ENVIRONMENTAL SCIENCE & POLICY 27S (2013) S15–S31

Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/envsci


# The likelihood and potential impact of future change in the large-scale climate-earth system on ecosystem services

*Simon N. Gosling* *

*School of Geography, The University of Nottingham, Nottingham NG7 2RD, United Kingdom*

ARTICLE INFO

Published on line 27 June 2012

*Keywords:*
Ecosystem services
Climate change
Impact
Review
Sea level rise
Ocean acidification
Amazonia dieback
Water security
Monsoon
THC and AMOC collapse

ABSTRACT

This article reviews the level of current scientific understanding regarding the impact of future change in the large-scale climate-earth system on ecosystem services. Impacts from sea level rise, ocean acidification, increases in ocean temperature, potential collapse of the thermohaline circulation; failure of the South Asia monsoon; the melting of sea ice, the Greenland Ice Sheet and the West Antarctic Ice Sheet; changes in water availability; and Amazonia forest dieback, are considered. The review highlights that while a number of uncertainties remain in understanding, there is evidence to suggest that climate change may have already affected some ecosystem services. Furthermore, there is considerable evidence to show that future climate change could have impacts on biodiversity, as well as secondary impacts on issues important to human society, including; habitability; land productivity and food security; water security; and potential economic impacts.



## 1. Introduction

Humans' relationships with the environment can be described by the ecosystem services and benefits to society that the environment provides. The Millennium Ecosystem Assessment divided ecosystem services into four categories: provisioning (e.g. food, crops, water, energy), regulating (e.g. carbon sequestration, coastal wave defence), cultural (e.g. recreational experiences, scientific discovery, spiritual and cultural inspiration), and supporting (e.g. nutrient cycling, water cycling, provisioning of habitat) (MEA, 2005). Climate change has the potential to cause abrupt negative changes in ecosystems and associated ecosystem services. Moreover, any such changes have the ability to trigger large-scale crises, human migration and rapid-onset shocks with serious economic and social repercussions. Addressing these issues should be among the main priorities for the international environmental science and policy community (Galaz et al., 2008).

The environmental characteristics at a location affect both a population's exposure to hazard and the availability of ecosystem services (Black et al., 2011) and ecosystem services determine the habitability and attractiveness of places and landscapes. To this end, changes in ecosystem services could result in resettlement and the movement of people. Indeed, work has demonstrated that there is a strong spatial coincidence between ''hotspots'' of continued rapid population growth and climate change ''hotspots'' in countries in Africa, South and Southeast Asia, Central America, the Pacific, and some small islands (Hugo, 2011).

Black et al. (2011) describe a conceptual framework for the 'drivers of migration', suggesting that there are five main drivers of migration – environmental, political, social, economic and demographic. While actual or perceived spatial and temporal differences in these five dimensions influence population movement, this article is primarily concerned with environmental drivers – in particular – ecosystem services. This is not an attempt to support either a minimalist

* Tel.: +44 0115 951 5437.
E-mail address: simon.gosling@nottingham.ac.uk.
1462-9011/$ – see front matter 
http://dx.doi.org/10.1016/j.envsci.2012.03.011

or maximalist approach to describing the drivers of migration (Suhrke, 1994), but rather to discuss the latest research on the likelihood and potential impact of future change in large-scale climate-earth system components on ecosystem services, within the larger context of global environmental migration. Indeed, the range and complexity of the interactions between the five drivers of migration outlined by Black et al. (2011) means that it is rarely possible to distinguish individuals for whom environmental factors are the sole driver (Foresight, 2011).

Gemenne (2011) notes that estimates and projections of migration due to environmental drivers are not satisfactory, with many appearing to have been put forward in order to generate media attention rather than to provide empirically grounded estimates and predictions. This article does not aim to estimate future migration based upon environmental projections. Instead, it reviews how ecosystem services might be affected by changes in the large-scale climate-earth system and to this end, indicate what some of the environmental changes that could drive future migration, might be.

Evidence, both observed and simulated by models is reviewed. The likelihood and impact on ecosystem services of changes in the following components of the large-scale climate-earth system are considered:

- Sea Level Rise (SLR).
- Ocean Acidification (OA).
- Increases in ocean temperature.
- Potential collapse of the Thermohaline Circulation (THC).
- Failure of the South Asia monsoon.
- The melting of sea ice, the Greenland Ice Sheet (GIS) and the West Antarctic Ice Sheet (WAIS).
- Changes in water availability.
- Amazonia forest dieback.

This review focuses on large-scale climate-earth system components only, because it was undertaken as part of the UK Foresight Migration and Global Environmental Change project (Foresight, 2011). To consider the ecosystem changes that could drive large-scale migration, it was considered appropriate to review only large-scale climate-earth system processes, to maintain a focus. It is acknowledged, therefore, that this does not present an exhaustive review of all components of the climate-earth system.

There are a number of reasons why these components of the large-scale climate-earth system were selected. Firstly, these components were selected because recent research has demonstrated that they may be vulnerable to large, abrupt, or effectively irreversible change (Gosling et al., 2011; Lenton, 2011; McNeall et al., 2011; Schellnhuber, 2009). Secondly, all these components were considered in recent assessments of the impact of future change in the large-scale climate-earth system on human society, thus highlighting that they are components of high significance to human society (Good et al., 2011; Hayashi et al., 2010). Thirdly, each component presents a clear potential to impact on ecosystem services and human migration (e.g. SLR could result in land loss, ocean acidification could impact on aquaculture), thus justifying a detailed review of the literature. Fourthly, some of the components have been associated with an increased understanding of their associated physical processes – and so in published articles too – in recent years, e.g. ocean acidification and Amazonia dieback (Good et al., 2011; Gosling et al., 2011). Finally, these components were considered to be of concern, with regards to the potential to effect ecosystem services and migration, in discussions with decision- and policy-makers involved with the Foresight Migration and Global Environmental Change project (Foresight, 2011).

The impacts of possible change in each component, on the four divisions of ecosystem services set out by the Millennium Ecosystem Assessment, are considered throughout.

While previous studies have assessed the potential magnitude of the impact of climate change on ecosystem services, the assessment of impact likelihood has been up until recently, less common. Where possible, studies have been included that give estimates of either the likelihood of the large-scale event occurring, or the ecological impact, through use of probabilistic projections or expert judgement of the Intergovernmental Panel on Climate Change (IPCC). Where appropriate, the year of impact and scenario – e.g. SRES (Nakićenović et al., 2000) – is cited. This review is unique because previous studies either focus on particular parts of an ecosystem, or a limited area such as Europe (Feehan et al., 2009; Levermann et al., 2012), or to general climate change rather than specific climatic events.

## 2. Inclusion criteria for articles included in this review

In total, 205 articles from the international scientific literature, books, conference proceedings or reports are cited in this article. The literature searches were conducted with the Thomson Reuters Web of Science online academic search engine. Its databases cover over 10,000 journals from 256 categories and includes over 110,000 proceedings from the most significant conferences worldwide (WoS, 2012). Keyword searches were conducted for each component of the large-scale climate-earth system considered, using various combinations of the words included in Table 1.

Searches were limited to publications with a publication date in the range 2007–2011, to ensure that the latest post-AR4 (of the IPCC) scientific knowledge was assessed, although prominent and noteworthy pre-2007 studies were included where background information was appropriate. To this end, this review is an update to work published since the AR4, but the review does not aim to determine whether there is a *change in risk* relative to the conclusions of the AR4 – the reader should refer to Good et al. (2011) and Gosling et al. (2011) if they are interested in that issue.

Results presented by the Web of Science searches were supplemented by using the "Related Records®" feature, which enhances the power of cited reference searching by searching across disciplines for all the articles that have cited references in common. Searches with the same keywords presented in Table 1 were also undertaken with Google Scholar (http://scholar.google.co.uk/) because unpublished government and institutional reports may not show on the results from Web of Science.

When an article was returned by Web of Science or Google Scholar, the abstract of that article was read to ascertain whether the article included specific details of how a change in

**Table 1 – Words used for searches in Web of Science and Google Scholar. For each large-scale climate-earth system component, searches were also conducted for "climate change", "global warming", "impact", "biodiversity", "ecosystem", and "services". Also displayed is the number of citations included in each section of this review (some citations may appear in more than one section).**

| Component of the large-scale climate-earth system | Key-words | Citations |
|---|---|---|
| Sea level rise | Coast; coastal; flooding; sea level rise; SLR | 26 |
| Ocean acidification | Ocean acidification; pH; coral reef | 30 |
| Increases in ocean temperature | Ocean temperature; bleaching; coral; sea surface temperature; SST; ocean warming | 22 |
| Potential collapse of the thermohaline circulation | Thermohaline circulation; THC; Atlantic Meridional Overturning Circulation; AMOC; collapse; shutdown; weakening | 13 |
| Failure of the South Asia monsoon | Monsoon; failure; Asia; rainfall | 16 |
| Melting of sea ice, the Greenland ice sheet and the west Antarctic ice sheet | Sea ice; melting; Greenland; Antarctic; ice sheet | 36 |
| Changes in water availability | Water scarcity; runoff; drought; flood; water availability | 25 |
| Amazonia dieback | Amazonia; Amazon; forest; dieback; tree; drought | 25 |

that large-scale climate-earth system component might affect ecosystem services. If the article did not, then it was excluded from the review. For example, there are numerous articles that document modelling studies of how SLR might be affected by climate change, but only SLR studies that investigated how SLR may affect ecosystem services (as defined by the The Millennium Ecosystem Assessment) were included in the review.

