulation collapse, due almost entirely to the reductions in runoff in South Asia. There are some indications that as climate recovers from an instantaneous thermohaline circulation collapse, then water resources scarcity is less than it would have been in the absence of collapse. In Europe, for example, 236 million people would be exposed to an increase in stress in 2085 under A2 emissions. Collapse in 2055 would increase this to 294 million, but if the collapse had occurred in 2035 the increase would only be 173 million.

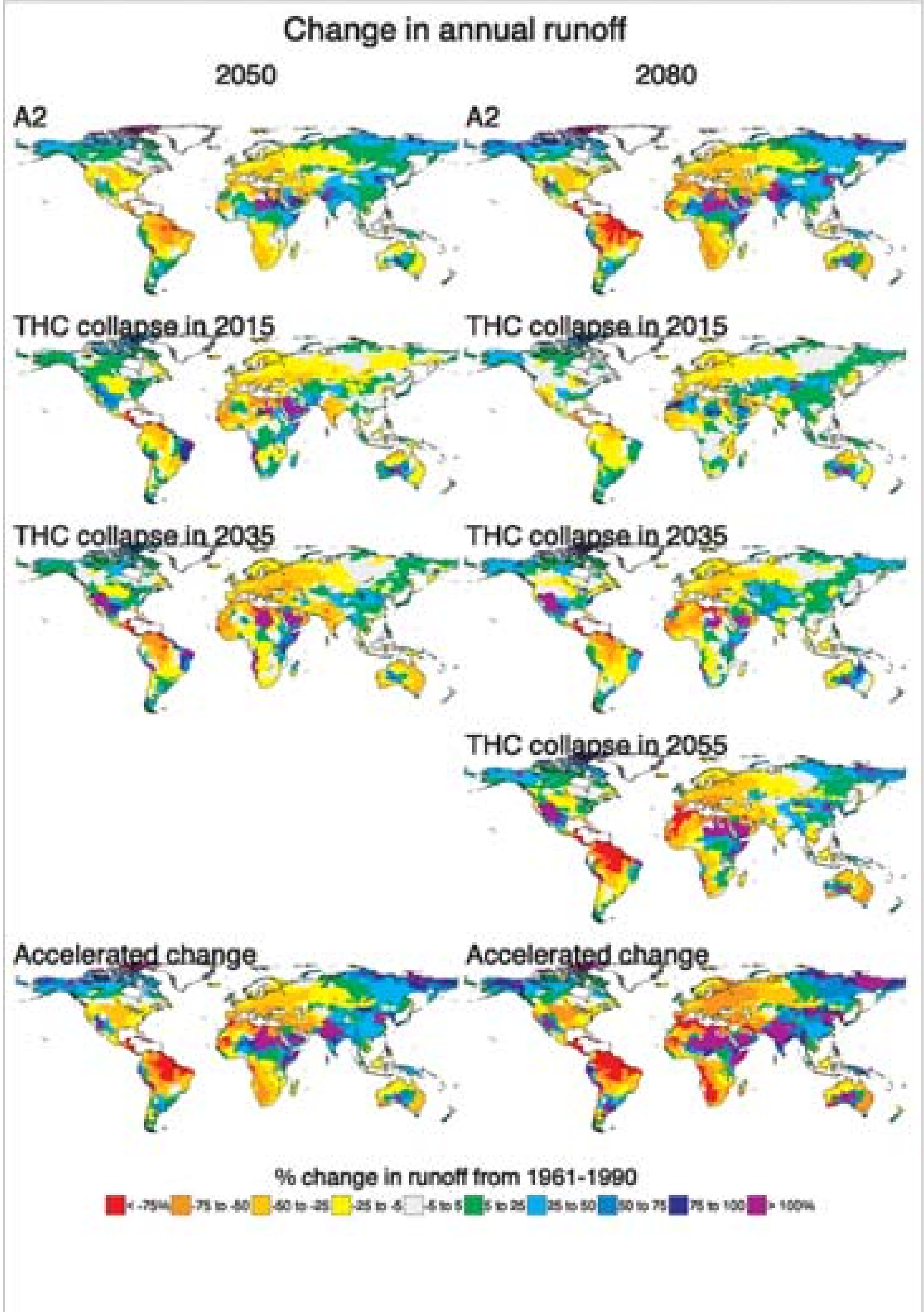

Figure 5: Change in average annual runoff by 2055 and 2085 under A2 emissions, accelerated climate change, and thermohaline circulation collapse in 2015, 2035 and 2055

Table 1: Regional effect of scenarios on exposure to water scarcity (millions of people with increase or decrease in water resources stress). The first column shows the numbers of people in stressed watersheds in the absence of climate change

	No climate change	A2		THC collapse in 2015		THC collapse in 2035		THC collapse in 2055		Accelerated change	
		Increase in stress	Decrease in stress	Increase in stress	Decrease in stress	Increase in stress	Decrease in stress	Increase in stress	Decrease in stress	Increase in stress	Decrease in stress
North Africa											
2055	270	268	3	263	3	266	1	-	-	272	3
2085	303	304	3	195	8	302	1	252	57	305	3
West Africa											
2055	137	49	81	98	49	99	40	-	-	89	75
2085	135	86	73	104	1	108	49	114	32	155	73
South and East Africa											
2055	192	69	134	14	131	13	178.	-	-	81	134
2085	151	79	83	109	45	17	127	18	90	79	85
South Asia											
2055	1664	107	1511	1441	75	1686	210	-	-	139	1547
2085	1433	149	1302	767	231	202	401	787	153	151	1303
East Asia											
2055	665	1	607	57	167	98	540	-	-	0	609
2085	429	0	379	31	219	11	360	0	376	0	379
Australasia											
2055	0	0	0	0	0	0	0	-	-	0	0
2085	0	0	0	0	0	0	0	0	0	0	0
Europe											
2055	176	210	0	176	0	278	0	-	-	304	2
2085	148	236	2	189	29	173	8	295	2	333	2
Central Asia											
2055	11	15	0	4	6	18	2	-	-	27	0
2085	9	22	0	1	8	1	6	23	0	27	0
North America											
2055	85	66	6	22	25	24	38	-	-	87	6
2085	96	84	7	43	8	4	15	27	61	102	35
Caribbean											
2055	0	21	0	26	0	36	0	-	-	36	0
2085	0	34	0	20	0	24	0	35	0	35	0
Central America											
2055	58	34	26	81	26	92	26	-	-	101	3
2085	33	65	3	32	0	69	6	83	3	95	5
South America											
2055	6	46	6	33	6	33	6	-	-	63	6
2085	6	58	6	14	5	33	4	31	6	73	6
West Asia											
2055	322	118	177	61	208	118	177	-	-	124	158
2085	319	131	145	9	206	92	156	131	154	131	149
Global											
2055	3586	1004	2551	2277	696	2762	1218	-	-	1323	2543
2085	3061	1248	2002	1515	750	1037	1133	1795	934	1485	2039

A1/B1 population scenario assumed

Accelerated climate change increases the numbers of people with an increase in water resources stress by 2055 from around 1 billion to approximately 1.3 billion, with most of the increase occurring in Europe, North and Central America, and West Africa. Accelerated change has relatively little effect on the numbers of people with an apparent decrease in water resources stress.

