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A review of recent developments in climate change science. Part I: Understanding of future change in the large-scale climate system

Peter Good,[1] John Caesar,[1] Dan Bernie,[1] Jason A. Lowe,[1] Paul van der Linden,[1] Simon N. Gosling,[2] Rachel Warren,[3] Nigel W. Arnell,[4] Stephen Smith,[5] Jonathon Bamber,[6] Tony Payne,[6] Seymour Laxon,[7] Meric Srokosz,[8] Stephen Sitch,[9] Nic Gedney,[1] Glen Harris,[1] Helene Hewitt,[1] Laura Jackson,[1] Chris D. Jones,[1] Fiona O'Connor,[1] Jeff Ridley,[1] Michael Vellinga,[1] Paul Halloran[1] and Doug McNeall[1]

Abstract
This article reviews some of the major lines of recent scientific progress relevant to the choice of global climate policy targets, focusing on changes in understanding since publication of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). Developments are highlighted in the following major climate system components: ice sheets; sea ice; the Atlantic Meridional Overturning Circulation; tropical forests; and accelerated carbon release from permafrost and ocean hydrates. The most significant developments in each component are identified by synthesizing input from multiple experts from each field. Overall, while large uncertainties remain in all fields, some substantial progress in understanding is revealed.

Keywords
Atlantic Meridional Overturning Circulation (AMOC), climate change, global climate, ice sheets, Intergovernmental Panel on Climate Change (IPCC), sea ice, tropical forest

1 Introduction and methods

There is now strong scientific evidence for a human contribution to recent climate change, and for potentially large future changes due to continued activities such as fossil fuel use (e.g. Solomon et al., 2007; Stott et al., 2010). As this evidence continues to develop, policy-makers have been increasingly active in setting out strategies to address climate change. Expert assessments of the latest scientific understanding regarding climate

[1] Met Office Hadley Centre, Exeter, UK
[2] University of Nottingham, UK
[3] University of East Anglia, UK
[4] University of Reading, UK
[5] Committee on Climate Change, London, UK
[6] University of Bristol, UK
[7] University College London, UK
[8] National Oceanography Centre, Southampton, UK
[9] University of Leeds, UK

Corresponding author:
Peter Good, Met Office Hadley Centre, FiztRoy Road, Exeter, EX1 3PB, UK.
Email: peter.good@metoffice.gov.uk

change are seen as critical to making effective decisions for both mitigation and adaptation.

The IPCC AR4 provided a major evidence base, which has been heavily drawn on by the policy-maker community (e.g. CCC, 2008; Copenhagen-accord, 2009). However, substantial research progress has been made since the last IPCC assessment, forming a vast body of post-AR4 scientific literature. The next comprehensive assessment by the IPCC is not expected to be published until 2013, while there are a number of policy decisions being made now which may benefit from the new information available.

This review (along with the companion paper by Gosling et al., 2011) aims to highlight some of the most significant scientific advances pertinent to the choice of global temperature targets for mitigation policy. More precisely, we ask what has changed in scientific understanding since IPCC AR4 which could suggest a changed view of dangerous global climate change? We focus on assessing changes in knowledge rather than updating the current state of knowledge. This is to assist attempts to revise decisions originally based on the AR4, and complements other recent reviews. Because of the difficulties in assessing changes in knowledge, we do not attempt the quantitative conclusions attempted elsewhere (e.g. Kriegler et al., 2009; Zickfeld et al., 2010).

While Gosling et al. (2011) assess impacts literature, our focus is on typically large-scale climate system components and we cover the following sectors, implicated as having potential for dangerous future change relevant to mitigation policy: ice sheets, sea ice, the Atlantic Meridional Overturning Circulation (AMOC), tropical forests and accelerated carbon release from permafrost and ocean hydrates. These sectors may be vulnerable to large, abrupt, or effectively irreversible change (Kriegler et al., 2009; Lenton et al., 2008; Schellnhuber, 2009). For each sector there have been reports of recent observed changes, albeit with active scientific debate regarding their significance or causes, and hence the implications for future change.