## 3. Sea level rise

The IPCC concluded that ''SLR and human development are together contributing to losses of coastal wetlands and mangroves and increasing damage from coastal flooding in many areas'' (IPCC, 2007b; p. 9) and that ''coastal wetlands including salt marshes and mangroves are projected to be negatively affected by SLR especially where they are constrained on their landward side, or starved of sediment'' (IPCC, 2007b; p. 12).

This could have serious implications for the well-being of societies dependent on coastal ecosystems services. For instance, regulatory and supporting ecosystem services such as accumulation and transformation of nutrients, the attenuation of waves and storms, binding of sediments, and supporting of rich ecological communities are provided by tropical and subtropical mangrove forests and temperate salt marshes. There is uncertainty regarding the *magnitude* of SLR under climate change–the IPCC showed that across six scenarios (B1, B2, A1B, A1T, A2 and A1Fi), the range of the rate of SLR during 2090–2099 was 1.5–9.7 mm/year (Meehl et al., 2007; p. 820). Moreover, the IPCC concluded that understanding of the effects of Greenland and Antarctic ice sheets loss was ''too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise'' in the 21st century (IPCC, 2007a; p. 14) and this is an opportunity for further research (see Fig. 1). Excluding these effects, the IPCC projected a SLR of 0.26–0.59 m at 2090–2099 relative to 1980–1999 for their highest-emissions scenario (A1Fi) (IPCC, 2007a; p. 13) and setting an upper limit is still controversial (Lowe and Gregory, 2010).

*Observational* studies suggest that by stimulating biogenic contributions to marsh elevation, increases in $CO_2$, may aid some coastal wetlands in counterbalancing SLR by resulting in marsh accretion estimates often between 1 and 15 mm per year, which is greater than the lower range of projected SLR rate (Langley et al., 2009; Loomis and Craft, 2010; McKee, 2011). However, in high marsh (marsh that is located above the mean high water level and is inundated only infrequently, during periods of extreme high tide and storm surge), many plants are less productive when inundated and accrete more slowly, a feedback that can quickly transform high marsh into open water (Gedan et al., 2009).

- Modelling studies are needed to quantity a best estimate or an upper bound for SLR in the 21st century, which accounts for the effecrs of Greenland and Antarctic ice sheets loss under climate change.
- Further research is needed to understand the imapct of ocean acidification on fish.
- Further research is needed to understand how the South Asia monsoon will respond to climate change and to quantity the impact of failure on ecosystem services.
- Further research is needed to quantity the likelihood of GIS and WAIS rapid melting under climate change, and whetter if they occured, the melting would be reversible.
- Detection and attribution studies are needed to quantify the effect that climate change has had on changes in ecosystem services historically.

**Fig. 1 – Opportunities for further research, evident from the knowledge gaps highlighted by this review.**

Global *modelling* studies suggest less optimistic impacts with climate change. It has been estimated that due to SLR, the total coastal wetland area of the Coral Triangle (Indonesian, Malaysia, the Philippines, East Timor, Papua New Guinea, and the Solomon Islands) could decrease by between 26% (B1 scenario) and 30% (A2) by 2100 relative to 2010 (McLeod et al., 2010a). Nicholls (2004) found that between 5% and 20% of current coastal wetlands could be lost due to SLR by the 2080s (A1Fi scenario) but potential wetland losses due to SLR only were relatively small when compared to the potential losses from direct and indirect human destruction of wetlands. This is confirmed by observations of the high stress that society can place on coastal ecosystems (Day et al., 2008; Richards et al., 2008; Valiela et al., 2001; Watkinson et al., 2007). Moreover, this implies that human society's attitude towards environmental conservation can be highly important in terms of maintaining the sustainability of ecosystem services in the future under climate change.

The Chongming Dongtan Nature reserve in the Yangtze Estuary could lose 11% and 39% of its terrestrial area in the case of a prescribed 0.22 m and 0.88 m SLR respectively by 2100 (Tian et al., 2010) – the reserve is a vital breeding area for migratory shorebirds. Elsewhere the area of tidal freshwater marshes in Georgia, U.S. have been estimated to increase by 2% under the IPCC mean SLR scenario (52 cm SLR relative to 1999 under A1B), but decline by 39% under the maximum scenario (82 cm SLR), while salt marshes could decline in area by 20% and 45%, respectively (Craft et al., 2009) – this is an area where biodiversity and ecosystem services associated with productivity and waste treatment are high. Akumu et al. (2010) simulated that a prescribed 1 m SLR could decrease coastal wetlands such as inland fresh marshes from about 225.67 $km^2$ in February 2009 to about 168.04 $km^2$ by the end of the century in north-eastern NSW, Australia. In a larger-scale modelling experiment, Dasgupta et al. (2009) found that 1.86% of coastal wetlands across 84 developing countries could be lost under a prescribed 1 m global SLR, as well as highlighting the vulnerability of low-elevation coastal zones and small island states.

Ocean biodiversity could be affected too. Anticipated SLR this century is potentially greater than normal rates of coral reef growth (~6 mm/yr) and as SLR increases it could have a material impact in synergy with other stressors, especially ocean acidification and storms, driving shallow reef communities towards an erosional state (Veron et al., 2009). A prescribed SLR of 0.5 m could eliminate up to 32% of sea-turtle nesting beaches in the Caribbean (Fish et al., 2005) and studies show SLR could have negative impacts on turtle nesting beaches in Greece (Mazaris et al., 2009), the northern Great Barrier Reef (Fuentes et al., 2010) and French Guiana (Caut et al., 2010). Modelling studies suggest SLR could negatively impact crab population numbers in the UK (Fujii and Raffaelli, 2008), whilst observations show migratory birds could be affected due to stopover habitat losses from SLR (Galbraith et al., 2002).

It should be noted that many of the impacts on ecosystem services from SLR described here could be realised sooner under a scenario of rapid melting of the GIS or the WAIS. For instance, Bamber et al. (2009) showed that assuming a lower limit for a collapse of the WAIS to be 400 years, collapse of the WAIS could lead to a 3.3 m SLR.

## 4. Melting of sea ice, the Greenland Ice Sheet and the West Antarctic Ice Sheet

Recent increased GIS melting, probably associated with warming, has been observed (Joughin et al., 2008; van de Wal et al., 2008) and shown to be migrating northward (Khan et al., 2010). Present-day losses from both the GIS and WAIS are approximately equivalent to 1.5 mm/year of SLR (van den Broeke et al., 2009; Velicogna, 2009). However, there may be a natural cycle of increase and decrease in the rates of ice sheet loss (Kerr, 2009), so short-term trends should not necessarily be extrapolated into the future. Satellite data since 1978 shows that annual average Arctic sea ice extent has shrunk by 2.7% per decade, with larger decreases in summer of 7.4% per decade (IPCC, 2007a; p. 7).

Recent reviews suggest that there is higher uncertainty associated with the likelihood of loss of the WAIS than there is with melting of the GIS with climate change (Kriegler et al., 2009; Notz, 2009). Notz (2009) argues that "tipping points" (e.g. Eisenman and Wettlaufer, 2009) are more likely to exist for the GIS and WAIS loss than for Arctic sea ice loss, and the issue of whether GIS loss may be reversible is hotly debated (Charbit et al., 2008; Lunt et al., 2004; Ridley et al., 2010). This presents an important avenue for further research (Fig. 1).

Losses of Arctic sea-ice extent, GIS and WAIS could have impacts on ecosystem services (Post et al., 2009). For instance, recent Arctic warming is faster than that of the Pleistocene–Holocene transition (Overpeck et al., 1996), which coincided with widespread vegetation shifts of boreal coniferous forest that developed as a result of a nearly ice-free Greenland (de Vernal and Hillaire-Marcel, 2008) and faunal extinctions across the Arctic (Guthrie, 2006).

Observations of trophic mismatch due to declines in sea ice extent have been observed in mammals (Ferguson et al., 2005; Simmonds and Isaac, 2007) and penguins (Jenouvrier et al., 2009a), as sea ice changes impose spatial separations between energy requirements and food availability (Moline et al., 2008). Changes in plant-growing season associated with warming over Greenland has dramatically reduced caribou populations (Post and Forchhammer, 2008). This has potential to affect cultural and provisioning ecosystem services; e.g. by affecting caribou harvest by local communities, which threatens their cultural integrity and subsistence traditions (Callaghan and Johansson, 2009).

Observations of reduced sea ice extent and annual duration of sea ice is lowering populations of polar bears (Derocher, 2005; Fischbach et al., 2007; Regehr et al., 2007), seals (Ferguson et al., 2005), walrus (Grebmeier et al., 2006), breeding birds (Gilchrist and Mallory, 2005), and lemmings (Callaghan et al., 2005). Simulations suggest that polar bear spring and summer optimal habitat declines of 36% and 42% could be realised in 2045–2054, and 55% and 68% in 2090–2099, relative to 1985–1995 under an A1B scenario (Durner et al., 2009). Antarctic emperor penguin population size could decline from around 6000 breeding pairs in present to ~2300 in 2030 and to ~400 in 2100, based on projections of Antarctic sea ice extent under an A1B scenario (Jenouvrier et al., 2009b). If global-mean warming reaches 2 °C, emperor penguin populations north of 70°S could disappear (Ainley et al., 2010).