Both thermohaline circulation collapse and accelerated climate change not only alter the annual volume of runoff, but in large regions change the timing of streamflow through the year – and this change in timing can have very significant impacts on resource availability and reliability. Thermohaline circulation collapse, for example, would mean more winter precipitation falling as snow in maritime western Europe, and runoff delayed until the snow melts in spring. Accelerated climate change, on the other hand, would lead to a shift in the timing of peak flows from spring to winter in areas where winter precipitation currently falls as snow (eastern Europe, and large parts of North America, for example), and the effective loss of a large free reservoir.

Figure 6 shows the effect of a permanent regime shift on average annual runoff (assuming no climate change). A permanent El Nino would decrease average annual runoff in southern Africa and north east Brasil, but increase average annual runoff in southern parts of North America, western South America, east Africa and (slightly) southern Asia. Permanent wet or dry monsoons have clear effects on runoff in south Asia.

Table 2 shows the effect of regime shift on the numbers of people with an increase or decrease in water resources stress in 2055, for selected regions. In each case, the table shows the effect compared to the 1961-1990 climate of (i) the regime shift rainfall anomaly and current temperature, (ii) the regime shift rainfall anomaly with 2050s A2 temperature, and (iii) A2 rainfall and temperature change.

Table 2: Millions of people exposed to change in water resources stress by 2055: regime shift

	Precipitation anomaly plus 1961-1990 temperature		Precipitation anomaly plus 2050 A2 temperature		2050 A2 temperature and precipitation	
	Increase in stress	Decrease in stress	Increase in stress	Decrease in stress	Increase in stress	Decrease in stress
Permanent El Nino						
South America	0	6	0	6	46	6
Central America	0	58	29	6	34	26
North America	7	28	62	28	66	6
South and East Africa	8	160	75	100	69	134
South Asia	0	1549	6	1450	106	1511
East Asia	0	642	85	86	1	607
Permanent dry monsoon						
South Asia	880	467	888	444	107	1511
East Asia	126	194	383	27	1	607
Permanent wet monsoon						
South Asia	0	1555	5	1449	107	1511
East Asia	0	567	85	86	1	607

A permanent El Nino has minimal effect on populations exposed to an increase in water stress, but by generating (slightly) more runoff in South and East Asia means that large numbers of people would see an apparent reduction in stress. A permanent dry monsoon would obviously increase substantially the numbers of people with an increase in water stress in south and east Asia (adding approximately 1 billion people in 2050); a permanent wet monsoon would mean that approximately 2 billion people in 2050 would experience an apparent decrease in water stress.

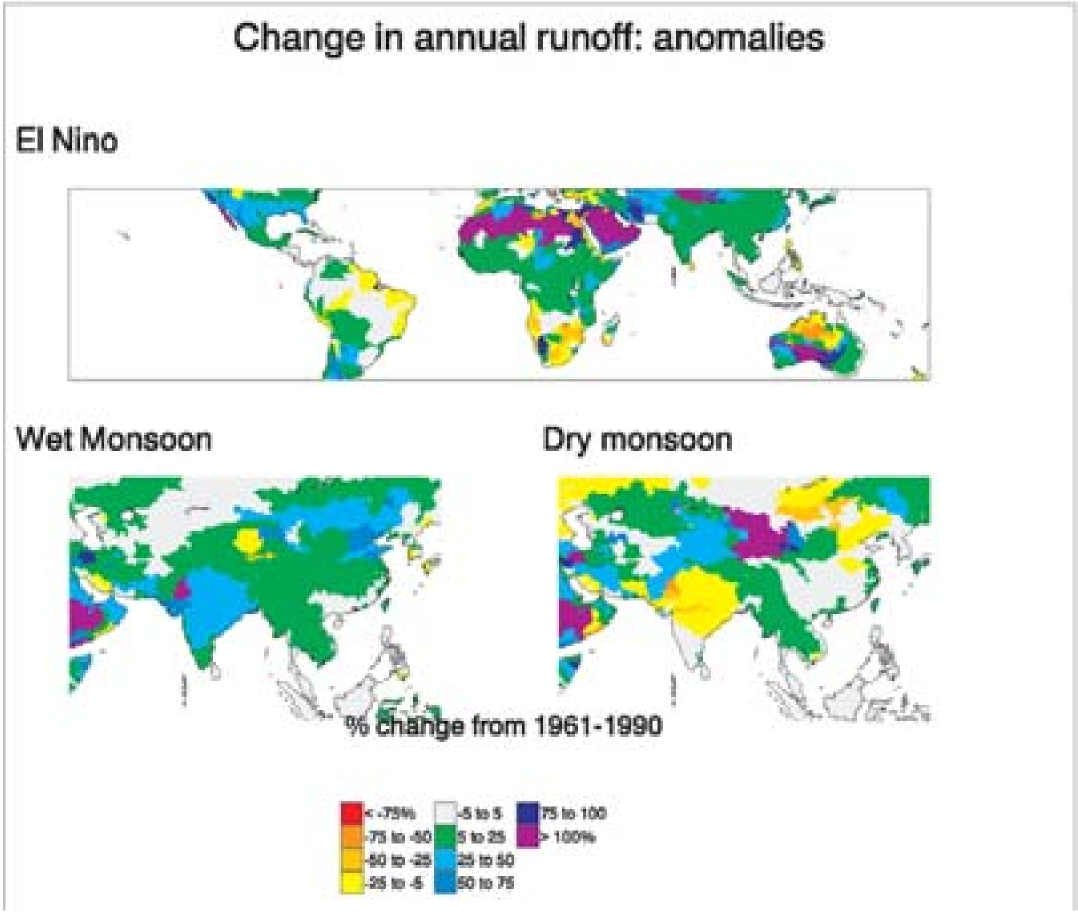

Figure 6: Effect of regime change (precipitation only) on average annual runoff

Table 3 summarises impacts of abrupt climate change on water resources by continent, based on the changes in runoff shown in Figure 5.