We attempt to identify the most significant changes in understanding (those most likely to stand the test of time) by synthesizing input from various experts in each research area. Experts are in the best position to make subjective judgements regarding the importance of and validity of assumptions behind studies in their specialism. Use of multiple experts helps to reduce but not eliminate the problem of subjectivity.

After a summary of our literature analysis and expert consultation method, we present results, structured for each sector as follows. First, an introduction lays out the key issues, before a discussion of observed recent changes (including any implications for future change). Next, other evidence for potentially dangerous future change is presented (including climate model studies, paleoclimate reconstructions and expert elicitation results) and then the potential consequences of such change. Finally, new work on cautions regarding scientific uncertainty is given, including information on potential climate model biases – pointing to areas where climate projections may be subject to revision as part of ongoing scientific progress. The majority of the journal articles we review postdate the AR4 report, although some earlier studies are included to give context to or explain the newer work. The key points from each sector are summarized finally in a table.

II Literature analysis and expert consultation method

In order to choose the scientific sectors and to produce an initial outline of key results for each sector, we made a preliminary search of the literature using the Thomson Reuters Web of Science online academic search engine. This search was partly guided by literature citing

Lenton et al. (2008) (a high-profile expert elicitation review of climate 'tipping elements' based on literature available shortly after the publication of the AR4 report). Other key resources included the associated probabilistic assessment by Kriegler et al. (2009), the 2009 special issue of PNAS on climate tipping points (Schellnhuber, 2009) and the review by Fussel (2009).

All of the sectors chosen were addressed in the 2009 PNAS special issue (Schellnhuber, 2009), and for each sector there have been reports of recent observed changes. Arctic summer sea ice loss was assessed by Lenton et al. (2008) as having a global temperature threshold of only 0.5–2 K above present, while ice sheets, the AMOC and tropical forests were all highlighted in the study of Kriegler et al. (2009).

Based on this initial search we chose at least two experts in each sector, including at least one internal to the UK Met Office, and one external (from a different institute). For the ice sheets sector we chose two internal and two external experts, given the very active debate on recent observed changes in this area.

The outline produced for each sector was sent to the internal Met Office expert(s) for revision, and then written up. The write-up for each sector was then sent to the external expert(s) for comments, revised, and sent back to the external expert(s) for further comments. The internal experts were given a further chance to comment before the final version was produced.

III Results

1 Ice sheets

a Introduction. Ice-sheet mass loss is of concern due to its impact on global sea level (van den Broeke et al., 2009), and potential amplification of global warming as low-albedo land surface is exposed (Hansen et al., 2008). The AR4 report noted an observed acceleration in ice-sheet loss, and attempted to take some account of it in their estimate of sea-level rise by 2100, but acknowledged the large associated uncertainties.

Increased ice-sheet mass loss occurs through two main mechanisms (van den Broeke, 2009). Increased surface melt is largely driven by higher air temperatures. 'Dynamic thinning' involves glacier acceleration and consequent increases in iceberg calving for sea-terminated glaciers. Land-terminated and sea-terminated glaciers can exhibit different behaviour as the former are not directly influenced by ocean changes.

Key issues addressed by recent studies include: what the observed ice-sheet loss implies for the rate of future sea-level change, the potential long-term sea-level rise, and the possibility of abrupt or irreversible changes.

b Observed recent changes. There have been further reports of increased losses from Greenland, which may be associated with oceanic warming and the recent retreat of calving ice tongues in coastal fjords (Rignot and Kanagaratnam, 2006; van den Broeke et al., 2009; Velicogna, 2009). In addition, mass loss in Greenland has been observed to be migrating northward (Khan et al., 2010). Present-day losses from both Greenland and Antarctica are now $\sim$1.4 mm/yr sea-level rise with roughly equal contributions from the west Antarctic ice sheet and Greenland and a neutral balance for the East Antarctic ice sheet (van den Broeke et al., 2009; Velicogna, 2009). These losses appear to have accelerated during 2002–2009, although the rate of acceleration is extremely sensitive to the measurement period selected (Velicogna, 2009). The speed of Pine Island Glacier in West Antarctica is the main indicator of dynamically driven ice loss from the ice sheet, and it is accelerating (Rignot, 2008; Wingham et al., 2009).