Estimates of SLR due to collapse of the WAIS include 3.3 m (Bamber et al., 2009), 5 m (Lythe et al., 2001), and 6 m (Nicholls et al., 2008); the range due to application of different models. While the associated SLR could take over 400 years to happen (Bamber et al., 2009), such SLR could have profound effects on the world's coasts (Olsthoorn et al., 2008), but it remains uncertain to what extent society would be able to respond (Nicholls et al., 2008). Nicholls et al. (2008) found that 8% of the global population could be threatened by the associated effects of a 5 m SLR, which has potential implications for coastal migration.

## 5. Ocean acidification

Absorption of $CO_2$ by the ocean has decreased ocean surface pH by 0.1 since pre-industrial times (IPCC, 2007a; p. 14). pH is projected to decrease by another 0.3–0.4 units under the IS92a scenario by 2100 (Meehl et al., 2007; p. 793). More recent modelling studies confirm these projections (Bernie et al., 2010) and the well-accepted conclusion that future changes in OA caused by emissions of $CO_2$ into the atmosphere are largely independent (although not completely) of the amounts of global-mean temperature rise, has been confirmed (Cao et al., 2007).

Coral reefs are the most widely recognised ecosystem threatened by OA (Kleypas and Yates, 2009). They support a variety of subsistence (Burke and Maidens, 2004), recreational (Burke et al., 2008), and commercial fisheries worldwide (Bryant et al., 1998) and calcifying organisms provide pearls, shells, and coral pieces for jewelry (Cooley et al., 2009). Global fisheries associated with coral reefs are valued at US$5.7 billion annually (Conservation International, 2008). Coral reefs provide a recreational ecosystem service, largely through tourism. Coral reef tourism equates for around 15% of GDP in Tobago (Burke et al., 2008) and is valued at around US$150–196 million for Belize (Cooper et al., 2008).

Coral reefs physically buffer coastal zones from storm waves, tsunamis and to some extent, SLR. This regulating ecosystem service could be compromised by OA. Without this service, losses could be greater, and coastal development could be more expensive (e.g., requiring seawalls) (Cooley et al., 2009). The global economic value of shoreline protection by coral reefs is estimated at US$9 billion per year (Cesar et al., 2003). Mangroves provide additional coastal protection in many reef systems but whether they will be affected by OA is unknown. Shoreline protection currently provided by mangroves is estimated at US$120–180 for Belize (Cooper et al., 2008) and US$28–50 for St Lucia (Burke et al., 2008).

Calcification of corals has declined by around 15% since 1990 in the Great Barrier Reef (De'ath et al., 2009) and Thailand (Tanzil et al., 2009). It has been suggested that atmospheric $CO_2$ increases will mean that corals could become increasingly rare beyond 2050 under SRES scenarios (Hoegh-Guldberg et al., 2007), as the world's oceans become undersaturated with respect to aragonite (Feely et al., 2009). Moreover, there is increasing evidence that among marine organisms that use aragonite to make their shells or skeletons (e.g. corals, snails and crabs), there will be "winners" and "losers" with increased OA (Hendriks et al., 2010; Kleypas and Yates, 2009; Riebesell et al., 2000; Ries et al., 2009).

There is evidence that OA negatively affects commercially valuable calcifying organisms such as mussels (Gazeau et al., 2007; Kurihara et al., 2009) and oysters (Kurihara et al., 2007). Developing nations in the Pacific rely on such organisms for about 7–20% of their catches and many of the small island states that comprise this region have limited agricultural alternatives (Cooley et al., 2009) for the provision of income and protein (Burke and Maidens, 2004). In contrast, industrial nations generally import or harvest such organisms as a luxury rather than an important source of protein (Cooley et al., 2009). Nevertheless, if a 10–25% decrease in US mollusc harvests from 2007 levels were to occur, $75–187 million in direct revenue could be lost each year henceforth (molluscs accounted for $748 million (19%) of 2007 US domestic ex-vessel revenues) (Cooley and Doney, 2009).

Non-calcifying organisms, mainly fish, may also be affected by OA, although this is a new and emerging theme. There are still several knowledge gaps (Cobb, 2010) and this represent one of the knowledge gaps highlighted by this review, which is worthy of further research (see Fig. 1). Recent evidence suggests OA can impair fish hearing and balance (Checkley et al., 2009), sense of smell (Munday et al., 2009), and sensing of predators (Munday et al., 2010), which may have serious consequences for fish populations. Moreover, OA has been projected to trigger marine oxygen holes (Hofmann and Schellnhuber, 2009), which cause 'dead zones' (Diaz and Rosenberg, 2008).

## 6. Changes in ocean temperature

The IPCC found that mean global sea surface temperature (SST) has increased by 0.13 °C per decade since 1979 (Trenberth et al., 2007; p. 237), and that it is "virtually certain to rise significantly" (Nicholls et al., 2007; p. 323) with climate change. The IPCC projections indicate that SST rise (°C) by the end of the 21st century, relative to 1980–1999, could be 1.5 (B1 scenario), 2.2 (A1B) or 2.6 (A2) (Nicholls et al., 2007; p. 323).

One of the most prominent impacts of rising ocean temperatures is coral bleaching. Sharp declines in the abundance and extent of coral reefs associated with increased bleaching have been shown to be driven in large part by elevated SSTs (Lough, 2008), which could have major implications for the future viability of coral reef systems and the ecosystem services they provide, e.g. see the previous section.

Major bleaching events in 1998 and 2002 affected entire reef systems (Berkelmans et al., 2004) and global climate modelling suggests that thermal thresholds could be exceeded more frequently (McLeod et al., 2010b), with the consequence that bleaching could recur more often than reefs can sustain, perhaps almost annually on some reefs as early as 2030 under an A2 or B2 scenario (Donner, 2009; Donner et al., 2005; Hoegh-Guldberg, 2005). Veron et al. (2009) showed that wide-scale temperature-induced mass coral bleaching causing mortality started when atmospheric $CO_2$ levels exceeded around 320 ppm, with sporadic but highly destructive mass bleaching occurring in most reefs world-wide at around 340 ppm – at the present level of around 387 ppm, allowing a lag-time of 10 years for sea temperatures to respond, most reefs world-wide are committed to an irreversible decline. However, it should be noted that future coral bleaching is likely to be highly heterogeneous and could produce more localised, rather than global, impacts of climate change (Selig et al., 2010). SLR and increasing storm intensity could exacerbate these impacts (Veron et al., 2009).

An ability of corals to respond to rising SSTs by adapting or acclimatising to changing conditions has been suggested (Baker et al., 2008; Berkelmans, 2009) but recovery after bleaching is not a *full recovery* and leads to a changed ecosystem (McClanahan, 2000) and/or reduced diversity (Lambo and Ormond, 2006). Furthermore, observed bleaching is seen as compelling *prima facie* evidence that corals are unable to adapt or acclimatise quickly enough to compensate for climate changes (Jones, 2008).

Changing species distributions and regime shifts are possible due to rising ocean temperatures. Reduced ice from ocean warming reduces Atlantic krill recruitment (Loeb et al., 1997), which in turn could have adverse effects for higher predators that depend upon krill for food (Reid and Croxall, 2001). Cheung et al. (2009) showed that by 2050, rising SSTs could cause high local fish extinction intensity along the southern Mediterranean coast, as well as expansion of new fish species into areas not previously occupied by them (invasion) around coastal South Africa and southeastern Australia due to limited availability of suitable habitats. Also climate change may lead to large-scale redistribution of global fish catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics, in 2050 under an A1B scenario (Cheung et al., 2010). Adverse complex responses to SSTs have been observed in the nesting phonologies of sea turtle species (Weishampel et al., 2010), the foraging habitats of Pacific walrus populations (Grebmeier et al., 2006), and abundance declines of cold-adapted marine mammals like the narwhal, beluga and polar bear, mediated via changes in prey distribution and abundance (Simmonds and Isaac, 2007).

## 7. Potential collapse of the thermohaline circulation

The Atlantic Ocean has a Meridional Overturning Circulation (AMOC), which transports large amounts of heat northwards in the Atlantic from the Equator. A key component of this is called the thermohaline circulation (THC), which is the meridional transport of heat and salt. The IPCC stated that it is ''*very likely*'' that the AMOC will slow down during the course of the 21st century – a multi-model ensemble showed an average weakening of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080–2099, under A1B (Meehl et al., 2007; p. 772). In terms of future AMOC shutdown (as opposed to weakening), two expert elicitation studies illustrated large uncertainty and subjectivity. For a 4–8 °C warming from years 2000 to 2200, the probability of complete shutdown was assessed to be at least 10% by Kriegler et al. (2009) and 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).

The impact of THC collapse on ecosystem services may not be confined to just the North Atlantic (Higgins and Vellinga, 2004) due to large-scale teleconnections and changes in precipitation patterns (Vellinga and Wood, 2008). Simulations by Link and Tol (2011) suggest that in economic terms, some countries could initially benefit from THC collapse – e.g. an improvement in water resources (assumed to change linearly with global warming, based upon equations presented by Downing et al., 1996) for Iraq in year 2100, equivalent to around 2.5% of GDP – and that at the global-scale, the impact on ecosystems (measured by species loss) could be relatively small compared with the impact on water resources. Moreover, it has been suggested that terrestrial ecosystem productivity could be affected much more by the fertilisation from increasing $CO_2$ concentration than by a THC shutdown and that although regional socioeconomic impacts of THC collapse might be large, damages would probably be small in relation to the respective GDPs of the countries affected (Kuhlbrodt et al., 2009).