Table 3: Summary water resources impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Increased flood risk in north, and increased drought risk in south, coupled with increases in demand for irrigation. Reduced navigation opportunities due to lower flows. Shift towards winter maximum alters ability to generate hydropower; lower summer flows reduces availability of cooling water	Increase in drought potential across most of Europe (perhaps offset by reduced irrigation demand). Water stored as snow over winter and released in spring snowmelt; increase spring flood risk and altered navigation and power generation opportunities. Increased icing of rivers and lakes.	Substantial increases in drought risk across most of Europe, coupled with increases in demand. Reduced navigation opportunities. Virtual elimination of snowmelt changes significantly power generation potential. Lower summer flows reduces availability of cooling water	
North America	Increased drought risk across much of central and east coast regions. Shift from spring to winter maxima reduces water available for irrigation in summer in central and western regions. Reduction in navigation opportunities.	Increases in runoff in east and west lead to increases in flood risk, but reduce drought risk. Increased drought risk in centre. Shift from winter to spring maxima across much of continent alters timing of flood risk and reduces winter navigation opportunities. Increase icing of rivers and lakes.	Increased drought risk across much of north America. Virtual elimination of spring snowmelt leads to major reductions in availability of water for summer irrigation. Reductions in navigation potential along major rivers. Reduced flood risk.	Permanent El Nino leads to increased risk of flooding in western US
South America	Reductions in runoff across much of continent lead to increased drought risk and reductions in hydropower generation potential; more resources (and power generation potential) available in south, but increased flood risk.	Increased drought risk and reduced power generation across much of continent, but reduced drought risk in eastern Brasil.	Major increase in drought risk and reduction in power generation potential across much of continent; more resources (and generation potential) in south.	Permanent El Nino leads to increased risk of flooding in southern continent, and increase in drought risk in north east Brasil
Asia	Increase in flood risk in south and east Asia; increased drought risk in central Asia and Middle East. Shift from spring to winter maximum in northern parts of region alter hydropower generation potential.	Small changes in runoff, and hence flood and drought risk, across much of Asia in decades after collapse. Increase in drought risk in southern Asia.	Large potential increase in flood risk in south and east Asia, and substantial increase in drought risk in central Asia and Middle East. Elimination of spring peak across much of region reduces availability of water for irrigation and power generation	Increase in flood risk across south Asia under permanent wet monsoon; increase in drought risk under permanent dry monsoon. Increased flood risk in east Asia under permanent El Nino; increased drought risk in south east Asia.
Africa	Increase in runoff in east Africa lessens drought risk, but drought risk increased in rest of continent.	Smaller changes in runoff than under A2 emissions, and therefore smaller changes in regional flood and drought risk	Increase in flood risk from east Africa; major increase in drought risk across most of rest of continent.	Increased drought risk in southern Africa under permanent El Nino.
Australasia	Increase in drought risk across most of region	Little different from A2 emissions	Major increase in drought risk across most of region	Increased drought risk under permanent El Nino

4. Energy

Virtually all of the literature on future energy demand is concerned with the effects of different economic growth rates, the 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, calculated with respect to a base "comfort" temperature (widely taken to be 18°C (65°F)). Figure 7 shows the (indicative) change in HDD and CDD by the 2050s, under the A2 emissions scenario, thermohaline circulation collapse, and accelerated climate change. HDD is calculated from daily mean temperature T_i simply as:

$$HDD = \Sigma\,(18 - T_i) \qquad \text{where } T_i \text{ is less than } 18^{o}C$$

CDD is calculated from:

$$CDD = \Sigma\,(T_i - 18) \qquad \text{where } T_i \text{ is greater than } 18\,^{o}C$$

Regional demand for energy for heating and cooling can be estimated by calculating population-weighted regional heating or cooling degree days, where the regional average HDD or CDD total is calculated by weighting each cell's HDD or CDD by relative cell population. Population-weighted regional HDDs and CDDs have been shown to be related to regional energy consumption (Diaz & Quayle, 1980), although the precise link between HDDs/CDDs and energy consumption will depend on the energy sources used and energy efficiency. Figure 8 shows percentage change in population-weighted regional HDDs and CDDs for the 2050s and 2080s, compared to the 1961-1990 baseline.

Gradual climate change reduces the demands for heating by at least 25% in Europe and North America by the 2050s, and by more in warm regions; accelerated climate change has an every greater effect. Thermohaline circulation collapse (superimposed on warming) would lead to large increases in heating demand relative to the situation immediately before collapse, bringing demands back to levels expected in the absence of climate change in Europe, North America and large parts of Asia, although has little effect on the gradual climate change-induced reductions in heating requirements in warm areas.