A key question is what these observed losses imply for likely future ice-sheet changes (Nick et al., 2009). To address this, the community has developed a better understanding of the causes of observed ice thinning in Greenland.

There is a component attributable to increased surface melt (a consequence of higher air temperatures). Increased surface melting is responsible for over half the recent increase in mass loss (van den Broeke et al., 2009) and responds rapidly to changes in air temperature. A pronounced warming in the summer melt season has been observed at coastal Greenland stations since the 1990s, mirroring the northern hemispheric warming over the same period (Hanna et al., 2008).

Very high ice thinning rates close to the coast have been attributed (Krabill et al., 2004) to both increased surface melting and dynamic thinning (speed-up of glaciers and consequent iceberg calving). However, new spatial analysis of the pattern of thinning (Sole et al., 2008) suggests that the iceberg calving mechanism is more important, and this has been shown to be due to increased ocean temperatures causing thinning for the three largest tide-water glaciers in Greenland (Howat et al., 2007; Joughin et al., 2004, 2008). This has the important implication that the presently large local rates of thinning close to the coast may cease once the ice sheet retreats from contact with the ocean (Sole et al., 2008). Progress is being made in the modelling of iceberg calving (Nick et al., 2009), and links to ocean circulation changes (analogous to that thought to be triggering change in West Antarctica) have been postulated (Holland et al., 2008). Recent research shows that while the link between increased surface melt and glacier speed (Zwally et al., 2002) plays a significant role in the summer speed-up and winter slowdown of land-terminating glaciers, it does not contribute greatly to increased mass loss as it is less important for calving glaciers (Joughin et al., 2008; van de Wal et al., 2008).

c Potential for dangerous change. Modelling reconstructions of the last interglacial period suggest that we are moving into a climate regime when the Greenland and West Antarctic ice sheets will become increasingly unstable (PALSEA, 2010). Furthermore, sea-level rise related to current warming may be rapid at first and slow over time as the ice sheets approach a new equilibrium (PALSEA, 2010). Paleoproxy studies have indicated the possibility that small changes in forcing (albeit with quite large changes in ocean temperature) can lead to sudden retreat of the west Antarctic ice sheet (Naish et al., 2009; Pollard and DeConto, 2009). A mechanism to bring warm water onto the Antarctic continental shelf, where it can melt the base of the ice shelves, has been identified (Thoma et al., 2008). The consequent retreat of the ice shelf grounding line (the boundary between the floating ice shelf and the grounded ice), glacial speed-up and increased mass loss from the ice sheet, has long been established. Recent field observations (Scott et al., 2009) confirm a previous mechanism by which thinning of the ice shelf can affect ice deep within the ice-sheet interior over decadal timescales (Payne et al., 2004). This raises the question of whether we are currently witnessing the beginning of a partial collapse of the west Antarctic ice sheet, concentrated in the Amundsen Sea Embayment. This region, because of its bedrock geometry, is particularly susceptible to small changes in grounding line position (Thomas et al., 1979).

Concerning reversibility of Greenland ice-sheet loss, one model study incorporating a detailed ice-sheet model has found evidence for multiple stable states, representing effectively irreversible loss, even if global climate returns to its pre-industrial state (Ridley et al., 2010). This demonstrates that a simple link between temperature thresholds and abrupt or irreversible change in particular elements of the climate system is not always appropriate. Other studies suggest that Greenland ice-sheet loss may be reversible (e.g. Lunt et al., 2004).

Of various possible climate thresholds considered by Kriegler et al. (2009), a complete melt of the Greenland ice sheet was assessed as the hardest to rule out for selected medium and high warming scenarios (exhibiting about 2–4 K and 4–8 K warming from years 2000–2200). Abrupt loss of the west Antarctic ice sheet is thought possible, although it is hard to quantify any threshold (Pollard and DeConto, 2009).

d Potential consequences. The most recent paleoproxy estimate of sea-level maximum during the last interglacial ($\sim$125 kyr ago) is 6.6–8 m (Kopp et al., 2009) with the likelihood that most of this rise emanated from Antarctica, although this is currently the only result suggesting such a high stand for Eemian sea level. The last interglacial may be a partial analogue for sustained future warming (Kopp et al., 2009), although it is unclear exactly how conditions during this period relate to potential future change. The estimated potential contribution to sea-level rise from west Antarctic ice-sheet loss has been reduced down to around 3.3 m over a sub-millennial timescale if assumptions are made about the varying vulnerability of ice as a function of local bedrock height (Bamber et al., 2009).