Arnell (2006) noted that THC collapse could increase water resources stresses in Europe and south and east Asia, which could affect the reliability of existing water resource management systems. Köhler et al. (2005) showed that THC collapse could lead to a reduction of extent in boreal and temperate forests and a decrease in carbon storage in high northern latitudes, as well as enhanced storage in mid-latitudes due to enhanced growing conditions.

THC collapse could have implications for fisheries and crop yields (Keller et al., 2000). Regional shifts in currents due to THC collapse could lower cod survival chances, which could lead to cod fisheries becoming unprofitable by the end of the 21st century (Kuhlbrodt et al., 2009; Link and Tol, 2011). A simulation experiment by Schmittner (2005) showed that a slowdown in the AMOC from16 Sv at experiment year 0 to less than 3 Sv at year 500 could lead to a collapse of North Atlantic plankton stocks to less than half of their initial biomass by year 500. This could have catastrophic effects on fisheries and human food supply in affected regions. This agrees with observational evidence from the Pacific and Atlantic that nutrient supply to the upper productive layer of the ocean is declining, in part because of a reduction in the strength of the AMOC (Curry and Mauritzen, 2005; McPhaden and Zhang, 2002). Also, paleological evidence suggests that North Atlantic plankton biomass has declined in the past by 50% during periods of a reduced AMOC (Schmittner, 2005). Simulations by Kuhlbrodt et al. (2009) showed that terrestrial ecosystem productivity was affected much more by the $CO_2$ fertilisation effect than by a THC shutdown, and that the level of warming in the 22nd to 24th century favoured crop production in northern Europe considerably, no matter whether the THC shut down or not.

## 8. Failure of the South Asia monsoon

The South Asia monsoon is a major provisioning and regulating ecosystem service, with over 22% of the world's population depending on it (Ashfaq et al., 2009) – it contributes 75% of the total annual rainfall in major parts of the region (Dhar and Nandargi, 2003). Understanding of how it may respond to climate change is uncertain (Wahl and Morrill, 2010), which is an opportunity for further research (see Fig. 1).

Global climate models show different responses of the monsoon circulation to climate change – e.g. some models exhibit a robust ENSO-monsoon contemporaneous teleconnection with climate change, such as the inverse relationship between ENSO and rainfall variations over India, while other models do not (Annamalai et al., 2007). Generally, global climate models fail to accurately simulate the South Asia monsoon (Kripalani et al., 2007). However, some studies do suggest monsoon failures could become more common with climate change (Ashfaq et al., 2009) and that South Asia may experience more frequent and longer droughts in the future (Abram et al., 2007; Overpeck and Cole, 2007). Little research has assessed the impact of potential future monsoon failure on ecosystem services – research is needed here (see Fig. 1).

Agriculture accounts for 18% of India's GDP, it employs 60% of the population, and 60% of the cropped area is rain-fed (Mall et al., 2007). The 2002–2003 monsoon failure demonstrated the sensitivity of ecosystem services in India to future events; a 19% decline in summer monsoon rainfall in 2002 resulted in a 18–20% decline in food grains production relative to the preceding year (Mall et al., 2007; Sikka, 2003). Prolonged dry periods associated with monsoon variability promoted terrestrialisation of wetlands in the Keoladeo National Park, India, with some wetland biodiversity loss (Chauhan and Gopal, 2001).

Historical evidence shows that droughts linked with four historical major monsoon failures (mid 17th century; mid 18th century; 1790–1796; and 1876–1878) were associated with reductions in crops harvests and severe famines (Davis, 2001; Lal and Islam, 2010), and societal unrest (Grove, 2007; Lieberman, 2003; Shen et al., 2007). Repeats of such monsoon failures in the future could be associated with different magnitude impacts because the population's sensitivity to monsoon failure may now be higher than ever due to the current harvesting of water beyond renewable limits, which makes it more difficult to meet water deficiencies, and increasing commercialisation of agriculture and water-intensive cultivation are subjecting farmers to higher income risks from adverse climate (Chand and Raju, 2009).

## 9. Amazonia forest dieback

Global climate modelling experiments indicate that climate change under a "business as usual scenario" could cause a major loss of the Amazon rainforest from the middle of this century onwards (Huntingford et al., 2008). In turn, this could induce a positive feedback on global climate, whereby additional $CO_2$ is released back into the atmosphere. It has been suggested that the main driver of such 'dieback' could, qualitatively, be related to projections of persistent 'El Niño-like' oceanic conditions that trigger large rainfall declines over Amazonia (Cox et al., 2004).

Recent observations of Amazonia response to a severe drought in 2005 demonstrated a high vulnerability to drying as well as potential for large carbon losses to exert positive feedback on climate change (Phillips et al., 2009). Whilst initial resistance to drought has been observed, this resistance also appears to break down following an imposed drought of 3 years or longer (Da Costa et al., 2010).

Amazonia is home to 25% of the world's terrestrial species (Dirzo and Raven, 2003) and comprises a total biomass that is equivalent to over 10 times the current annual global $CO_2$ emissions to the atmosphere (Saatchi et al., 2007). The region performs around 15% of global terrestrial photosynthesis (Field et al., 1998) and it is increasing the amount of carbon stored annually (sequestration) as a result of climate change (Phillips et al., 2009) rather than being carbon neutral (Luyssaert et al., 2008). Therefore dieback of Amazonian forests would compromise an important regulating ecosystem service and could have severe secondary impacts on biodiversity as well as impact regional and global climate as a result of $CO_2$ release (Marengo, 2006; Phillips et al., 2002).

Modelling studies suggest high uncertainty in response under climate change scenarios due to uncertainties associated with climate projections and forest response. Probabilistic simulations by Malhi et al. (2009) indicated a 53% probability of transition to a rainfall regime more suitable for seasonal forest and a 26% probability of approaching a rainfall regime more appropriate for savannah, by 2070–2099 under an A2 scenario. Other probabilistic estimates are presented by Salazar et al. (2007) – they calculated a 75% probability that Amazonia forest area could decrease by 3% for the period 2020–2029 and by 18% for 2090–2099 (A2 scenario). Sitch et al. (2008) applied patterns of climate change projections to different vegetation model formulations and found that loss of some Amazon forest is robust to different vegetation model formulations, but they found significant uncertainty in the magnitude of forest loss. Similarly, Huntingford et al. (2008) showed that the potential for human-induced climate change to trigger the loss of Amazon rainforest appears robust within the context of uncertainties associated with climate model parameters and forest models. Importantly, model simulations to 2100 can substantially underestimate long-term committed forest loss (in simulations where forest loss occurs) because the global terrestrial biosphere can continue to change for decades after climate stabilisation (Jones et al., 2009).

Other modelling studies show that Amazonia dieback is highly dependent on assumptions about the $CO_2$ fertilisation effect – which itself is highly uncertain – to the point where inclusion/exclusion of the effect yields decreases/increases in Amazonia forest loss under climate change scenarios (Lapola et al., 2009; Rammig et al., 2010). Importantly, there is evidence to suggest that the $CO_2$ fertilisation effect may not persist for more than a few years (Leakey et al., 2009) and that the benefit may be significantly reduced by concurrent fertilisation of vines, which can shorten the lifespan of trees (Phillips et al., 2002).

$CO_2$ doubling modelling experiments show that further anthropogenic deforestation of the Amazon basin for conversion to pasture and cropland coupled with climate change, has the potential to increase the basin-average temperature by up to around 3.5 °C (Costa and Foley, 2000). Possible increases in human migration push factors from urban areas in Brazil (Carr, 2009) pose a contributing risk factor towards further destruction of Amazonia with climate change. The implementation of Protected Areas (PAs) is important for maintaining the ecosystem services currently presented by the region (Soares-Filho et al., 2010). Moreover, climate change may increase vulnerability to fire, which suggests that regional management may be critical in determining the Amazon forest fate (Golding and Betts, 2008; Malhi et al., 2009). Owing to the long-term decrease in carbon storage that results, fires could act as a positive feedback on climate change (Gough et al., 2008).

## 10. Changes in water availability

The IPCC concluded that all IPCC regions ''show an overall net negative impact of climate change on water resources and freshwater ecosystems (high confidence)'' under climate change and that ''areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources (very high confidence)'' (Kundzewicz et al., 2007; p. 175).

Observations show that forest ecosystems are highly vulnerable to increases in drought with climate change (Allen et al., 2010). European temperate woodlands are considered to be particularly vulnerable to drought, e.g. France (Verbeeck et al., 2008), Germany (Gartner et al., 2008) and the Netherlands (van der Werf et al., 2007). Other observational studies show that North American forests could be vulnerable to increased tree mortality due to the increased survival of bark beetles during drought episodes (Bentz et al., 2010) and changes in floods and droughts are already having impacts on desert ecosystems, e.g., population reductions (Thibault and Brown, 2008), displacement (Kelly and Goulden, 2008) and local extinction of certain desert species (Foden et al., 2007).

