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Abrupt change in climate and climate models

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Abstract

First, we review the evidence that abrupt climate changes have occurred in the past and then demonstrate that climate models have developing capacity to simulate many of these changes. In particular, the processes by which changes in the ocean circulation drive abrupt changes appear to be captured by climate models to a degree that is encouraging. The evidence that past changes in the ocean have driven abrupt change in terrestrial systems is also convincing, but these processes are only just beginning to be included in climate models. Second, we explore the likelihood that climate models can capture those abrupt changes in climate that may occur in the future due to the enhanced greenhouse effect. We note that existing evidence indicates that a major collapse of the thermohaline circulate seems unlikely in the 21st century, although very recent evidence suggests that a weakening may already be underway. We have confidence that current climate models can capture a weakening, but a collapse of the thermohaline circulation in the 21st century is not projected by climate models. Worrying evidence of instability in terrestrial carbon, from observations and modelling studies, is beginning to accumulate. Current climate models used by the Intergovernmental Panel on Climate Change for the 4th Assessment Report do not include these terrestrial carbon processes. We therefore can not make statements with any confidence regarding these changes. At present, the scale of the terrestrial carbon feedback is believed to be small enough that it does not significantly affect projections of warming during the first half of the 21st century. However, the uncertainties in how biological systems will respond to warming are sufficiently large to undermine confidence in this belief and point us to areas requiring significant additional work.

1 Introduction

If the Earth's climate system was a linear system, with inputs and outputs proportional to each other, then modelling the climate system would be trivial and concerns over

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abrupt climate change due to increasing greenhouse gases in the atmosphere would be unwarranted. However, the Earth's climate system is dominated by a suite of non-linear phenomenon (Rial et al., 2004) that make understanding the Earth's climate, and how climate may evolve in the future an enormous challenge. Some of these non-linearities are at the core of key components of the Earth System such as the phase changes of water, the Clausius-Clapeyron equation, or whether an organism is alive or dead.

The Earth's climate system is effectively a closed system. Energy from the Sun is cycled through the various components of the climate system so that outputs of one component of the system become inputs for another component, creating feedbacks. It is useful to define "climate system" here: we do not mean the traditional "mean state of the atmosphere" (e.g. Hann, 1908) or "averaged weather" (WMO, 1984). We use a more modern definition of climate (e.g. Claussen, 2004) that includes the atmosphere, ocean, marine and terrestrial biosphere, cryosphere and lithosphere and the interactions (the flows of mass, energy, momentum including biogeochemistry) between these components. We define a threshold as a point where the climate system responds to forcing in a nonlinear way and the response is fast compared to the forcing (Alley et al., 2003). That is, over some time period the change in the response is much larger than the change in the forcing. We will also use "abrupt" to describe a climate change that occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause of the change (Alley et al., 2003). A smooth and gradual change in some determining quantity of the climate system (e.g., radiation balance, land surface properties, sea ice, etc.) can cause a variety of different responses depending on the nature of the system. If the system contains more than one stable equilibrium state then transitions to structurally different states are possible and we will highlight examples from the ocean and terrestrial systems. Upon the crossing of a bifurcation point the evolution of the system is no longer controlled by the time scale of the forcing, but rather determined by its internal dynamics. In these definitions, the magnitude of the

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forcing and the response to the forcing as well as the time scale are important. If non-linear change, thresholds and feedbacks are crucial to the Earth's climate we should be able to identify clear examples in the observational record. We demonstrate that this is indeed the case and show that to explain the observational record we need to use non-linear processes, thresholds and feedbacks. It is therefore reasonable to believe that these will also be key to explaining those changes that could occur in the future.

The tool to project how the Earth's climate will change in the future is the climate model (see McAvaney et al., 2001). Climate models are mathematical representations of components of the Earth's climate system. Until recently, climate models tended to focus on the atmosphere and oceans with relatively little attention to the cryosphere or terrestrial systems and biogeochemical cycles were rarely represented (see McGuffie and Henderson-Sellers, 2001). More recently, climate models (also called Earth System Models to identify their increasingly broad scope) have substantially increased their investment in cryospheric, biospheric and biogeochemical processes and are increasingly reliable tools for large-scale climate projection (McAvaney et al., 2001). To be confident in the capacity of climate models it would be important to show that they can simulate those changes, thresholds and feedbacks that are important in the climate system. We present evidence that climate models can capture elements of non-linear change thresholds and feedbacks and then point to some key areas where non-linear change is possible in the future.