Various observational methodologies have been used to project sea-level rise by 2100. Semi-empirical methods based on past change (Rahmstorf, 2010) suggest that a rise of more than 1 m is possible (significantly larger than the AR4 upper bound estimate of 0.59 m). However, the mechanisms of past change used to calibrate these results may differ from those of future change. Another study (Pfeffer et al., 2008) used physical constraints to suggest that a total sea-level rise of more than 2 m by 2100 is very unlikely, with a value of 0.8 m being a more likely outcome.

e Cautions (uncertainties). While substantial progress in understanding has been made, it is still unclear what the recent observed changes imply for long-term future ice-sheet loss (Nick et al., 2009). New observations suggest that there may be a natural cycle of increase and decrease in the rates of mass loss from coastal glaciers (Murray et al., 2010), so short-term trends should not necessarily be extrapolated into the future.

2 Sea ice

a Introduction. The AR4 report highlighted a significant decreasing trend in Arctic sea ice areal extent. Possible impacts include loss of biodiversity and regional climate modifications (e.g. Lawrence et al., 2008), although there may be benefits such as opening of new trade routes. The trend in the summer minimum extent was especially marked. Research studies typically focus on change in the summer areal extent, because the ice reaches a minimum at the end of summer, and because the most reliable observations are available for areal extent (although ice thickness is another key quantity that is expected to reduce with global warming).

b Observed recent changes. Following concern about the imminent collapse of arctic summer sea ice, due to a large dip in 2007 (Stroeve et al., 2007), summer sea ice extent recovered back to the long-term trend line in 2009 (Fetterer et al., 2010). However, the summer minimum in 2010 was the third lowest in the satellite record (since 1979), and estimates of thickness suggest that the ice is significantly thinner as a result of being largely composed of thin first-year ice. It has been argued that the dip in 2007 was not particularly unusual in the context of the observational record (e.g. Notz, 2009), especially given that variability might be expected to increase as the sea ice thins (Goosse et al., 2009; Notz, 2009).

c Potential for dangerous change. Abrupt reductions in future Arctic summer sea ice extent are seen in projections from several CMIP3 models (Holland et al., 2006). It is still considered likely that Arctic sea ice decline would be reversible (Notz, 2009), although some consequences of a temporary, but complete, seasonal loss of sea ice (e.g. for biodiversity) might be irreversible.

Some new methods combining observational constraints with model projections suggest that summer sea ice in the Arctic may disappear earlier than predicted by many (but not all) AR4 models, probably before the end of the century under a mid-range non-mitigation emission scenarios (Boe et al., 2009; Wang and Overland, 2009). The expert elicitation study of Lenton et al. (2008) (which pre-dated the above literature on observationally constrained projections) estimated a global temperature threshold for loss of Arctic summer sea ice as being between 0.5 and 2 K above present.

d Potential consequences. A new study suggested that the risk of Arctic permafrost degradation and consequent methane release may be increased during periods of rapid sea ice loss, as regional climate warming is amplified due to albedo feedbacks (Lawrence et al., 2008).

e Cautions (uncertainties). Although model skill has improved, AR4 models show large uncertainty, in terms of differences in contemporary sea ice mass budgets, partly due to a lack of relevant observations to validate models (Holland et al., 2010).