Southern Mediterranean ecosystems are particularly vulnerable to water stress and desertification processes with climate change (de Dios et al., 2009; Gao and Giorgi, 2008), as a consequence of large projected decreases in precipitation and glacier meltwater, and consequent drought stress (Giorgi and Lionello, 2008). Mountain conifer species, butterflies, amphibians and temperate trees are particularly at risk in this area (Benito Garzon et al., 2008; Wilson et al., 2007). Mediterranean beach tourism in the Mediterranean – an important cultural ecosystem service and source of income in the region – may also be affected (Moreno and Amelung, 2009).

Freshwater availability is a major provisioning ecosystem service. A recent study (Vorosmarty et al., 2010) showed that globally, whilst water security increases with affluence, so do threats to biodiversity – the actions taken to reduce water scarcity (e.g. dam construction and flow diversions) typically results in habitat loss and reductions in fish diversity and water quality. This is particularly relevant, given that recent simulations suggest that drought frequency could increase globally under climate change (Hirabayashi et al., 2008; Sheffield and Wood, 2008). Moreover, drought can – in conjunction with socio-economic factors – affect the vulnerability of key food crops to drought (Simelton et al., 2012).

In 2000, approximately 1.6 billion people were considered to be living in watersheds classed as water stressed (having access to less than 1000 $m^3$/person/year water); equivalent to 27% of the world's population (Arnell et al., 2011). Simulations by Rockstrom et al. (2009) showed that in 2050 (A2 scenario) around 59% of the world's population could be exposed to irrigation water shortage. A number of modelling studies show that the number of people affected by increased water stress due to climate change could be in the range (based upon SRES scenarios and multiple forcing climate models) of around 0.4–1.7 billion, 0.7–2.8 billion, and 0.9–4.5 billion, in the 2020s, 2050s, and 2080s, respectively (Arnell et al., 2011; Gosling et al., 2010; Hayashi et al., 2010).

## 11. Synthesis

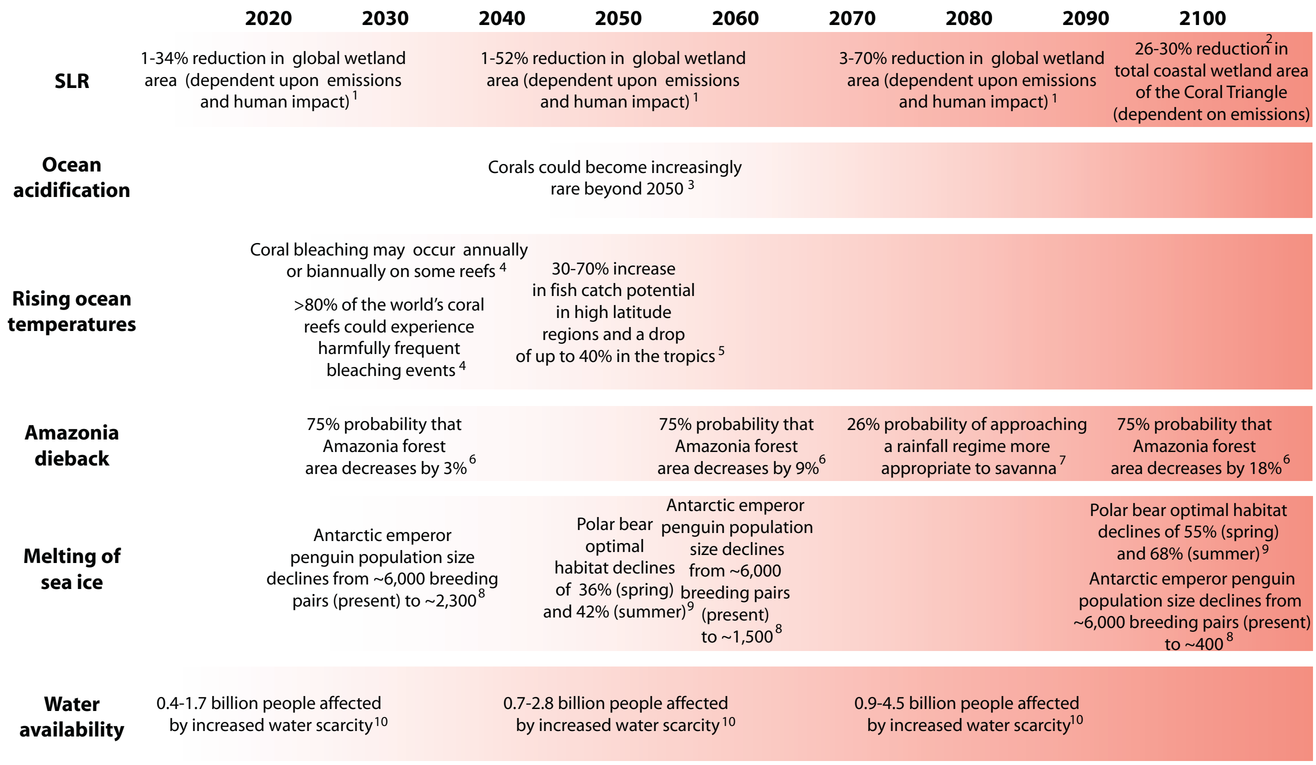
A detailed global-scale modelling study, with consistent baseline and future scenarios would be needed to assess quantitatively whether ecosystem services in any particular regions of the globe are more vulnerable than others to large-scale changes in the climate-earth system. To this end, such a conclusion is not possible from a literature review and this was not an aim of this review. However, it is possible to make a qualitative statement on which regions regularly appear as vulnerable, based upon the frequency of mention in this review. The regions include the Mediterranean (Benito Garzon et al., 2008; Cheung et al., 2009; Day et al., 2008; de Dios et al., 2009; Gao and Giorgi, 2008; Giorgi and Lionello, 2008; Kundzewicz et al., 2008; Mazaris et al., 2009; Moreno and Amelung, 2009; Wilson et al., 2007), low-elevation coastal zones and small island states (Burke et al., 2008; Cooley et al., 2009; Cooper et al., 2008; Dasgupta et al., 2009; Day et al., 2008; McLeod et al., 2010a) and dryland margins (Alo and Wang, 2008; Foden et al., 2007; Gosling et al., 2010; Kelly and Goulden, 2008; Thibault and Brown, 2008).

It is also possible to make a mixture of qualitative and quantitative statements on the impacts of changes in the large-scale climate-earth system on ecosystem services that are of particular importance to human society (see Table 2). The statements can be divided according whether to they arise from observational studies or modelling projection studies. Moreover, the statements can be grouped into four broad sectors, which were chosen based upon a value judgment of what aspects of human society are most directly linked with the impacts and which are drivers of migration (Black et al., 2011; Foresight, 2011); habitability, land productivity and food security, water security, and potential economic impacts. A further distinction can be made, based upon whether the impacts are local scale impacts or, regional or global in nature (Table 2). With some changes in the large-scale climate-earth system, effects may be an agglomeration of numerous local scale impacts (e.g. the impact of OA on marine organisms), while for others, effects may be much larger-scale (e.g. the impacts of SLR on coastal habitability or the $CO_2$ positive feedback effects of Amazonia dieback). This highlights the complexity of the impacts reviewed here and it means that the environmental management response needs to be multi-sectoral and to operate at a multitude of spatial and temporal scales.

Fig. 2 summarises the projected impacts reviewed here, chronologically. Text entries are placed so that the centre of the text indicates the approximate onset of a given impact, which is also where the colour starts increasing from pale to deep in accordance with the magnitude of impact, though it should be noted that many of the impacts of climate change will be non-linear (Schneider, 2004). Adaptation to climate

**Table 2 – Impacts of changes in the large-scale climate-earth system on ecosystem services that are of particular importance to human society. Modelling projection studies are displayed in italics, observational studies in standard font. Impacts that are regional or global in nature are underlined, while local impacts are not.**