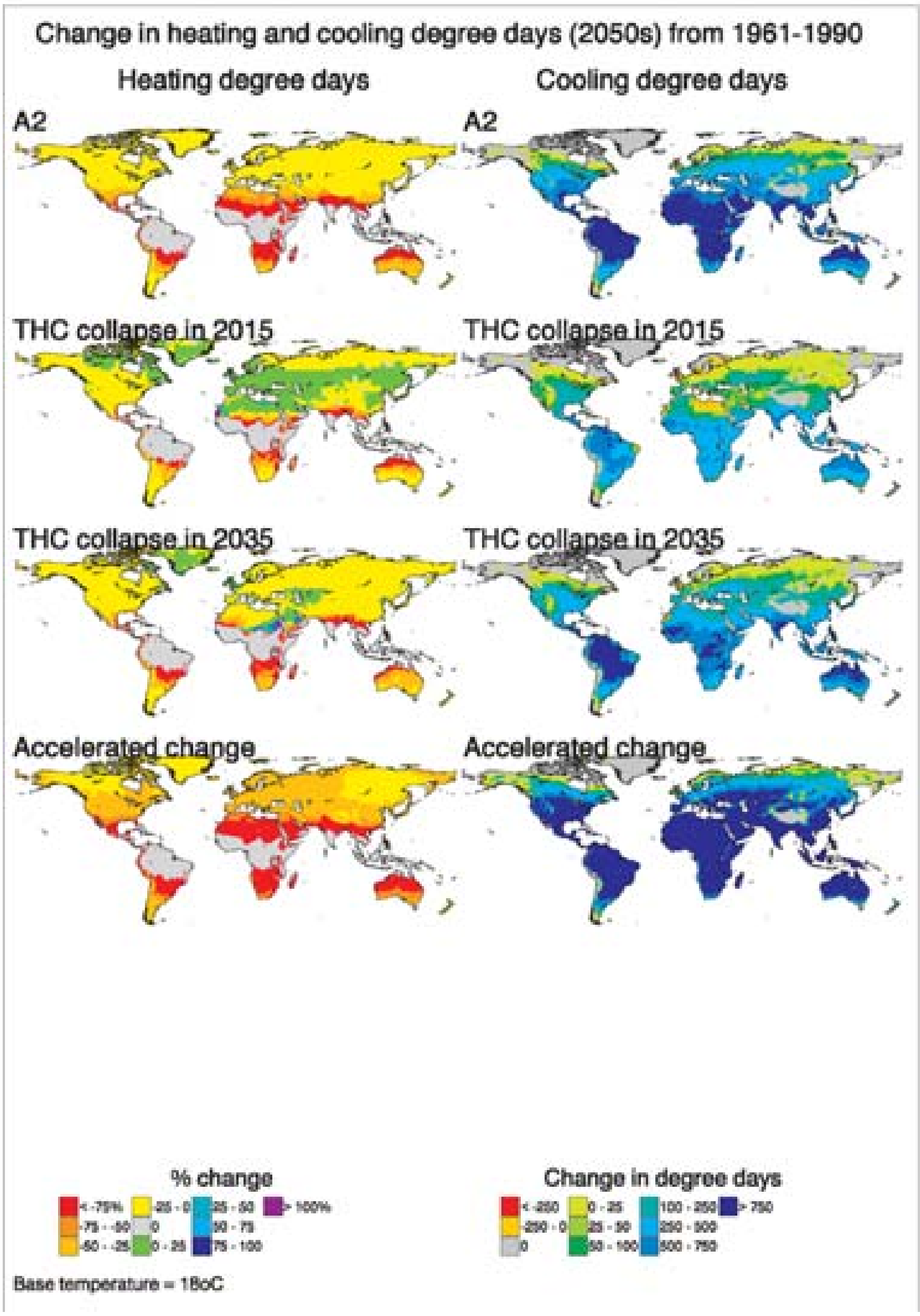

Figure 7: Change in heating and cooling requirements by 2055

Gradual climate change increases cooling demands by very large percentages – 150% by 2050 in Europe and 80% in North America – and accelerated climate change increases these percentages still more. Thermohaline circulation collapse ameliorates substantially these increases in cooling demands, particularly in Europe and North America.

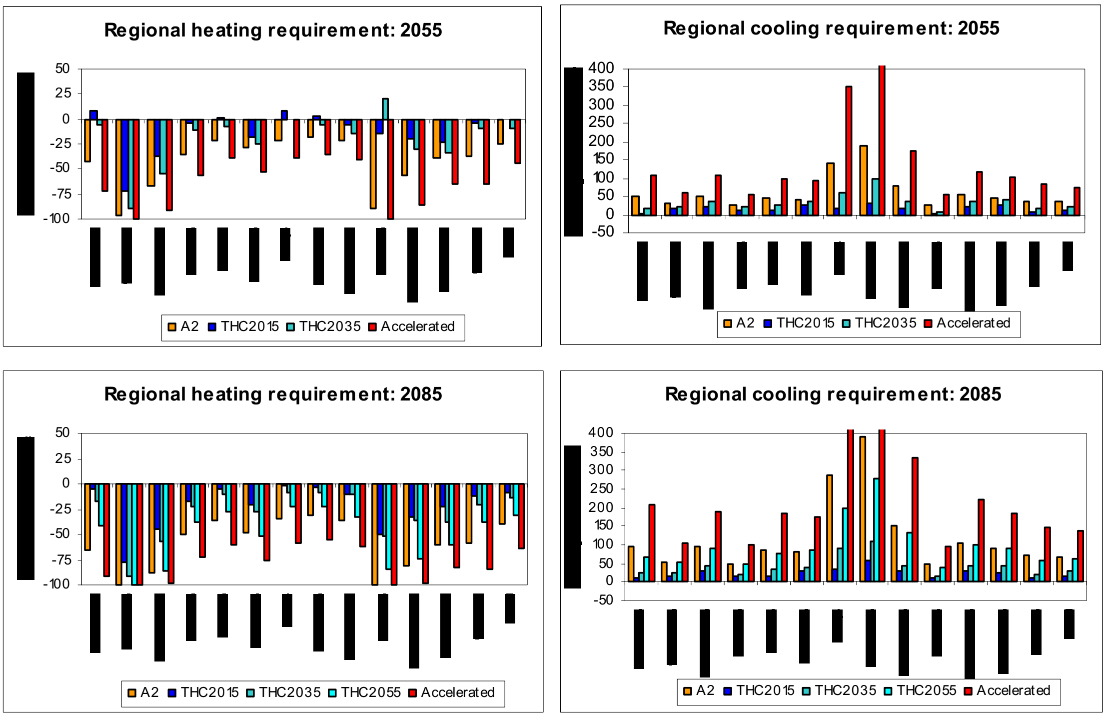

Figure 8: Change in regional heating and cooling energy requirements, by 2055 and 2085

Climate change has five broad impacts on energy *production*: it affects the viability of renewable resources, energy from biomass schemes, the availability of cooling water, the extraction of offshore oil and gas, and the physical infrastructure associated with production and transmission of energy.

The key renewable resources affected by climate change are hydropower (affected by the volume and timing of river flows) and wind. Scenarios for change in wind are highly uncertain, so it is not possible to project changes in wind generation potential. The viability of energy from biomass depends on biomass productivity, which for the species most frequently used depends on temperature through the year and, particularly, the length of the growing season. Thermal power generation (whether fossil or nuclear) requires cooling water from rivers or the sea; changing river flows (and water temperatures) will affect reliability of access to cooling water. Both the extraction of offshore oil and gas and, more generally, infrastructure involved in the production and distribution of energy are exposed to changes in extreme climatic events, such as the occurrence of ice storms.