3 Atlantic Meridional Overturning Circulation (AMOC)

a Introduction. The Atlantic Ocean has a Meridional Overturning Circulation (AMOC), which transports large amounts of heat northwards in the Atlantic from the Equator. A key part of this is called the thermohaline circulation (THC), which is the meridional transport of heat and salt. Disruption of the AMOC would have a major impact on the Northern Hemisphere climate, with likely detrimental impacts on human and animal systems. The IPCC AR4 concluded that:

> it is very likely that the Atlantic Ocean Meridional Overturning Circulation will slow down during the course of the 21st century. A multi model ensemble shows an average reduction of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080 to 2099. (IPCC AR4: 752)

Key issues addressed by recent studies include whether or not an AMOC slowdown is detectable, the possibility of complete shutdown – and subsequent reversibility, and the potential regional impacts on sea level and climate.

b Observed recent changes. Recent monitoring (Cunningham et al., 2007; Kanzow et al., 2007) has revealed large variability in the strength of the AMOC on daily to seasonal timescales. This large variability casts doubt over a previous report of decreases in AMOC transport from several hydrographic sections (Bryden et al., 2005), although it does not explain the observed water mass changes below 3000 m. Recent results based on radar altimeter and Argo in situ floats also suggest that there has been no slowdown, at least over the altimeter era (1993–present; Willis, 2010). In contrast, two ocean state estimation studies (Balmaseda et al., 2007; Wunsch and Heimbach, 2006) do indicate a slowdown, but these results need to be treated with caution as Saunders et al. (2008) show that some models do not capture the structure of the AMOC below 3000 m. It has been suggested, based on model studies, that anthropogenic aerosols may have temporarily slowed the weakening of the AMOC and that such weakening would only become significant several decades into the 21st century (Delworth and Dixon, 2006).

c Potential for dangerous change. Regarding the possibility of AMOC shutdown, a recent study (Swingedouw et al., 2007) with one climate model found that additional melt from Greenland could lead to complete AMOC shutdown in an experiment where CO_2 was stabilized at twice the pre-industrial concentration. However, a previous study with a different model (Ridley et al., 2005) had found no effect from similar levels of meltwater input. Mikolajewicz et al. (2007) showed results from an earth system model with atmospheric and ocean GCMs which produces a complete shutdown under a high emission scenario, but not before 2100.

Reversibility following shutdown is a key issue for the AMOC. Hofmann and Rahmstorf (2009) showed that hysteresis still occurs in a new low-diffusivity model. This is contrary to previous theoretical arguments that hysteresis might be a product of diffusivity of the low-resolution simplified ocean models used to perform the long-term integrations required to investigate this issue.

Some new studies evaluated the potential AMOC change by the year 2100. Schneider et al. (2007) analysed AR4 models and found that predictions of AMOC change (weighted by skill to represent current-day fields) showed that the AMOC will weaken by 25–30% by the year 2100. Two expert elicitation studies (Kriegler et al., 2009; Zickfeld et al., 2007) illustrated the large uncertainty and subjectivity concerning the risk of future AMOC shutdown. However, for the high temperature corridor of Kriegler et al. (2009) (4–8 K warming from years 2000–2200), the probability of complete shutdown was assessed to be at least 10%. Comparable results were found by the exercise reported by Zickfeld et al. (2007) (based on experts assessing broadly the same literature as in Kriegler et al., 2009). It is thought unlikely that the AMOC would significantly weaken with a 2°C global average warming.

d Potential consequences. There is some new work on the impacts of AMOC weakening. Two studies (Kuhlbrodt et al., 2009; Vellinga and Wood, 2008) found sea-level rise of several tens of cm along parts of North Atlantic coast (see also Landerer et al., 2007; Yin et al., 2009). They find that regional cooling would partially offset the greenhouse gas warming, and various other impacts may be substantial but hard to quantify such as change in tropical precipitation patterns and change in ocean currents leading to declining fish stocks and ecosystems (Schmittner, 2005).

e Cautions (uncertainties). New understanding has been gained about potential biases in climate model simulations of the AMOC. There is further evidence that a bias in ocean fresh water transport seen in various climate models may make the AMOC overly stable in current models (Weber et al., 2007). Hofmann and Rahmstorf (2009) also suggested that fundamental model selection bias could lead to models being too stable to AMOC shutdown. Large uncertainty remains regarding the influence of Greenland melting on the AMOC (Ridley et al., 2005; Swingedouw et al., 2007): this effect combines two poorly understood systems. A further uncertainty is the effect on the AMOC of the so-called Agulhas leakage – the transport of warm salty water from the Indian to the Atlantic Ocean by eddies shed from the Agulhas Current (Biastoch et al., 2009). This process is not well represented in climate models, which generally do not resolve ocean eddies.