| Habitability | Land productivity and food security | Water security | Potential for economic impacts from loss of ecosystem services |
|---|---|---|---|
| | OA negatively affects mussels and oysters, which are relied upon by many developing nations in the Pacific and there are limited agricultural alternatives (Cooley et al., 2009) for the provision of protein (Burke and Maidens, 2004). | Cook et al. (2010) describe four historical major monsoon failures associated with severe droughts. | |
| | *Climate change and increases in ocean temperature may lead to large-scale redistribution of global fish catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics, in 2050 (Cheung et al., 2010).* | Chand and Raju (2009) argue that Monsoon Asia's population's sensitivity to monsoon failure may now be higher than ever due to the current harvesting of water beyond renewable limits, which makes it more difficult to meet water deficiencies. | |
| *SLR could reduce habitability due to loss of coral reefs, sandy shores and landward progression of estuaries (Brierley and Kingsford, 2009).* | Cook et al. (2010) describe four historical major monsoon failures. Historical evidence shows that the droughts linked with each failure were associated with reductions in crops harvests and severe famines. | Recent observations of Amazonia response to a severe drought in 2005 demonstrated a high vulnerability to future drying as well as potential for large carbon losses to exert positive feedback on climate change (Phillips et al., 2009). | Up to 15% of GDP for some small islands (e.g. Tobago) is from tourism associated with coral reefs but they are at risk from OA and rising SSTs (Burke et al., 2008). |
| Cook et al. (2010) describe four historical major monsoon failures. Historical evidence shows that the droughts linked with each failure were associated with societal unrest. | India is highly vulnerable to monsoon failures; a 19% decline in summer monsoon rainfall in 2002 resulted in a 18–20% decline in food grains production from the preceding year (Mall et al., 2007; Sikka, 2003). | *The southern Mediterranean and its ecosystems have been identified as particularly vulnerable to water stress and desertification processes under climate change conditions (de Dios et al., 2009; Gao and Giorgi, 2008), as a consequence of large projected decreases in precipitation and glacier meltwater, and consequent drought stress (Giorgi and Lionello, 2008).* | Global fisheries associated with coral reefs are valued at US$5.7 billion annually (Conservation International, 2008) but they are at increasing risk from OA. |
| *Collapse of the WAIS could lead to a 3.3 m SLR (Bamber et al., 2009), which could have profound effects on the world's coasts (Lonsdale et al., 2008; Olsthoorn et al., 2008; Poumadère et al., 2008), but it remains uncertain to what extent society would be able to respond (Nicholls et al., 2008).* | Changes in plant-growing season associated with warming, has dramatically reduced caribou populations in Greenland (Post and Forchhammer, 2008; Post et al., 2009), which in turn has the potential to affect caribou harvest by local communities, which threatens their subsistence traditions (Callaghan and Johansson, 2009). | *The number of people affected by increased water scarcity due to climate change is simulated to be around 0.4–1.7 billion, 0.7–2.8 billion, and 0.9–4.5 billion, in the 2020s, 2050s, and 2080s, respectively, globally (Arnell, 2004; Arnell et al., 2011; Gosling et al., 2010; Hayashi et al., 2010).* | Increasing commercialisation of agriculture and water-intensive cultivation in Monsoon Asia are subjecting farmers to higher income risks from future monsoon failures (Chand and Raju, 2009). |
| | *The total coastal wetland area of the Coral Triangle is estimated to decrease by 26–30% in 2100 relative to 2010 (McLeod et al., 2010a).* | *The Mediterranean, southern Africa and mid-western USA are areas at high risk to reduced water availability (Gosling et al., 2010).* | *Shifts in currents associated with THC weakening could cause fishery industries to become unprofitable (Kuhlbrodt et al., 2009; Link and Tol, 2009).* |
| | *Modelling studies suggest SLR could negatively impact crab population numbers in the UK (Fujii and Raffaelli, 2008).* | *THC collapse could affect global water resources (Link and Tol, 2011). Specifically, collapse could increase (relative to gradual climate change) water resources stresses in Europe and south and east Asia, and could cause changes to the timing of river flows through the year, which in turn could affect reliability of existing water resource management systems (Arnell, 2006).* | The global economic value of shoreline protection by coral reefs is estimated at US$9 billion per year (Cesar et al., 2003) but these are at risk from ocean acidification and rising sea surface temperatures (SSTs). |
| | OA negatively affects commercially valuable calcifying organisms such as mussels (Gazeau et al., 2007; Kurihara et al., 2009) and oysters (Kurihara et al., 2007). | | |




1. Simulated range across four SRES scenarios (A1Fi, A2, B2 and B1) (Nicholls, 2004).
2. Simulated under the SRES B1 and A2 scenarios respectively (McLeod et al., 2010a).
3. This assumes atmospheric CO2 concentrations follow the SRES A1B, A2 or A1Fi scenarios (Hoegh-Guldberg et al., 2007).
4. Simulated under the SRES A2 and B2 scenarios (Donner et al., 2005).
5. Simulated under the SRES A1B scenario (Cheung et al., 2010).
6. Simulated under the SRES A2 scenario (Salazar et al., 2007).
7. Simulated under the SRES A2 scenario (Malhi et al., 2009).
8. Simulated under the SRES A1B scenario (Jenouvrier et al., 2009b).
9. Simulated under the SRES A1B scenario (Durner et al., 2009).
10. Simulated range across two SRES scenarios (A2 and B2) (Arnell, 2004).

**Fig. 2 – A chronology of the impact of future change in the large-scale climate-earth system on ecosystem services, where studies have attempted to quantify the magnitude of a given impact under a changed climate for a given time in the future. Entries are placed so that the centre of the text indicates the approximate onset of a given impact. Adaptation to climate change is not included in these estimations.**

change is not included in the estimations. Fig. 2 can be compared with Figure SPM.2 of the IPCC (2007b; p. 16) and the updated ''reasons for concern burning embers'' diagram presented by Smith et al. (2009; p. 4134). This review is unique, however, because it focuses on ecosystem services only. A limitation of all three figures is that the simulations used to inform them, are based upon the application of different climate models and scenarios. To some extent, this is accounted for in the diagrams, by providing information on the scenarios, but it should, nevertheless, be noted that an inherent degree of uncertainty is associated with the figures, and that impact sectors may not necessarily be directly comparable (having come from different studies). Nevertheless, the figures present a useful summary for policy-makers. Fig. 2 is in large agreement with Figure SPM.2 of the IPCC (2007b; p. 16) and the diagram presented by Smith et al. (2009; p. 4134), which indicates that compared with results reported in the IPCC Third Assessment Report in 2001, smaller increases in global mean temperature rise are now estimated to lead to significant or substantial consequences. Importantly, impacts may start to occur from as early as 2020 (see Fig. 2).

## 12. Conclusion

This review has highlighted that there is considerable evidence to show that future climate change could have impacts on biodiversity, as well as secondary impacts on issues important to human society, including; habitability; land productivity and food security; water security; and potential economic impacts. While the studies reviewed here do not estimate whether these impacts will affect migration, they do – in conjunction with other drivers of migration (Black et al., 2011) – have the *potential* to. However, it is important to note that the changes in ecosystem services presented here (e.g. see Table 2), may not play a *direct role* in migration, and recent research shows – in the Mediterranean region as a case study – that environmental factors play a limited and largely *indirect role* in migration – with only extreme forms of environmental stress (e.g. declining rainfall) having an impact on internal migration but unlikely to result in massive international migration (de Haas, 2011). This is supported elsewhere; for example – Kniveton et al. (2011) used agent-based model simulations for Burkina Faso to show that in terms of climate change, a change to a drier environment produces the largest total and international migration fluxes when combined with changes to inclusive and connected social and political governance. Moreover, after an exploration of the effects of environmental change on UK internal migration, Fielding (2011) concludes: ''when it comes to internal migration, social-system-and-social-system-change, trumps environmental-drivers-and-environmental-change every time.''

It is for these reasons that this review has not attempted to estimate how changes in ecosystem services associated with changes in the large-scale climate-earth system may affect the numbers of migrants in the future, specifically. Indeed, migration is complex, multi-casual and non-linear and an environmentally deterministic approach that does not account for the importance of human agency in migration outcomes is not appropriate (Foresight, 2011). For instance, while collapse of the WAIS could lead to a 3.3 m SLR (Bamber et al., 2009), a straightforward calculation that estimates the resident population 'at risk' from this SLR and then assumes that a certain proportion of this population is likely to move in the future, is not suitable. Nevertheless, the secondary impacts displayed in Table 2 could operate in combination with social, political and demographic factors, to act as an indirect driver of future migration.

This review found a proportionally larger amount of evidence to suggest that ecosystem services are vulnerable to changes in the large-scale climate-earth system, in three regions, above others. These include the Mediterranean, low-elevation coastal zones and small island states, and dryland margins. Significantly, the latter two have recently been highlighted as regions where understanding the links between migration and environmental change are particularly important (Foresight, 2011). Impacts on ecosystem services could act as indirect drivers of migration in these regions, so efforts need to focus on the adaptive capacity and resilience of populations in these regions to be able to cope with projected changes in ecosystem services.

This review shows that there is evidence to suggest that climate change may have already affected some elements of ecosystem services (e.g. trophic mismatch due to declines in sea ice extent; calcification of corals; effects of floods and droughts on desert ecosystems) and that some are vulnerable to climate change (e.g. drying of Amazonia; grain yields associated with the South Asia monsoon). However, a robust conclusion on whether climate change has already *caused* any past ecosystem changes, definitively, is not possible at this moment in time. This is because there are no detection and attribution studies that have focussed on ecosystem services, specifically. Up until now, such studies have focussed attributing more general atmospheric changes to climate change (Christidis et al., 2011; Stott et al., 2011), rather than ecosystem services. So, while some of the evidence for recent changes in ecosystem impacts presented in this review are inline with what could be expected from climate change, they may not be directly attributed to it. To this end, this represents a worthy avenue for further research (see Fig. 1).

A number of key uncertainties remain in understanding the impact of large-scale climate-earth changes on ecosystem services and there are a number of other knowledge gaps, which call for further research (Fig. 1). Such uncertainties mean it is not possible to state with high confidence the likelihood of the impact of some large-scale changes in the climate system on ecosystem services.

For the possible future changes in the large-scale climate-earth system considered, there could be impacts on provisioning, regulating, cultural and supporting ecosystem services. These impacts may not always be adverse in some regions, however. Careful monitoring of the world's ecosystems and the services they provide will facilitate the observation of ''early warnings'' of the impacts of both; (1) sudden or abrupt changes in the large-scale climate-earth system that may be decades or even centuries ahead such as the collapse of the AMOC and WAIS; and (2) near term gradual changes such as increasing ocean temperatures and ocean acidification. With the aid of such early warnings, it will be possible to implement adaptation measures and plan for the future, to lessen the magnitude of the impact on societies that rely upon ecosystem services that may be affected. Moreover, efforts could be made to explore ways to reverse some of the observed declines in ecosystem services (e.g. coral bleaching), in a move to promote sustainability of future ecosystem services.