Table 4: Summary energy sector impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Increase in summer cooling requirements and reduction in heating requirements; reduction in hydropower potential in many regions, and reduction in availability of cooling water in summer	Increase in winter heating requirements; reduction in hydropower potential in many regions, and reduction in availability of cooling water. Increased disruption from ice storms	Very large increases in summer cooling requirements and reductions in winter heating requirements; major reductions in hydropower potential and reduction in availability of cooling water	
North America	Increase in summer cooling requirements, reduction in winter heating requirement; reduction in hydropower potential in west; reduction in availability of cooling water	Small increases in summer cooling requirements; increases in winter heating requirements in north east. Small change in hydropower potential; increased disruption from ice storms in east	Very large increases in summer cooling requirements, majr reduction in winter heating requirements. Reduction in hydropower potential in west, and availability of cooling water in east.	Permanent El Nino: potential for increase in hydropower potential in south west; reduction in north west
South America	Reduction in heating requirements in south; large increase in cooling requirements across continent. Reduction in hydropower generation potential in north; increase in south	Little difference from A2 emissions	Major reduction in heating requirements in south; very large increase in cooling requirements across continent. Reduction in hydropower generation potential in north; increase in south	Permanent El Nino: potential for increase in hydropower potential in west
Asia	Reduction in heating requirements in China; large increase in cooling requirements. Increase in hydropower potential in China	Increase in heating requirements in China; increase in cooling requirements in south and east Asia. Increased runoff leads to greater hydropower potential in China.	Manor reduction in heating requirements in China; large increase in cooling requirements. Increase in hydropower potential in China	
Africa	Reduction in heating requirements; increase in cooling requirements. Increased hydropower potential in East Africa, reduced potential in southern Africa	Increase in heating requirements in north Africa, reduction elsewhere coupled with increase in cooling requirements. Increased hydropower potential in East Africa, reduced potential in southern Africa	Virtual elimination of heating demands; major increase in cooling demands. Increased hydropower potential in East Africa, reduced potential in southern Africa	
Australasia	Reduced heating requirements; increase in cooling needs. Reduced hydropower potential.	As A2 emissions	Virtual elimination of heating requirements; major increase in cooling needs. Reduced hydropower potential.	Reduced hydropower potential under permanent El Nino

5. Health

5.1 Thermal effects on health

Both cold and hot spells lead to an increase in mortality, through exacerbation of respiratory and circulatory problems, with effects depending on climatic conditions and degree of acclimatisation and adaptation. In northern Europe, for example, excess mortality is greater in winter than in summer, whilst in southern Europe most heat-related deaths occur during hot spells in summer. Increased mortality in summer in northern Europe under higher temperatures would therefore be offset to a large degree by reduced mortality in winter; in contrast, higher temperatures in southern Europe would result in increases in summer mortality far greater than reductions in winter mortality.

Table 5: Summary health sector impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Increased summer mortality across Europe; reduced winter mortality in northern Europe. Increased potential for many disease burdens, but controlled through public health policies	Major increase in winter mortality across Europe, with reduction in summer mortality. General reduction in transmission potential for most major climate-sensitive diseases.	Major increases in summer mortality across Europe, and large decreases in winter mortality in the north. Increased potential for many disease burdens, but controlled through public health policies	
North America	Increased summer mortality across continent, offset by reduced winter mortality in the north. Increased potential for many disease burdens, but controlled through public health policies	Slight increase in winter mortality in north and east, and small decrease in summer mortality (relative to A2) in first few decades. Small change in transmission potential.	Large increase in summer mortality across continent, offset by reduced winter mortality in the north. Increased potential for many disease burdens, but controlled through public health policies	
South America	Increased hot-season mortality, and increased potential for disease transmission across much of continent.	Reduction in hot-season mortality, compared to A2 emissions.	Increased hot-season mortality, and increased potential for disease transmission across much of continent.	Permanent El Nino: Increase in flood-related ill-health in west
Asia	Increased hot-season mortality, and increased potential for disease transmission. Increased risk of flood-related ill-health.	Low increase in hot-season mortality and flood-related ill-health, compared to A2 emissions	Major increase in hot-season mortality, and increased potential for disease transmission. Big increased in risk of flood-related ill-health.	Permanent El Nino: increase in drought-related ill-health and mortality Permanent wet monsoon: Increase in flood-related ill-health in south and east Permanent dry monsoon: increase in drought-related ill-health and mortality
Africa	Increased hot-season mortality, and increased potential for disease transmission	Similar to A2 emissions	Increased hot-season mortality, and increased potential for disease transmission	Permanent El Nino: increase in drought-related ill-health and mortality in south and east
Australasia	Increased hot-season mortality, and increased potential for disease transmission	Similar to A2 emissions	Increased hot-season mortality, and increased potential for disease transmission	

5.2 Disease and ill-health

Climate change can alter the burden of ill-health through changes in the distribution of disease vectors and the frequency of extreme events (particularly floods). Many disease vectors are insensitive to climate, and so climate change has no obvious effect. Other vectors do have climatic limitations, however, which vary between vectors; some are limited by high temperatures, but most are limited by low temperatures. The precise effects of a change in disease transmission potential are heavily determined by the quality of public health measures in place.

6. Agriculture

6.1 Agricultural productivity

The effects of climate change on crop productivity depend on changes in the seasonal timing of temperature and water availability, changes in CO_2 concentrations, and changes in the prevalence of pests and diseases. As a general rule, crop productivity increases where higher temperatures lead to a longer growing season (at the poleward limits of cultivation of a particular crop), and decreases where higher temperatures increase heat stress and water shortage (at the equator-ward limits of cultivation). Equatorial and tropical regions where crop growth is currently temperature-limited (or water-limited) are therefore likely to experience the greatest reductions in productivity. Increased heat stress during extreme events can also reduce productivity in temperate regions, and effects on pests and disease depend on local climatic limits. Increases in CO_2 concentration tend to increase productivity of most key food crops, with effects depending on interactions with changes in temperature, water availability and nutrient status.

Figure 9 gives an indication of changes in the broad geographic extent of crop suitability (based on growing degree days and the ratio of actual to potential evaporation: Ramankutty et al., 2002) under the scenarios considered. The pattern appears generally robust, but patterns for individual crops would show greater variability with climate. The regime change scenarios resulted in the same changes in crop suitability as the A2 emissions scenario.

6.2 Global food production and risk of hunger

Global food prices are related to global production, and (for non-subsistence crops at least) may not bear much relation to changes in local productivity. Gradual climate change results in a general shift in world food production to higher latitudes, with increases in production of cereals in developed countries possibly compensating to a degree for reductions in production in developing countries (Parry et al., 2004). However, crop prices would rise under most scenarios, leading to an increase in risk of hunger, particularly in Africa – although the effect depends on how global food markets operate in the future.