This paper therefore provides an overview of the evidence for abrupt change in the Earth's climate system. We highlight those processes that are important to climate change mainly on time scales of a century or so (Rial, 2004, discuss abrupt climate change on millennial timescales). Our focus is to establish the capacity of climate models to capture these processes as a basis for assessing our confidence in climate models as a tool for projecting future climates.

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2 Abrupt climate change in the past

In terms of abrupt climate change, the ocean has been a focus of attention with the thermohaline circulation receiving greatest attention. The thermohaline circulation (THC) transports heat (order of 10^{15} watts) and salt into high latitudes of the North Atlantic. There, the heat is released to the atmosphere, cooling the surface waters. The cold, relatively salty water sinks (as north Atlantic Deep Water, NADW) and flows southward out of the Atlantic basin. Both paleo-studies (e.g., Broecker, 1997, 2000) and modelling studies (e.g., Manabe and Stouffer, 1988, 1997; Vellinga and Wood, 2002) suggest that disruptions in the THC can produce abrupt climate changes. Some modelling studies (Rahmstorf, 1995; Tziperman, 1997; Rind et al., 2001) suggest that there are thresholds where the THC may suddenly weaken or collapse causing abrupt climate changes.

The palaeoclimate community have established, over several decades, a convincing case for the existence of non-linear and abrupt climate changes centred on the stability of the THC. Data from sediments, ice cores and corals show large, widespread, abrupt climate changes have occurred repeatedly throughout the past glacial interval (see Rahmstorf, 2002). The most dramatic of these abrupt climate changes are the warm Dansgaard-Oeschger events, characterised by a warming in Greenland by 8 to 16°C within about a decade (Huber et al., 2006) and the cold Heinrich events where cooling occurred over the century time-scale, but the warming that ended them took place within decades (Cortijo et al., 1997; Voelker, 2002). While the strongest impact of Dansgaard-Oeschger and Heinrich events were centred on the North Atlantic, significant change also occurred in tropical wetlands (Chappellaz et al., 1993; Brook et al., 2000) and in the Asian monsoon region (Wang et al., 2001).

There is now good evidence of a link between these abrupt surface climate changes to aspects of the ocean circulation (Clark et al., 2002). Heinrich events are likely caused by ice-sheet instability (Hemming, 2004) and the exceedence of internal thresholds that maintain ice-sheet mass. The resulting iceberg discharge provides an influx of fresh

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water sufficient to shut down or significantly reduce the deepwater formation in the Atlantic. Cold events at the end of the last ice age were likely caused by meltwater from land-based ice sheets (Teller et al., 2002). It is important to note that these major changes in ocean circulation, due to an increased influx of fresh water, indicate either that the ocean circulation happened to be close to a threshold (Ganopolski and Rahmstorf, 2001) or is typically sensitive to changes in fresh water forcing.

Climate model studies have been performed in which fresh water discharge from ice sheet instability (Heinrich event) or a meltwater release (e.g. 13 000 years ago) were prescribed, and its effects on ocean circulation and climate simulated. Results suggest that major fresh water input could have suppressed NADW and explain many of the observed climate changes including the high-latitude northern cooling, the shift in the intertropical convergence zone and the hemispheric see-saw (Vellinga and Wood, 2002; Dahl et al., 2005; Zhang and Delworth, 2005, Stouffer et al., 2005). Climate models can therefore broadly reproduce the observed variations during abrupt events of this type and this provides confidence that these models can simulate the abrupt changes found in the observed records.