## Acknowledgements

This article has been commissioned as part of the Foresight Project on Global Environmental Migration. The author is grateful to the project's team – in particular, Professor Neil Adger, Professor Nigel Arnell and Professor Richard Black – for support and advice, as well as to four anonymous reviewers for very helpful and insightful comments, which helped to improve the quality and value of the final manuscript.

## REFERENCES

Abram, N.J., Gagan, M.K., Liu, Z.Y., Hantoro, W.S., McCulloch, M.T., Suwargadi, B.W., 2007. Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch. Nature 445, 299–302.

Ainley, D., Russell, J., Jenouvrier, S., Woehler, E., Lyver, P.O., Fraser, W.R., Kooyman, G.L., 2010. Antarctic penguin response to habitat change as Earth's troposphere reaches 2 °C above preindustrial levels. Ecological Monographs 80, 49–66.

Akumu, C., Pathirana, S., Baban, S., Bucher, D., 2010. Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. Journal of Coastal Conservation 15, 15–22.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R.,

Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259, 660–684.
Alo, C.A., Wang, G.L., 2008. Potential future changes of the terrestrial ecosystem based on climate projections by eight general circulation models. Journal of Geophysical Research-Biogeosciences 113, 1–16.
Annamalai, H., Hamilton, K., Sperber, K.R., 2007. The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. Journal of Climate 20, 1071–1092.
Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change-Human and Policy Dimensions 14, 31–52.
Arnell, N.W., 2006. Global impacts of abrupt climate change: an initial assessment. Tyndall Centre for Climate Change Research, Working Paper.
Arnell, N.W., van Vuuren, D.P., Isaac, M., 2011. The implications of climate policy for the impacts of climate change on global water resources. Global Environmental Change 21, 592–603.
Ashfaq, M., Shi, Y., Tung, W.W., Trapp, R.J., Gao, X.J., Pal, J.S., Diffenbaugh, N.S., 2009. Suppression of south Asian summer monsoon precipitation in the 21st century. Geophysical Research Letters 36, 1–5.
Baker, A.C., Glynn, P.W., Riegl, B., 2008. Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine Coastal and Shelf Science 80, 435–471.
Bamber, J.L., Riva, R.E.M., Vermeersen, B.L.A., LeBrocq, A.M., 2009. Reassessment of the potential sea-level rise from a collapse of the West Antarctic ice sheet. Science 324, 901–903.
Benito Garzon, M., Sanchez de Dios, R., Sainz Ollero, H., 2008. Effects of climate change on the distribution of Iberian tree species. Applied Vegetation Science 11, 169–178.
Bentz, B.J., Fetteg, C.J., Hayes, J.A.H., 2010. Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. Bioscience 60, 602–613.
Berkelmans, R., 2009. Bleaching and mortality thresholds: how much is too much? Ecological Studies 205, 103–119.
Berkelmans, R., De'ath, G., Kininmonth, S., Skirving, W.J., 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23, 74–83.
Bernie, D., Lowe, J., Tyrrell, T., Legge, O., 2010. Influence of mitigation policy on ocean acidification. Geophysical Research Letters 37, 1–5.
Black, R., Adger, W.N., Arnell, N.W., Dercon, S., Geddes, A., Thomas, D., 2011. The effect of environmental change on human migration. Global Environmental Change 21 (Suppl. 1), S3–S11.
Brierley, A.S., Kingsford, M.J., 2009. Impacts of Climate Change on Marine Organisms and Ecosystems. Current Biology 19, 602–614.
Bryant, D., Burke, L., McManus, J., Spalding, M., 1998. Reefs at Risk: A Map-based Indicator of Threats to the World's Coral Reefs, Washington, DC, USA. World Resources Institute, pp. 1–60.
Burke, L., Greenhalgh, S., Prager, D., Cooper, E., 2008. Coastal Capital—Economic Valuation of Coral Reefs in Tobago and St. Lucia. World Resources Institute, Washington, DC, pp. 1–76.
Burke, L., Maidens, J., 2004. Reefs at Risk in the Caribbean. World Resources Institute, Washington.
Callaghan, T., Björn, L., Chapin III, F., Chernov, Y., Christensen, T., Huntley, B., Ims, R., Johansson, M., Riedlinger, D., Jonasson, S., 2005. Arctic tundra and polar desert ecosystems. Arctic climate impact assessment. In: Environmental Information Coalition, National Council for Science and the Environment, Washington, DC, pp. 243–352.
Callaghan, T.V., Johansson, M., 2009. The changing, living tundra: a tribute to Yuri Chernov. In: Golovatch, S.I., Makarova, O.L., Babenko, A.B., Penev, L.D. (Eds.), Species and Communities in Extreme Environments. Pensoft, Moscow, pp. 13–52.
Cao, L., Caldeira, K., Jain, A.K., 2007. Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. Geophysical Research Letters 34 , http://dx.doi.org/10.1029/2006GL028605.
Carr, D., 2009. Population and deforestation: why rural migration matters. Progress in Human Geography 33, 355–378.
Caut, S., Guirlet, E., Girondot, M., 2010. Effect of tidal overwash on the embryonic development of leatherback turtles in French Guiana. Marine Environmental Research 69, 254–261.
Cesar, H.J.S., Burke, L., Pet-Soede, L., 2003. The Economics of Worldwide Coral Reef Degradation. Environmental Economics Consulting, Zeist, The Netherlands, p. 23.
Chand, R., Raju, S., 2009. Dealing with effects of monsoon failures. Economic & Political Weekly 44, 29–34.
Charbit, S., Paillard, D., Ramstein, G., 2008. Amount of $CO_2$ emissions irreversibly leading to the total melting of Greenland. Geophysical Research Letters 35, 1–5.
Chauhan, M., Gopal, B., 2001. Biodiversity and management of Keoladeo National Park (India)—a wetland of international importance. In: Gopal, B., Junk, W.J., Davis, J.A. (Eds.), Biodiversity in Wetlands: Assessment, Function and Conservation. Backhuys Publishers, Leiden, Netherlands, pp. 217–256.
Checkley, D.M., Dickson, A.G., Takahashi, M., Radich, J.A., Eisenkolb, N., Asch, R., 2009. Elevated $CO_2$ enhances otolith growth in young fish. Science 324, 1683.
Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D., 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries 10, 235–251.
Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., Pauly, D., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology 16, 24–35.
Christidis, N., Stott, P.A., Brown, S.J., 2011. The role of human activity in the recent warming of extremely warm daytime temperatures. Journal of Climate 24, 1922–1930.
Cobb, M., 2010. Acid seas block Nemo's nose. Journal of Experimental Biology 213, iii.
Conservation International, 2008. In: International, C. (Ed.), Economic Values of Coral Reefs, Mangroves, and Seagrasses: A Global Compilation. Conservation International, Arlington, VA, p. 23.
Cook, E.R., Anchukaitis, K.J., Buckley, B.M., D'Arrigo, R.D., Jacoby, G.C., Wright, W.E., 2010. Asian Monsoon Failure and Megadrought During the Last Millennium. Science 328, 486–489.
Cooley, S.R., Doney, S.C., 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters 4, 1–26.
Cooley, S.R., Kite-Powell, H.L., Doney, S.C., 2009. Ocean acidification's potential to alter global marine ecosystem services. Oceanography 22, 172–181.
Cooper, E., Burke, L., Bood, N., 2008. Coastal Capital: Economic Contribution of Coral Reefs and Mangroves to Belize. World Resources Institute, Washington, DC, p. 6.
Costa, M.H., Foley, J.A., 2000. Combined effects of deforestation and doubled atmospheric $CO_2$ concentrations on the climate of Amazonia. Journal of Climate 13, 18–34.