Accelerated climate change would exaggerate this pattern, leading to greater increases in food prices. Thermohaline circulation collapse would lead to reductions in production in high latitudes, again leading to an increase in food prices.

6.3 Forest products

As with agricultural products, the effects of climate change depend on changes in the growing season, water availability and the prevalence of pests and diseases. With rising temperatures, potential productivity will increase at the poleward limits of forest growth – although actual poleward expansion may be limited due to a slow rate of migration – and will decrease at the warm margins due to heat stress, increased fire risk and water stress. Under very high rates of change, commercial tropical forest productivity would be reduced by heat stress and water shortages.

Table 5: Summary agriculture sector impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Decline in crop productivity in south; increase for some crops in north. Decline in forest productivity in south, and potential for increase in north	Decline in crop and forest productivity across Europe	Major decline in crop productivity in south, and substantial increases in north. Decline in forest productivity in south, and potential for increase in north	
North America	Decline in crop productivity in parts of mid-west due to increased drought; higher productivity in north	Similar effects to A2 emissions	Reduction in crop productivity in mid-west, and increase in north	
South America	Decline in crop productivity due to higher temperatures, with major decline in north east Brasil.	Similar effects to A2 emissions	Large decline in crop productivity due to higher temperatures, with widespread reduction in crop production in north east Brasil.	Permanent El Nino: reduction in coastal fishery productivity
Asia	Widespread reduction in crop productivity, with major decreases in central Asia; potential for increase in farmed area in east Asia	Reduction in crop productivity in south east Asia due to reduction in monsoon	Widespread reduction in crop productivity, with major decreases in central Asia; potential for increase in farmed area in east Asia	Permanent El Nino: reduced agricultural productivity in south and east Permanent dry monsoon: reduced agricultural productivity, and decline in soil fertility Permanent wet monsoon: increased risk of crop loss in floods
Africa	General reduction in crop productivity, with major reductions in south; increase in numbers of people at risk of hunger	Similar effects to A2 emissions	General large reduction in crop productivity, with very major reductions in south; large increase in numbers of people at risk of hunger	Permanent El Nino: reduced agricultural productivity in south and east
Australasia	Decrease in crop productivity in parts of Australia	Similar effects to A2 emissions	Decrease in crop productivity in parts of Australia	Permanent El Nino: reduced agricultural productivity

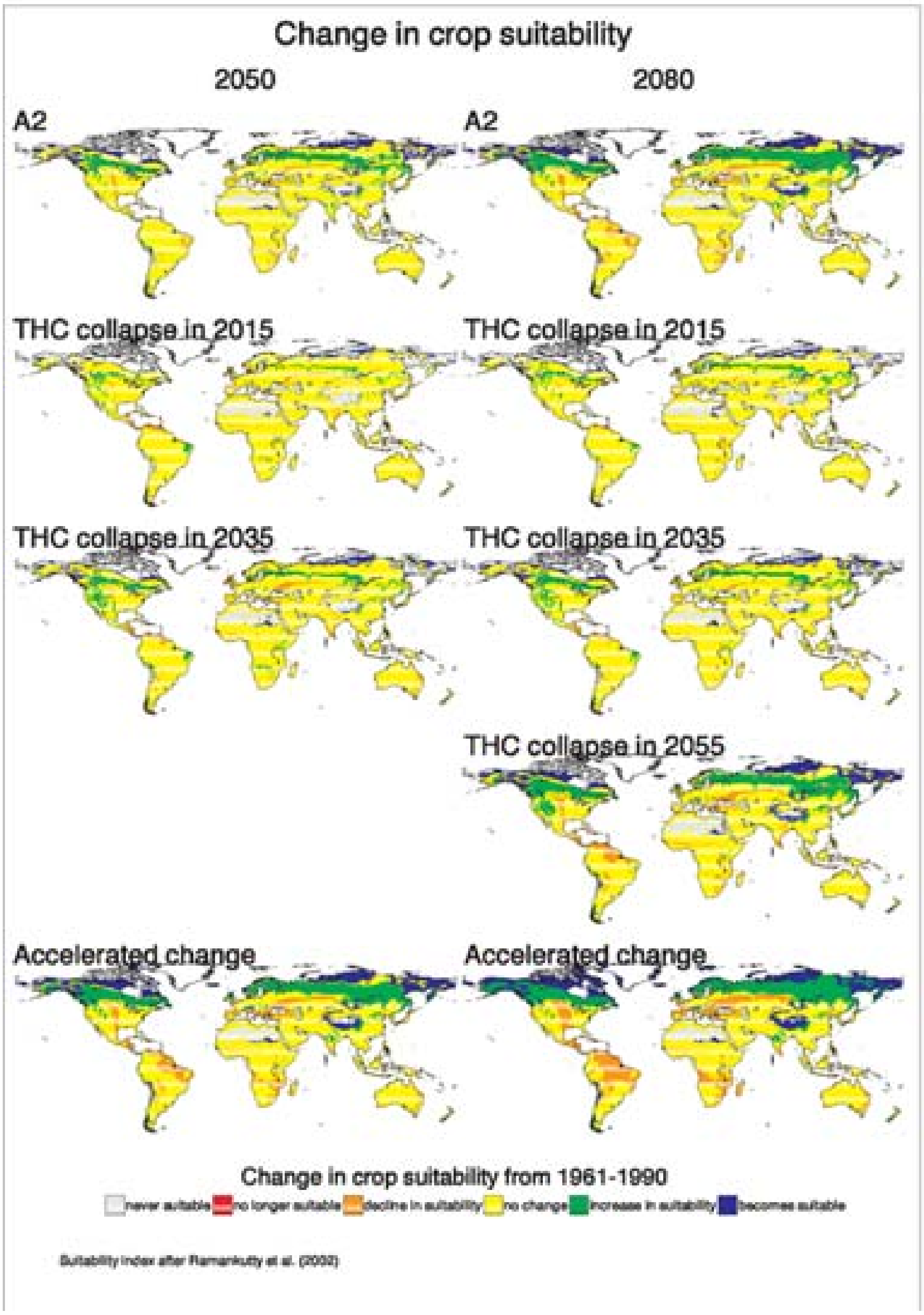

Figure 9: Crop suitability change

7. Biodiversity

Climate change will have an effect on biodiversity through changing potential ecosystem types in an area, and by changing species composition and abundance within an ecosystem type. As a general rule, the most sensitive ecosystem types or species are those at the climatic limits of their distributions or with the most specialised requirements. Biodiversity, however, is challenged not only by climate change, but also by other pressures such as land cover change, urbanisation and pollution, and large parts of the land surface are heavily modified by human actions: these actions and pressures may offset, or exaggerate, the effects of climate change.