These changes, driven by large-scale perturbations in the physical climate, led to major changes in atmospheric methane (Chappellaz et al., 1993) and dust aerosols with lower methane content and higher mineral dust aerosol concentrations characterizing cold phases (Mayewski et al., 1994). Coincident with the methane and dust changes were large-scale changes in the vegetation patterns. Williams et al. (2002) demonstrate that abrupt changes in climate led to rapid changes in eastern North American and European vegetation. While the response of vegetation was site and regionally specific, dependent on local taxa and climate conditions, they showed regional taxon migrations, changes from shrubs to trees and changes in species frequency. Williams et al. (2002) showed that the timescale of vegetation response was of order 100–200 years with rapid migration at continental scales led by the establishment of distant satellite populations by rare long-distance seed dispersals (Clark et al., 1998). Williams et al. (2002) argue that abrupt climate change increases the potential for rapid response times within the vegetation by increasing the mortality rates for mature trees via fire, wind and disease. In addition, in some areas such as near the tree line there are opportunities to promote rapid succession because low tree densities encourage rapid seedling establishment if conditions otherwise permit. Finally, at least in the past, the higher amounts of herbaceous plants allowed a more rapid response to climate change due to higher reproductive rates. Williams et al. (2002) argue therefore that the rapid and widespread response to abrupt climate change in the past indicates a tight coupling between the vegetation and climate and that there is no evidence that this coupling need be less in the present or future.

Shuman et al. (2002) explored the impact of the abrupt climate changes at the beginning and end of the Younger Dryas (12 900–11 600 BP) in vegetation. They argue that vegetation responses to abrupt climate change were coherent across sub-continental scales and that these responses were more driven by the changes in climate than ecological factors. The sychchroneity of the large-scale vegetation changes, across wide geographical areas, suggests an abrupt change in vegetation rather than a slow succession in vegetation. Shuman et al. (2002) also point to quite rapid long-distant (>300 km/century) changes in plant types as well as local changes in abundance.

Shuman et al. (2002) and Williams et al. (2002) are two recent examples that highlight the observational evidence that vegetation can respond relatively rapidly to abrupt climate change on century time scales. Responses include quite rapid migrations, change in the frequency of vegetation types locally, and local extinctions. Given abrupt climate change in the past drove large-scale responses in vegetation it seems reasonable to anticipate large-scale changes in vegetation in the future if abrupt climate changes occurs. In the context of timescales of climate change, it is noteworthy that in comparison with observed pre-industrial rates of change in atmospheric CO_2, the current rate of increase is abrupt. The function, distribution and the local species diversity of vegetation, as well as the physical climate, are all likely to respond to the change in CO_2. These changes affect net carbon budget as well as the exchange of sensible and latent heat with the atmosphere generating a feedback that may either amplify or suppress the consequences of the increasing CO_2. This will be discussed in more detail later.

There is evidence from climate models that the biospheric feedback can be represented adequately and capture major transitions in vegetation. According to palaeoclimatic reconstructions, North Africa was wetter and the Sahara was much smaller than today (Prentice et al., 2000) during the Holocene climate optimum (9000–6000 years ago). Annual grasses and shrubs covered what is now desert, and the Sahel reached some 500 km north of its present location (Claussen et al., 1999). Rial et al. (2004) discuss how, during the Holocene optimum, orbital changes led to stronger insolation during the Northern Hemisphere summer that strengthened the North African summer monsoon (Kutzbach and Guetter, 1986).

At about 6000 BP, an abrupt change in vegetation and climate occurred over the Sahara (Claussen et al., 1999). Ganopolski et al. (1998) showed that to simulate this change, a model needed to include vegetation feedbacks. This includes the albedo feedback identified by Charney et al. (1975), but also feedbacks relating to roughness, evapotranspiration and carbon (see Pitman, 2003). Claussen et al. (1999) showed that slow (and smooth) changes in the radiation due to orbital changes were able to trigger abrupt change in vegetation due to the existence of these feedbacks. Rial et al. (2004) suggest that these results imply that the Sahara is now in a single, quite stable equilibrium condition (i.e., desert), but that the North African climate is sensitive to changing feedbacks relating to vegetation, a result consistent with Joussaume et al. (1999). Others have suggested that the evidence supports multiple equilibrium states (Claussen, 1997) with the possibility of abrupt changes when thresholds are crossed (Brovkin et al., 1998; Kleidon et al., 2000). Schneider (2003), in discussing these results, highlights the possibility that they point to potential irreversible change in the Earth System. Specifically, it seems reasonable to suggest that if slow orbital changes can induce non-linear behavior due to interactions with vegetation feedbacks, then the rapid increase in atmospheric CO_2 and the associated global warming might also drive non-linear change, in particular in areas close to vegetation boundaries.