4 Tropical forests

a Introduction. Recent research into the future vulnerability of tropical forests has largely, but not exclusively, focused on the Amazon, which features high biodiversity (Dirzo and Raven, 2003), and performs around 15% of global terrestrial photosynthesis (Field et al., 1998). Some climate model projections (e.g. Cox et al., 2000) suggest that the Amazon may be vulnerable to dieback induced by anthropogenic climate change.

More recent studies have examined several key issues in more detail. These include the forest uptake of carbon, its vulnerability to changes in climate (especially rainfall and temperature) and potential beneficial effects of increased carbon dioxide concentration. New information on these issues is emerging from decadal field campaigns tracking tree characteristics, observations of the Amazon forest response to the 2005 drought, and from multiyear experimental droughts, as well as new numerical model studies. The key issue of potential future changes in Amazonian climate have been addressed in a number of new climate model studies. The timescales of forest loss and regrowth, and the impact of fire have also been investigated.

b Observed recent changes. Field campaigns have shown that tropical forests, including old growth forests in the Amazon and Africa, are increasing the amount of carbon which they store annually, with models broadly in line with observations of decadal change (Lewis et al., 2009b; Phillips et al., 2009). Lewis et al. (2009a) suggest that the recent observed decadal trends in tropical forest characteristics are most likely due to increasing resource availability, potentially from rising CO_2.

Much has been learned about Amazon forest vulnerability from observations of its response to the 2005 drought. This has demonstrated that the Amazon forest is vulnerable to possible future drying (Phillips et al., 2009), although there is ongoing debate regarding how exactly the forest responded (Saleska et al., 2007; Samanta et al., 2010).

c Potential for dangerous change. Multiyear experimental droughts in two sites in eastern Amazonia have provided new information about forest vulnerability (da Costa et al., 2010), which appears consistent with the response to naturally occurring droughts (Phillips et al., 2010). In some areas, forest has been found to be more susceptible to extended droughts, of three years or more, than to annual drought. It has been suggested that the vulnerability of above-ground biomass storage to extended drought is significantly higher than in some vegetation models used in climate projections (Galbraith et al., 2010).

The potential beneficial effects of increased CO_2 have been investigated in extra-tropical field studies, which suggest that the CO_2 fertilization effect may not persist for more than a few years, due to limited nitrogen supply (Leakey et al., 2009; Norby et al., 2010), although this may not be true in tropical regions.

A number of model studies have explored potential future changes in Amazonian climate and its effects on simulated vegetation. Following on from the original Met Office Hadley Centre (HadCM3LC model) result of extensive dieback (Cox et al., 2000), several studies have explored the HadCM3LC projections further. The simulated drying pattern over Amazon seen in HadCM3LC has been found to be plausible because it may be currently masked by aerosol forcing in the real climate (Cox et al., 2008). However, this drying pattern is not found in all climate models. Sitch et al. (2008) applied patterns of climate change from HadCM3LC to different vegetation model formulations. They found that loss of some Amazon forest is robust to different vegetation model formulations. On the other hand, they found significant uncertainty in the amount of forest loss. Galbraith et al. (2010) provided further information about the mechanisms of simulated forest loss under HadCM3LC-like climate change, in particular the important role of temperature effects on forest resilience in the future, while Good et al. (2010) showed that in HadCM3LC the tropical mean negative effect of temperature on forest resilience is approximately balanced by positive CO_2 fertilization.

Projections from a range of other climate models were analysed by Malhi et al. (2009), who found that dry-season water stress is likely to increase over eastern Amazonia. Lapola et al. (2009) provide further information on climate model uncertainty: when patterns of climate change from GCMs other than HadCM3LC are used, the Amazon forest response is highly dependent on assumptions about the (highly uncertain) CO_2 fertilization effect (which in their vegetation model prevents dieback under climate change patterns from most GCMs).