A number of studies have examined the regional and global-scale implications of climate scenarios for ecosystem type or characteristics such as net primary productivity (e.g. Levy et al., 2004; Leemans & Eickhout, 2004; Bakkenes et al., 2006). In the most general terms, climate change leads to a poleward or upward shift in many ecosystems; boreal forests would replace tundra, and temperature forests replace boreal forests. However, ecosystems (particularly forested ecosystems) cannot adjust at rates greater than around 0.05^{o}C/decade, so extensive migration polewards is unlikely. Where high temperatures are not limiting factors – in subtropical and tropical regions – the impacts of climate change will depend on changes in precipitation. Increased drought (and attendant water shortage and increased fire risk) makes ecosystems around the Mediterranean, for example, vulnerable to climate change, and under some climate simulations reductions in rainfall in the Amazon basin in particular lead to major dieback of rain forest (Levy et al., 2004).

At the finer species scale, a number of studies (e.g. Bakkenes et al., 2002; Thomas et al., 2002; Thuiller et al., 2005) have demonstrated large changes in abundance with rising temperatures and changing water availability for many species: approximately a third of all plant species present in a given location in Europe could disappear from that location by the middle of the 21st century under gradual climate change (Bakkenes et al., 2002).

Accelerated climate change would obviously increase significantly the risk of ecosystem or biodiversity change – but no studies have yet examined the effects of very high rates of change. Thermohaline circulation collapse would lead to large but opposite changes in ecosystem characteristics (Higgins & Vellinga, 2004; Higgins & Schneider, 2005). Across Europe and eastern North America these changes would be largely temperature-driven, with the southward movement of boreal forest into the temperate forest zone (e.g. in England: Higgins & Schneider, 2005). The precise effects, however, depend not only on the degree of cooling, but its distribution through the year. Many ecosystems can cope with lower temperatures during winter, when they are largely dormant, but substantial reductions in spring and summer temperatures would have much greater adverse impacts. Across the rest of the world ecosystem characteristics would be affected by the rainfall changes associated with thermohaline circulation collapse (Higgins & Vellinga, 2004: see

Figures 1 and 2). Similarly, the primary effects of regime change on biodiversity will be through changes in precipitation volume and timing.

Palaeoecological evidence (e.g. Tinner & Lotter, 2001; Williams et al., 2002 in Europe) shows substantial changes in vegetation composition following short-duration climatic shifts during the Holocene, and specifically in response to previous cooling events.

Table 6: Summary biodiversity sector impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Northward shift in ecosystems; increased fire and drought damage in southern Europe	Southward shift in ecosystems, with expansion of boreal forests.	Major northward shift in ecosystems, and increase in fire and drought damage. Loss of high-altitude ecosystems. Major loss of species diversity	
North America	Northward shift in ecosystems; expansion of desert areas in south west.	Southward encroachment of boreal forest in east; expansion of forest species into central grasslands	Major northward shift in ecosystems; loss of high altitude ecosystems. Large increase in desert extent	Permanent El Nino: increase in forest productivity in west
South America	Change in precipitation leads to decline in forest cover; risk of desertification in south	Reduced rainfall threatens forest ecosystems in particular	Risk of major forest decline due to reductions in rainfall; increased desertification in south	Permanent El Nino: reduced productivity in parts of east with reduced rainfall; increased forest productivity in west. Reduced productivity of Pacific fisheries
Asia	Northward shift of boreal forest in high latitudes; increased ecosystem productivity in south and east Asia; decline in productivity of central Asian grasslands	Southward encroachment of boreal forest in north. Smaller increase in ecosystem productivity in south and east than under A2 emissions	Major northward shift of boreal forest in high latitudes; increased ecosystem productivity in south and east Asia; decline in productivity of central Asian grasslands	Permanent El Nino: decline in tropical forest in south and east Asia; Permanent dry monsoon: decline in forest and grassland productivity in south Asia Permanent wet monsoon: increase in forest and

				grassland productivity in south Asia
Africa	Increased forest productivity in tropical regions and east; lower rainfall results in ecosystem degradation in west and south	Similar to A2 emissions	Increased forest productivity in tropical regions and east; lower rainfall results in ecosystem degradation in west and south	Permanent El Nino: reduction in ecosystem productivity in east and south Africa
Australasia	Reduced precipitation leads to increased desertification; loss of high-altitude ecosystems	Similar to A2 emissions	Reduced precipitation leads to increased desertification; loss of high-altitude ecosystems	

8. Settlements and infrastructure

The layout, design and construction of urban areas, buildings and transport infrastructure reflects local climatic conditions. Buildings in cold environments are designed to deal with low temperatures; buildings in warm environments are designed to cope with high temperatures, and urban environments in very wet areas are arranged to cope with large volumes of drainage water. Climate change will affect the performance and integrity of such infrastructure, affecting for example energy use (heating or cooling), comfort or system reliability. Many urban environments also have large stocks of old (and historically-significant) buildings, which may be very difficult to adapt.

Table 7: Summary settlements and infrastructure sector impacts

	A2 climate change	Thermohaline circulation collapse	Accelerated climate change	Regime shift
Europe	Increased heat discomfort and need for cooling; reduced disruption through icing and cold weather, and increased coastal navigation opportunities in north.	Increased need for heating; increased cold-related disruption of transport and energy networks (snow, icing). Increased disruption to coastal navigation in north due to increased ice cover.	Major increase in cooling needs and discomfort in buildings; increased heat-related disruption of transport and energy networks; reduced cold-weather disruption of transport and infrastructure networks	
North America	Increased heat discomfort and need for cooling; reduced disruption through icing and	Increased need for heating in east, and increase in east in frequency of cold-related disruption	Major increased heat discomfort and need for cooling; reduced disruption through	

	cold weather; increased navigation opportunities on Great Lakes	of transport and energy networks	icing and cold weather; increased navigation opportunities on Great Lakes	
South America	Increased heat discomfort and need for cooling	Similar to A2	Increased heat discomfort and need for cooling	
Asia	Increased heat discomfort and need for cooling; reduced disruption through icing and cold weather in north. Increased urban drainage problems in south and east.	Increased need for heating in north, and increase in network disruption due to cold or icing events; similar to A2 in south and east Asia	Increased heat discomfort and need for cooling; reduced disruption through icing and cold weather in north. Increased urban drainage problems in south and east.	Permanent wet monsoon: increased urban drainage problems
Africa	Increased heat discomfort and need for cooling.	Similar to A2	Increased heat discomfort and need for cooling.	
Australasia	Increased heat discomfort and need for cooling.	Similar to A2	Increased heat discomfort and need for cooling.	