Wang and Eltahir (2000a, b) have also explored the issue of stable equilibria for the Sahel region and the role of vegetation in affecting this system. Wang and Eltahir (2000a) suggest that the extended period of drought since the 1960s may represent a change from a self-sustaining wet climate equilibrium to a self-sustaining dry equilibrium. Their suggestion is that an initial rainfall anomaly, caused by sea surface temperature changes, caused vegetation changes that altered the availability of moisture for the atmosphere in the longer term and to determine the equilibrium state. Wang and Eltahir (2000b) found that vegetation in their model is partly responsible for the low-frequency variability in the atmosphere–biosphere system characteristic of the Sahel and for the transition between equilibrium states. Rooting depth within the perennial grassland determines which of the equilibria the modelled system occupies at any given time. In the model, moist (i.e., favourable) growing seasons facilitate greater root growth of perennial grasses, while dry (unfavourable) growing seasons lead to shallow root growth. Shallow roots lead to less evapo-transpiration and less atmospheric moisture, causing a positive feedback (Wang and Eltahir, 2000b).

3 Abrupt climate changes in the future?

Most of the large, past abrupt changes in the palaeo-record are attributed to large-scale changes in the THC. This does not mean the THC is the only mechanism that can trigger abrupt change, but it may be the only mechanism that operates on a large enough spatial and temporal scales where impacts are clearly visible on the palaeo-record. Since the THC has been the centre of much attention in explaining the palaeo-record, its potential role in future climate changes is also important. However, other contributors to future abrupt change exist, in particular relating to terrestrial systems and these will also be discussed.

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3.1 Thermohaline-circulation changes

Under increasing CO_2 in the future, the climate warms (Houghton et al., 2001) and in most climate models the THC weakens. A feature common to all climate model projections is the increase of northern hemisphere high latitude temperature and an increase in high latitude precipitation. These effects tend to make the high latitude surface waters lighter and hence increase the stability on the water column. The increased stability hinders and may reduce NADW formation. This weakens the THC, potentially to the point that a threshold is exceeded and THC collapse occurs leading to abrupt climate change. The actual climate changes associated with a THC shut down include a relative cooling of the North Atlantic and surrounding land areas due to the loss of heat transport from low latitudes in the Atlantic and the subsequent release of this heat into the high latitude atmosphere. However, it must be noted that this cooling is relative to the general warming experienced by most of the planet as the GHG increase. Few, if any, regions actually experience a cooling relative to present day when GHG increase.

Projecting the behaviour of this system into the future is challenging. There is a wide range in the THC responses among climate models to increasing greenhouse gases in the atmosphere. A set of coordinated experiments designed and supported by the Coupled Model Intercomparison Project (CMIP) and Paleo-Model Intercomparison Project (PMIP) are exploring this issue (http://www.gfdl.noaa.gov/~kd/CMIP.html). In one set of integrations, the role of the surface fluxes in the weakening of the THC was investigated (Dixon et al., 1999; Mikolajewicz and Voss, 2000; Gregory et al., 2005). In a second set of integrations, the THC and the more general climate response to a specified, idealized external source of fresh water on the North Atlantic Ocean was studied (Manabe and Stouffer, 1997; Rind et al., 2001, Stouffer et al. 2005). Preliminary results of these experiments indicate that in most models the changing surface heat fluxes are most important in weakening the THC as the climate warms. The surface waters become warmer and lighter, hindering the vertical mixing and weakening the THC.

The response within the ocean to the changing water fluxes is more varied. In most

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climate models the water flux changes weaken the THC (some by up to 60% by 2100). However, the spread in model responses is much larger than to the changes in the surface heat fluxes. These results imply that the location and pattern of the fresh water influx and the subsequent water flux changes are important and can explain much of the differences in the model THC response to increasing GHG. The further away the additional fresh water input is from the deepwater production areas, the less effective it is in changing the THC (Manabe and Stouffer, 1997; Rind et al., 2001). Even where the water flux anomalies are specified, there are a wide range of THC responses which suggests that the water fluxes are the main cause for the spread in the THC responses among the climate models (Stouffer et al., 2005).

Due to its spatial scale, global role and the amount of heat and salt transported the THC is the most likely cause of abrupt climate change in the climate system on decadal to centennial time scales under global warming scenarios. However, none of the climate models involved in CMIP simulates an abrupt change before 2100.