Jones et al. (2009) investigated issues of timescales of dieback and reversibility. They showed that the long-term committed forest loss (in earth system model simulations where forest loss occurs) can be substantially larger than in transient simulations to 2100. Thus, a threshold can be crossed before the impacts are apparent. They found that in one model (HadCM3LC) the global temperature threshold for forest dieback is as low as 2°C, although this threshold is likely to be very model-dependent. They also showed that timescales for regrowth can be very long, although there are uncertainties due to model-dependent strength of vegetation-climate coupling.

There is also increasing recognition that anthropogenic effects other than greenhouse warming are critical for the forest. Interactions between effects of climate change and human activity in the forest (e.g. deforestation and associated increased fire risk, currently absent from GCMs) are very important. Combined effects may be larger than the sum of individual influences. Golding and Betts (2008) and Malhi et al. (2009) showed that climate change may increase vulnerability to fire, arguing that regional management may be critical in determining the forest fate. Owing to the long-term decrease in carbon storage that results, fires will act as a positive feedback on climate change (Gough et al., 2008).

In the expert elicitation study of Kriegler et al. (2009), there was wide uncertainty about the probability of Amazon dieback for their 'medium temperature corridor' (around 2–4 K warming from years 2000–2200), but for the 'high temperature corridor' (4–8 K warming), dieback probability was assessed to be at least 30%.

d Cautions (uncertainties). While Lewis et al. (2009a) found that models broadly reproduce recent changes in tropical forest carbon, large uncertainties remain (Grainger, 2010). Malhi et al. (2009) demonstrated that there is substantial uncertainty in rainfall projections in particular: there is a large intermodel spread in projections and model simulations of present-day rainfall over Amazon are rather poor. A large spread in vegetation model responses to a given climate change pattern was found by Lapola et al. (2009) and Sitch et al. (2008). Lapola et al. (2009) and Rammig et al. (2010) emphasized the critical and uncertain role of CO_2 fertilization in forest projections. Also, the details of vegetation response to drought in models may be different from that observed during the 2005 drought (Phillips et al., 2009) and in experimental droughts (Galbraith et al., 2010).

5 Accelerated carbon release from permafrost and ocean hydrates

a Introduction. Large amounts of carbon are stored in permafrost, and in ocean methane hydrates. Release of these stores could occur through anthropogenic warming, melting permafrost or destabilizing methane hydrates (e.g. O'Connor et al., 2010). This could act as a positive feedback, leading to further increases in the rate of anthropogenic warming. Release of carbon from either store is effectively irreversible from a human perspective, due to the long timescales required to establish these stores. Permafrost thawing could release additional carbon into the atmosphere either directly or indirectly by modifying wetlands emissions (Schuur et al., 2008; Zhang et al., 2009). Key issues include the amount of carbon in these stores, the potential thresholds and timescales of release, and the fate of the carbon once it is released from the permafrost or hydrate store.

6 Terrestrial permafrost

a Observed recent changes. Recent observations suggest that high-latitude permafrost regions are experiencing thawing (Jorgenson et al., 2006).

b Potential for dangerous change. Schuur et al. (2008) estimate that there is about 1672 PgC stored in northern circumpolar permafrost areas. The permafrost model of Khvorostyanov et al. (2008) for the Yedoma region of eastern Siberia simulated a release of 75% of the 500GtC stock over 3–4 centuries through a potentially self-sustaining feedback. This corresponds to an average release rate about one third of the current rate of CO_2 emission from fossil fuel burning.

There is still substantial uncertainty regarding the timescales of release (O'Connor et al., 2010). Methane hydrates in permafrost could destabilize and release methane to the atmosphere on a timescale of decades to centuries if the hydrate becomes exposed through coastal erosion (Shakhova et al., 2005) but timescales as long as millennia are possible. The risk of methane release from permafrost may also be increased if rapid sea ice loss occurs, as this amplifies regional climate change due to albedo feedbacks (Lawrence et al., 2008).

c Cautions (uncertainties). Large uncertainties exist regarding the amount of carbon stored in peat and permafrost (Hugelius and Kuhry, 2009), in important complex vertical and horizontal variations in permafrost properties, different mechanisms of permafrost loss and whether carbon is released as CO_2 or methane, the indirect effect of wetlands emissions and interaction with fire (O'Connor et al., 2010).