8. Economic and social implications

The impacts of abrupt climate change on water, energy, health, agriculture, biodiversity and settlements will have regional and global economic impacts, which have not yet been evaluated using common metrics: integrated assessments have had to make assumptions about the aggregated economic impact of abrupt events (e.g. Mastrandrea & Schneider, 2001).

The preceding overview of the potential effects of abrupt climate change, however, suggests the following major global-scale economic impacts:

Thermohaline circulation collapse

- Shift in concentration of economic activity southwards in Europe and North America;
- Major increases in costs of maintaining and adapting urban and transport infrastructure in northern Europe and eastern North America;
- Substantial reductions in crop production in North America and central Asia, affecting global food markets

Accelerated climate change

- Shift in concentration of economic activity northwards in Europe and North America
- Major increases in costs of maintaining and adapting urban and transport environments across most of the world

- Reductions in crop productivity in North America and central Asia, affecting global food markets
- Increased frequency of hazard-related impacts and costs

Regime change

- Permanent El Nino increases flood hazard costs in North and South America
- Permanent El Nino reduces commercial fisheries productivity, and hence increases world food prices
- Permanent wet monsoon increases flood costs in south Asia
- Permanent dry monsoon threatens security of food supplies in south Asia

Potential impacts of gradual or abrupt climate change on security, population movements and conflict are extremely speculative. However, climate change will exacerbate existing tensions between regions and groups within regions, both through differential impacts and differing abilities to adapt.

10. Conclusions

This desk study has reviewed the potential effects of abrupt climate change across the world, by sector. There have been very few quantitative assessments of the effects of abrupt climate change at any scales, and many of the conclusions of the review are highly speculative. It is also not possible to evaluate the relative importance of each potential impact. Given the non-trivial likelihood of abrupt climate change occurring, there is clearly a need for more quantitative assessments across sectors, at both local and global scales. The report has not considered explicitly the implications of abrupt climate change for adaptation strategies or indeed the effectiveness of adaptation. However, it is clear that the implications of abrupt climate change for adaptation actions and strategies need to be examined in some detail.

The key potential impacts of each potential abrupt climate change considered in this review are:

Thermohaline circulation collapse

Collapse is superimposed on global warming: the later the collapse, the larger the warming on which the collapse is superimposed. Impacts of collapse on a world that was not warming would be greater.

- Impacts will be felt across the world, not just around the North Atlantic
- Collapse increases (relative to gradual climate change) water resources stresses in Europe and south and east Asia, and changes to the timing of river flows through the year would affect reliability of existing water resource management systems
- Collapse would lead to a reduction in cooling energy demands relative to the situation immediately before collapse (but still an increase over demands in the absence of any climate change), and an increase in heating energy demands

relative to the situation immediately before collapse (back to levels expected in the absence of climate change).

- Collapse would lead to increases in winter mortality across Europe and parts of eastern North America and Asia, but decreases in summer mortality in the same areas. In these regions, the net effect would probably be to increase mortality.
- Collapse would reduce crop productivity across much of Europe and parts of Asia, increasing burdens on the global food market and adversely affecting poor regions elsewhere.
- Europe, parts of northern Asia, and eastern North America would experience major changes in "natural" ecosystems, with a general shift from temperate toward boreal systems. Ecosystems in other parts of the world would be affected by changing patterns of precipitation.
- Settlements and infrastructure in Europe and parts of North America would be exposed to increased cold-weather disruption, although the later the collapse the less the impact this would have.
- It is possible that collapse would lead to a general southwards shift in the centre of economic activity in Europe and eastern North America, although again the effect would depend on when the collapse occurred.

Accelerated climate change

- Accelerated climate change exaggerates considerably the impacts of gradual climate change, and is would produces changes at rates considerably in excess of ability of both natural and human systems to adapt.
- Accelerated climate change increases the numbers of people at risk of increased water scarcity, particularly in Europe, North and Central America, and Africa. Major reductions in snowfall across large parts of eastern and northern Europe, North America and northern Asia would lead to significant changes in the timing of river flows through the year, challenging significantly the reliability of water resources systems.
- Accelerated climate change leads to very large increases in demands for energy for cooling, particularly in Europe and western Asia; by the 2050s, cooling requirements globally would be increased by over 75%, relative to the situation without climate change. Demands for energy for heating would be reduced by almost 50%.
- Accelerated climate change would increase substantially heat-related mortality, and lead to major disruptions in the patterns of many climate-sensitive diseases. Increases in flooding in south and east Asia in particular would increase the burden of flood-related ill-health.
- Accelerated climate change would lead to very substantial reductions in crop productivity, due to heat stress and water shortage, in most crop-producing regions, although this may be offset to a degree by the effects of higher CO_2 concentrations.
- Accelerated climate change would threaten many natural ecosystems, with widespread poleward movement of potential ecosystem types.

- Higher temperatures in particular would have significant impacts on the comfort and performance of settlements and infrastructure across the world.

Regime change

The effects of permanent regime change are highly uncertain, and although direct impacts are likely to be restricted to specific regions, these impacts may have global-scale consequences.

A shift to a permanent El Nino would increase water resource stress across large parts of south and east Asia, south and east Africa, and eastern South America, and increase the frequency of flooding in western South America and the south west of North America. It would reduce crop productivity in Asia and Africa, leading to increased risk of hunger and malnutrition; it would also encourage ecosystem degradation. Changes in ocean characteristics would reduce fisheries production in the eastern Pacific, again affecting both subsistence economies and world food prices.

A shift to a permanent dry south Asian monsoon would lead to major reductions in crop productivity in south Asia, and consequent increased risk of hunger and rises in food prices (and hence impacts on hunger in other poor regions). The reduction in flooding would reduce flood losses, but would also slow down the rate of deposition of sediments and result in reductions in soil fertility.

A shift to a permanent wet south Asian monsoon would have the primary effect of increasing flood losses and reducing harvests, leading also to increased risk of hunger. Urban drainage problems in south Asian cities, and associated disease and ill-health, would be exacerbated.

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