Overall, it seems likely that models can produce reliable projections of THC behavior over the next century or so in response to likely greenhouse gas emissions but the reliability of longer term projections is unknown. The important question of potential irreversibility of a THC shutdown remains unanswered. Climate models suggest that over the next century, a slow down of the THC would not be abrupt but would take many decades to more than a century to fully spin down. Therefore, there is no climate model evidence to support speculation that the THC could collapse within years or a few decades in response to global warming. This is not inconsistent with the paleoclimate records where much faster transitions occurring over a few decades occur associated with large ice sheet instabilities and to sudden changes in meltwater that are very much larger than changes in forcing expected over the 21st century. Schneider (2004) discusses the impact of THC collapse in terms of an integrated assessment of climate change and its implications for policy. He points out that few assessments of the full impact of climate change incorporate abrupt climate changes. This risks policy development being based on a sub-set of possible futures and a sub-set biased

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towards changes that are relatively slow to emerge.

To cause an abrupt collapse of the THC in the 21st century requires a major change in the forcing, for example a sudden melting of the Greenland ice cap. Observations have shown increasing melt around the periphery and on the surface of the Greenland ice sheet over the past 25 years and simulations indicate that the ice sheet will significantly reduce in volume and area over the coming centuries if warming is sustained (Huybrechts et al., 2004; Gregory et al., 2004; Toniazzo et al., 2004). Climate model simulations coupled with three-dimensional ice sheet models show that a significant flow of meltwater from Greenland could freshen the surface waters in high latitudes of the North Atlantic, and contribute to slowing the THC. This could cause a strong and abrupt weakening of the THC by the end of the 21st century under an average climatic warming scenario (Fichefet et al., 2003).

Although there is a clear potential for increased Antarctic fresh water input from increased melting of ice shelves and ice bergs (Marsland and Wolff, 2001; Williams et al., 2001; Beckmann and Goosse, 2003; Shepherd et al., 2003), and an increased flux of ice across grounding lines (Thomas et al., 2004), total fresh water volumes are likely to be significantly lower than for Greenland. In addition, the fresh water would be spread out over a much larger area, leading to a lower local rate of freshening of surface waters. The response of the Atlantic THC to changes in the Antarctic ice sheet is poorly understood. Some studies suggest that if meltwater changes are imposed as surface salinity changes, the Atlantic THC will intensify as the waters around Antarctica become lighter (Seidov et al., 2001). However, Seidov et al. (2005) found that an external source of fresh water in the Southern Ocean resulted in a surface freshening throughout the world ocean, leading to a weakening of the Atlantic THC. In both model results, the Southern Hemisphere THC associated with Antarctic bottom water formation, weakened causing a cooling around Antarctica.

In late 2005 evidence began to emerge of observational data suggesting the Atlantic currents that form part of the THC had weakened (Bryden et al., 2005). Data suggest that the Gulf Stream current had weakened by 30% over 50 years ago. This may be natural variability, or a response to increasing fresh water input and a clear picture will likely take a decade or two to resolve.

3.2 Carbon, vegetation and biogeochemical cycles

The Earth's land surface stores about 2000 Gt of carbon (Prentice et al., 2001) which is more than twice that stored in the atmosphere as CO_2. The amount of carbon exchanged annually between the terrestrial and atmospheric systems varies remarkably. In the 1980s it was about -0.2 ± 0.7 Gt C y^{-1} (a net uptake, Prentice et al., 2001) but from 1990 to 1999 the net land-atmosphere exchange was -1.4 ± 0.7 Gt C y^{-1}. This net uptake of carbon by the terrestrial biosphere includes a natural sink due to biological activity and a source due to land clearance. During the 1980s, the sink into the biosphere was between -3.8 to $+0.3$ Gt C y^{-1} (believed caused by some types of land cover change (LCC), mainly northern hemisphere reafforestation, nitrogen fertilization and the fertilization effect of increased CO_2). This was counteracted by a release of approximately 0.6–2.5 Gt C y^{-1} due to other types of LCC due mainly to deforestation in the tropics (Prentice et al., 2001). Clearly, a vast amount of carbon is exchanged between the Earth's surface and the atmosphere naturally, and Human activity has modified this exchange via land cover change and indirectly through the fertilization effect of increased CO_2.