7 Ocean hydrates

a Observed recent changes. There have recently been isolated observations of methane gas escaping from the seabed into the overlying water column along the West Spitsbergen continental margin. This release may be due to warming of the West Spitsbergen current over the past 30 years (Westbrook et al., 2009) and is supported by process-based modelling (Reagan and Moridis, 2009).

Methane gas venting to the atmosphere from subsea permafrost in the sediments of the East Siberian Arctic seas has also been reported (Shakhova et al., 2010), although there is no direct evidence to establish whether this release is due to anthropogenic climate change or represents an ongoing adjustment to flooding during the last deglaciation.

b Potential for dangerous change. Shallow water hydrates are the most vulnerable and could release significant amounts of methane as a result of as little as a 1°C increase in seafloor temperature (Reagan and Moridis, 2008). Model studies (Archer et al., 2009; Reagan and Moridis, 2007) have indicated that there is potential for human activity to cause a significant fraction of ocean methane hydrates to destabilize, and for the consequent impact on the severity of anthropogenic global warming. Thresholds for hydrate release and the severity of such a release are, however, very poorly quantified (e.g. Archer et al., 2009). Archer (2007) suggested that any such release is most likely to take place on timescales of millennia or longer. This is because methane hydrates are stored in sediment columns, which provide thermal insulation from anthropogenic warming. However, the possibility of much more rapid release cannot currently be ruled out.

c Cautions (uncertainties). Substantial uncertainties remain, affecting the amount and timescale of methane release (Archer et al., 2009; O'Connor et al., 2010). These include: the amount of methane stored in ocean hydrates (the uncertainty range is around an order of magnitude of 170–1000 GtC according to a review by Archer, 2007), where it is concentrated geographically, the magnitude of future ocean warming at these locations, how the warming will propagate through the sediment column, and how much of the methane will escape the sea floor to reach the ocean and atmosphere. Archer et al. (2009) suggest that all these uncertainties

Table 1. Summary of key findings for each scientific sector

Sector	Summary of key findings
Ice sheets	Increased loss from Greenland and Antarctic ice sheets observed, but we now know more about the various processes responsible. Possible stages in the melting of Greenland identified in one model simulation, suggesting it may not be able to recover once certain limits are reached. Evidence that sea-level rise by 2100 may exceed the 95th percentile AR4 model-based projection of 59cm, but that a rise significantly above 2m by 2100 is very unlikely.
Sea ice	New analyses using observations suggest that Arctic summer sea ice may disappear earlier than predicted by many (but not all) AR4 models. The record low in 2007 raised concerns about rapid loss of Arctic sea ice within a few decades. Subsequent ice recovery and further analyses have reduced this concern.
Atlantic Meridional Overturning Circulation	Ocean circulation is highly variable and improved observations cast doubt on previously reported evidence of recent slowdown. Improved understanding of the ocean processes that affect the potential collapse of the Atlantic Ocean conveyor belt and irreversibility. These processes are not all well represented in models.
Tropical forests	Tropical forests, including old growth forests, are increasing the amount of carbon they store. New evidence for vulnerability to extended drought. Models may not correctly reproduce the mechanisms by which drought affects the forest.
Carbon emission from permafrost and ocean hydrates	Some observational evidence of thawing permafrost and of methane gas escaping from the seabed into the ocean. One model simulation of the permafrost in the Yedoma region of Siberia exhibited a potentially self-sustaining feedback. Likelihood, size and timescale of carbon release from permafrost and ocean hydrates still very uncertain.

have a very large impact on the potential climate impacts.

IV Conclusions

In this review we have highlighted some of the major post-AR4 advances in physical climate science, focusing on those areas relevant to the framing of policies for mitigation. While we have attempted to highlight the most significant relevant developments, this process is subjective so it is inevitable that some important papers are not included. The body of literature reviewed here does represent substantial progress in understanding likely future changes in the large-scale climate system. We summarize the main lines of progress in Table 1.

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