If something happened to significantly affect the flux of carbon between the atmosphere and the terrestrial (or indeed oceanic) system this could substantially change the likely trajectory of atmospheric CO_2 concentrations through the 21st century. In the 1990s there was significant debate that as CO_2 increased in the atmosphere, there would be a large scale fertilization of the world's vegetation and a negative feedback on CO_2 would develop. There is evidence that this does indeed occur in a range of experimental studies with young trees (e.g. Saxe et al., 1998; Norby et al., 1999), but it appears that various limitations including nutrients and water will prevent a long term feedback (Oren et al., 2001; Luo et al., 2004; DeLucia et al., 2005).

Rather than provide a long-term sink for CO_2, evidence is beginning to accumulate

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that the terrestrial system might become a significant source. While abrupt changes in biogeochemical systems, of relevance to our capacity to simulate the climate of the 21st century with climate models are not well understood (Friedlingstein et al., 2003) there are some key pieces of evidence that provide a guide to possible roles.

3.2.1 Abrupt changes in vegetation and carbon in the future

Perhaps the most dramatic recent finding of the role of the biosphere in feedbacks over the next century was provided independently by Cox et al. (2000) and Friedlingstein et al. (2001). Both groups found that as the Earth warms due to increasing CO_2, the capacity of the terrestrial biosphere to absorb and store carbon declines. Cox et al. (2000) showed that the terrestrial biosphere functioned as a sink to about 2050 and then turns into a source. While vegetation continues to take up CO_2 past 2050, the rate was reduced and overwhelmed by the collapse of the soil carbon sink that released vast amounts of carbon into the atmosphere. Friedlingstein et al. (2001) found that the size of the sink increased at first, but then declined as temperature increased. In a major intercomparison exercise, Cramer et al. (2001) compared results from six of these global biospheric models to prescribed increases in CO_2 (these were not experiments performed within a climate model). The results, as well as the coupled results from Cox et al. (2000) and Friedlingstein et al. (2001) differ in detail, but demonstrate an important but uncertain role for the future biosphere.

The amplification of warming resulting from loss of terrestrial carbon found by Cox et al. (2000) was mainly due to loss of soil carbon. However, above-ground loss of vegetation also occurred, centred significantly on the Amazon forests. The implication that warming over the 21st century could cause abrupt change and die-back of the Amazon forests was of sufficient importance for Cox et al. (2004) to explore this in more detail and they show that drying and warming in South America under increasing CO_2 leads to a continuous reduction in the forest of Amazonia. The cause of the Amazon die-back in the Hadley Centre climate model used by Cox et al. (2000, 2004) was associated with warming of around 9°C in the model by 2100 over the Amazon due to increasing CO_2 and an associated decline in rainfall from 4.56 mm d^{-1} (which is low relative to the observed value) to 1.64 mm d^{-1} between 2000 and 2100. This warming and drying places considerable pressure on the vegetation and a total of around 50 Gt C is lost to the atmosphere (35.6 Gt from the vegetation and 14.3 Gt from the soil). By the end of the 21st century, Cox et al. (2004) report a reduction in broadleaf tree cover in the Amazon from 80% to 27% and an increase in bare soil from 5% to 55%.

The die-back of the Amazon causes a positive feedback in the Hadley Centre model to amplify the warming and drying trend driven by the larger scale climate. The key mechanism is the emergence of an El Nino-type sea surface temperature warming pattern in the model due to increasing CO_2 . This reduces rainfall over the Amazon region. In addition, the increasing CO_2 and physiological feedbacks by the vegetation to increasing CO_2 contributes further warming. The resulting reduction in evaporation then further suppresses rainfall. The contribution of this physiological response to the rainfall reduction was about 20% (Betts et al., 2004) through both additional warming and reduced evaporation. The forest die-back induced rainfall reductions of 20% while the loss of carbon that amplifies atmospheric CO_2 adds a further 5% (Betts et al., 2004).

Whether the response in the Hadley Centre model and the emergence of an El Nino-like sea surface temperature pattern in the model is realistic is uncertain, although Cox et al. (2004) point to other models that indicate a similar response. Further, the response of the vegetation in the Hadley Centre climate model is also likely to be model dependent. However, if rainfall were to decline over the Amazon by the amounts found by Cox et al. (2004) then a major, rapid and permanent change in the Amazon would seem inevitable. Given the scale of response in Cox et al. (2004), the inclusion in climate models of the capacity to simulate this feedback is clearly important in climate projection studies. It is highly likely that this type of feedback is critical in regional projection studies in sensitive areas.

3.2.2 Abrupt change in soil carbon: present and future

About half of the carbon taken up through the vegetation is stored in the soil. Globally, soils store about 300 times the amount of carbon now released annually thought burning fossil fuels (Schulze and Freibauer, 2005). We have a poor understanding of the dynamics of soil carbon and the parameterization of the relationship between soil carbon and the forcing factors that affect soil carbon are rather uncertain. For example, Cox et al. (2000) used a parameterization of soil carbon that assumed the rate of soil carbon respiration rate doubles with each 10°C of warming (Raich and Schlesinger, 1992) and includes a dependence on soil moisture. There is some support for the soil-carbon-temperature relationship (Jones and Cox, 2001) and some evidence that it is too simplistic (Giardina and Ryan, 2000).

A major piece of observed evidence has recently been published that seems to support the Cox et al. (2000) results that suggest a strong potential feedback between warming temperatures and soil carbon loss. Bellamy et al. (2005) report a large-scale loss of soil carbon over England that cannot be explained by land use change. The most reasonable explanation for soil carbon loss appears to be higher soil respiration rates due to regional warming over England. A second piece of evidence, by Heath et al. (2005) show that while higher CO_2 does cause a short-term increase in growth of European trees, it also leads to an increase in the soil microbial activity and a decline in soil carbon sequestration. The studies of Bellamy et al. (2005) and Heath et al. (2005) are localized geographically and are not conclusive but they point to a very worrying phenomenon of positive feedback between soil carbon storage and warming – that as global temperatures warm, soils may reduce their storage of soil carbon and the out-gassing of this carbon will act as a positive feedback to amplify warming. This is effectively the process Cox et al. (2000) modeled – although their results anticipated the soil becoming a source of CO_2 by roughly 2050 while Bellamy et al. (2005) suggest that this has already occurred over England. This is a significant concern: Cox et al.'s (2000) results suggested that the weakening of the biospheric sink as temperatures increase leads, by 2100, to CO_2 levels nearly 300 ppmv higher and ~2.0°C extra warming between 1860 and 2100 compared to a standard IPCC scenario (IS92a). This suggests that studies of global warming over the 21st century may have underestimated the amount of warming and the rate of warming.

4 Discussion and conclusions

The long term observed record of climate change is highlighted by abrupt changes in climate. These abrupt changes are commonly attributed to fluctuations in the thermohaline circulation that drives physical climate changes that in turn drive changes in the terrestrial vegetation, carbon and methane balances. There is also some evidence of internal thresholds within the terrestrial system that allows abrupt changes to occur when driven by external forcing such as gradual changes in solar insolation. The fact that abrupt changes in the climate system are now clear in the observed record, and we are beginning to identify likely mechanisms to explain these changes has provided the impetus to look at whether the climate models used to simulate future climates can capture these mechanisms to a level that reinforces our confidence in the models.

In the case of the ocean circulation and the THC an evaluation of the capacity of the models to simulate the response of the THC to changes in fresh water influx has begun to be explored. At present, the responses of the climate models to a fresh water influx vary, but it is uncertain whether this is due to differences in the physical parameterisations, resolution or due to differences in the amounts and location of fresh water perturbations or both. The scale of any likely perturbation in the THC in the 21st century is unlikely to initiate a THC. However, significant reductions in the heat transferred by the THC could still drive significant regional climate changes, in particular in Western Europe, potentially reducing greenhouse-induced warming or possibly reversing the warming to a small regional scale cooling.

An assessment of the capacity of climate models to simulate abrupt changes in the THC, and associated changes in climate is therefore that it seems probable that climate models can produce reliable projections of the behaviour of the THC over the 21st century but our confidence beyond that is very limited. The probability of the collapse of the THC over the 21st century is low (but not zero) and Schneider's (2004) recommendation to include the probability of a THC collapse in assessments of climate change and subsequent policy development appears sensible given that this reduces bias in existing assessments that assume slow rates of climate change.

While we have some confidence in our capacity to simulate the impact of rising greenhouse gases on the THC, there is little confidence in our capacity to model the impact of warming on the terrestrial carbon cycle. Building a reliable parameterization of terrestrial processes, including above and below ground carbon and vegetation dynamics and vegetation succession is at the cutting edge of existing scientific capacity. Those models that now exist, developed and implemented by several groups (see Sitch et al., 2003), contain a series of significant components that are highly uncertain (interactions of soil respiration with increasing temperature and changing soil moisture) or do not contain processes that might significantly influence the response of vegetation to climate change (nutrient limitation, orography, predators and pests and human-interference via land clearance, cropping etc.). The climate models run for the fourth Assessment report by the Intergovernmental Panel on Climate Change do not include terrestrial carbon or dynamic vegetation and so it is difficult to evaluate the contribution made by these processes to climate projections. However, efforts are ongoing to compare parameterizations, explore model sensitivities and improve the way various processes are parameterized. At present, the probability of an abrupt change in terrestrial carbon storage is unknown since too few models have been run that include the processes in fully coupled simulations of the 21st century. We also cannot assess the likelihood of a collapse of major world ecosystems, such as the Amazon, by 2050 or 2070.

The results, from observational studies, of substantial losses in soil carbon over England (Bellamy et al., 2005) or the heat wave in Europe that is reported to have killed 30 000 people (Beniston, 2004; Trigo et al., 2005), both of which are consistent

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with global warming, may be early signs that large-scale change is already underway. We cannot rule out that some of those changes may be abrupt and the result of a relatively slow signal evolution in the presence of large natural variability.

A key problem with the parameterization of abrupt changes in Earth System Models is that recent observations of examples of system thresholds being exceeded and abrupt changes occurring are, by definition, rare. Where abrupt changes occur as a fundamental property of the system, for example the thermohaline circulation, a capacity to simulate this response in an Earth System Model may well exist and we might improve our capacity to simulate these phenomenon by improving the parameterization of the ocean in general. However, terrestrial ecosystems are not described in an Earth System Model via the equations for fluid dynamics. Major non-linearities in the terrestrial system are the result of interactions between the biogeochemical, water and energy cycles. These involve many complex processes, poorly understood thresholds, population dynamics and competition and even an evolutionary response of subsets of a system to climate change. It may be that our observations of these systems, constrained by the climate of the recent past are not a good basis for parameterizing the response of these systems in the future. On-going observational campaigns, on long timescales at representative sites of sensitive systems, is the only way we can determine the reliability of our existing models and the only way we can learn and then parameterize significant processes and responses of those processes to climate change. Some "sensitive systems" have been identified. Foley (2005) asked whether the Arctic as we know it today is already lost based on an analysis by Chapin et al. (2005). The Amazon appears vulnerable to warming and there is some evidence that the Gulf Stream is weakening has begun (Bryden et al., 2005). An attempt to capture the scale and location of these sensitive regions was provided by H. J. Schellnhuber (see Kemp, 2005). Already, areas like the Arctic need to be added.

In conclusion, the evidence from the paleo-record clearly demonstrates that the Earth's climate system has been affected by abrupt changes in the past. Evidence is beginning to accumulate that abrupt changes may strongly affect the future climate of the Earth under warming driven by CO_2. Our capacity to model some abrupt changes is beginning to mature, particularly where those changes are fundamental properties of the Earth System described well by physical equations. Where the abrupt changes are tied in with biological activity, such as the carbon cycle and the fluxes of carbon between the atmosphere, vegetation and soils it is clear that a substantial amount of work is required before we can be confident that the simulated responses of these systems is captured in Earth System Models. However, at least on timescales of several decades into the future, there is not yet convincing modelling evidence that abrupt change will be driven by a thermohaline or terrestrial biosphere-driven abrupt change of sufficient magnitude to significantly enhance or moderate existing projections of warming due to CO_2. This implies that existing projections of the future climate, decades into the future, are unlikely to be seriously limited by lack of knowledge of those mechanisms that drive abrupt change. Post 2050, there are indications that abrupt, or at least accelerating change is possible due to major carbon cycle responses. In the longer term (but still in a present day child's life expectancy) there is accumulating evidence that both ocean and terrestrial systems have the potential to drive abrupt changes. Given that we are currently committing ourselves to that future through increasing emissions of greenhouse gases, developing an improved capacity to model abrupt changes in Earth System Models is clearly a key priority for science strategy over the next decade.

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