Cox, P.M., Betts, R.A., Collins, M., Harris, P.P., Huntingford, C., Jones, C.D., 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. Theoretical and Applied Climatology 78, 137–156.
Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H.Y., Machmuller, M., 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers Ecological Environment 7, 73–78.
Curry, R., Mauritzen, C., 2005. Dilution of the Northern North Atlantic ocean in recent decades. Science 308, 1772–1774.
Da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., Da Costa, M., De Athaydes Silva Jr., J., Braga, A.P., De Gonçalves, P.H.L., De Oliveira, A.A.R., Fisher, R., Phillips, O.L., Metcalfe, D.B., Levy, P., Meir, P., 2010. Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. New Phytologist 187, 579–591.
Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D., Yan, J., 2009. The impact of sea level rise on developing countries: a comparative analysis. Climatic Change 93, 379–388.
Davis, M., 2001. Late Victorian Holocausts: El Nino Famines and the Making of the Third World. Verso Books.
Day, J.W., Christian, R.R., Boesch, D.M., Yanez-Arancibia, A., Morris, J., Twilley, R.R., Naylor, L., Schaffner, L., Stevenson, C., 2008. Consequences of climate change on the ecogeomorphology of coastal wetlands. Estuaries Coasts 31, 477–491.
De'ath, G., Lough, J.M., Fabricius, K.E., 2009. Declining coral calcification on the Great Barrier Reef. Science 323, 116–119.
de Dios, R.S., Benito-Garzon, M., Sainz-Ollero, H., 2009. Present and future extension of the Iberian submediterranean territories as determined from the distribution of marcescent oaks. Plant Ecology 204, 189–205.
de Haas, H., 2011. Mediterranean migration futures: patterns, drivers and scenarios. Global Environmental Change 21 (Suppl. 1), S59–S69.
de Vernal, A., Hillaire-Marcel, C., 2008. Natural variability of greenland climate, vegetation, and ice volume during the past million years. Science 320, 1622–1625.
Derocher, A.E., 2005. Population ecology of polar bears at Svalbard, Norway. Population Ecology 47, 267–275.
Dhar, O.N., Nandargi, S., 2003. Hydrometeorological aspects of floods in India. Natural Hazards 28, 1–33.
Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.
Dirzo, R., Raven, P.H., 2003. Global state of biodiversity and loss. Annual Review of Environment and Resources 28, 137–167.
Donner, S.D., 2009. Coping with commitment: projected thermal stress on coral reefs under different future scenarios. PLoS One 4 , http://dx.doi.org/10.1371/journal.pone.0005712.
Donner, S.D., Skirving, W.J., Little, C.M., Oppenheimer, M., Hoegh-Guldberg, O., 2005. Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biology 11, 2251–2265.
Downing, T.E., Eyre, N., Greener, R., Blackwell, D., 1996. Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles. Environmental Change Unit, Oxford.
Durner, G.M., Douglas, D.C., Nielson, R.M., Amstrup, S.C., McDonald, T.L., Stirling, I., Mauritzen, M., Born, E.W., Wiig, O., DeWeaver, E., Serreze, M.C., Belikov, S.E., Holland, M.M., Maslanik, J., Aars, J., Bailey, D.A., Derocher, A.E., 2009. Predicting 21st-century polar bear habitat distribution from global climate models. Ecological Monographs 79, 25–58.
Eisenman, I., Wettlaufer, J.S., 2009. Nonlinear threshold behavior during the loss of Arctic sea ice. Proceedings of the National Academy of Sciences of the United States of America 106, 28–32.
Feehan, J., Harley, M., van Minnen, J., 2009. Climate change in Europe. 1. Impact on terrestrial ecosystems and biodiversity. A review. Agronomy for Sustainable Development 29, 409–421.
Feely, R.A., Doney, S.C., Cooley, S.R., 2009. Ocean acidification: present conditions and future changes in a high-$CO_2$ world. Oceanography 22, 36–47.
Ferguson, S.H., Stirling, I., McLoughlin, P., 2005. Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. Marine Mammal Science 21, 121–135.
Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281, 237–240.
Fielding, A.J., 2011. The impacts of environmental change on UK internal migration. Global Environmental Change 21 (Suppl. 1), S121–S130.
Fischbach, A.S., Amstrup, S.C., Douglas, D.C., 2007. Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. Polar Biology 30, 1395–1405.
Fish, M.R., Cote, I.M., Gill, J.A., Jones, A.P., Renshoff, S., Watkinson, A.R., 2005. Predicting the impact of sea-level rise on Caribbean sea turtle nesting habitat. Conservation Biology 19, 482–491.
Foden, W., Midgley, G.F., Hughes, G., Bond, W.J., Thuiller, W., Hoffman, M.T., Kaleme, P., Underhill, L.G., Rebelo, A., Hannah, L., 2007. A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags. Diversity and Distributions 13, 645–653.
Foresight, 2011. Migration and Global Environmental Change, Final Project Report. The Government Office for Science, London, UK.
Fuentes, M., Limpus, C.J., Hamann, M., Dawson, J., 2010. Potential impacts of projected sea-level rise on sea turtle rookeries. Aquatic Conservation-Marine and Freshwater Ecosystems 20, 132–139.
Fujii, T., Raffaelli, D., 2008. Sea-level rise, expected environmental changes, and responses of intertidal benthic macrofauna in the Humber estuary, UK. Marine Ecology-Progress Series 371, 23–35.
Galaz, V., Moberg, F., Downing, T., Thomalla, F., Warner, K., 2008. Ecosystem Under Pressure. Commission on Climate Change and Development, Stockholm.
Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., Page, G., 2002. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Waterbirds 25, 173–183.
Gao, X.J., Giorgi, F., 2008. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global and Planetary Change 62, 195–209.
Gartner, S., Reif, A., Xystrakis, F., Sayer, U., Bendagha, N., Matzarakis, A., 2008. The drought tolerance limit of *Fagus sylvatica* forest on limestone in southwestern Germany. Journal of Vegetation Science 19, 757–768.
Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J.P., Middelburg, J.J., Heip, C.H.R., 2007. Impact of elevated $CO_2$ on shellfish calcification. Geophysical Research Letters 34, 1–5.
Gedan, K.B., Silliman, B.R., Bertness, M.D., 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science 1, 117–141.
Gemenne, F., 2011. Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes. Global Environmental Change 21 (Suppl. 1), S41–S49.
Gilchrist, H.G., Mallory, M.L., 2005. Declines in abundance and distribution of the ivory gull (*Pagophila eburnea*) in Arctic Canada. Biological Conservation 121, 303–309.
Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global and Planetary Change 63, 90–104.

Golding, N., Betts, R., 2008. Fire risk in Amazonia due to climate change in the HadCM3 climate model: potential interactions with deforestation. Global Biogeochemical Cycles 22, GB4007.
Good, P., Caesar, J., Bernie, D., Lowe, J.A., van der Linden, P., Gosling, S.N., Warren, R., Arnell, N.W., Smith, S., Bamber, J., Payne, T., Laxon, S., Srokosz, M., Sitch, S., Gedney, N., Harris, G., Hewitt, H., Jackson, L., Jones, C.D., O'Connor, F., Ridley, J., Vellinga, M., Halloran, P., McNeall, D., 2011. A review of recent developments in climate change science. Part I. Understanding of future change in the large-scale climate system. Progress in Physical Geography 35, 281–296.
Gosling, S.N., Bretherton, D., Haines, K., Arnell, N.W., 2010. Global hydrology modelling and uncertainty: running multiple ensembles with a campus grid. Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences 368, 4005–4021.
Gosling, S.N., Warren, R., Arnell, N.W., Good, P., Caesar, J., Bernie, D., Lowe, J.A., van der Linden, P.J., O'Hanley, J.R., Smith, S.M., 2011. A review of recent developments in climate change science. Part II: the global-scale impacts of climate change. Progress in Physical Geography 35, 443–464.
Gough, C.M., Vogel, C.S., Schmid, H.P., Curtis, P.S., 2008. Controls on annual forest carbon storage: lessons from the past and predictions for the future. Bioscience 58, 609–622.
Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L., 2006. A major ecosystem shift in the northern Bering Sea. Science 311, 1461–1464.
Grove, R.H., 2007. The Great El Nino of 1789–93 and its global consequences: reconstructing an extreme climate event in world environmental history. Medieval History Journal 10, 75–98.
Guthrie, R.D., 2006. New carbon dates link climatic change with human colonization and Pleistocene extinctions. Nature 441, 207–209.
Hayashi, A., Akimoto, K., Sano, F., Mori, S., Tomoda, T., 2010. Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. Climatic Change 98, 87–112.
Hendriks, I.E., Duarte, C.M., Alvarez, M., 2010. Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. Estuarine Coastal and Shelf Science 86, 157–164.
Higgins, P.A.T., Vellinga, M., 2004. Ecosystem responses to abrupt climate change: teleconnections, scale and the hydrological cycle. Climatic Change 64, 127–142.
Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., Kimoto, M., 2008. Global projections of changing risks of floods and droughts in a changing climate. Hydrological Sciences Journal 53, 754–772.
Hoegh-Guldberg, O., 2005. Low coral cover in a high-$CO_2$ world. Journal of Geophysical Research-Oceans 110, 1–11.
Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. Science 318, 1737–1742.
Hofmann, M., Schellnhuber, H.J., 2009. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. Proceedings of the National Academy of Sciences of the United States of America 106, 3017–3022.
Hugo, G., 2011. Future demographic change and its interactions with migration and climate change. Global Environmental Change 21 (Suppl. 1), S21–S33.
Huntingford, C., Fisher, R.A., Mercado, L., Booth, B.B.B., Sitch, S., Harris, P.P., Cox, P.M., Jones, C.D., Betts, R.A., Malhi, Y., Harris, G.R., Collins, M., Moorcroft, P., 2008. Towards quantifying uncertainty in predictions of Amazon 'dieback'. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 1857–1864.
IPCC, 2007a. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 1–18.
IPCC, 2007b. Summary for policymakers. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 7–22.
Jenouvrier, S., Barbraud, C., Weimerskirch, H., Caswell, H., 2009a. Limitation of population recovery: a stochastic approach to the case of the emperor penguin. Oikos 118, 1292–1298.
Jenouvrier, S., Caswell, H., Barbraud, C., Holland, M., Strœve, J., Weimerskirch, H., 2009b. Demographic models and IPCC climate projections predict the decline of an emperor penguin population. Proceedings of the National Academy of Sciences of the United States of America 106, 1844–1847.
Jones, C., Lowe, J., Liddicoat, S., Betts, R., 2009. Committed terrestrial ecosystem changes due to climate change. Nature of Geoscience 2, 484–487.
Jones, R.J., 2008. Coral bleaching, bleaching-induced mortality, and the adaptive significance of the bleaching response. Marine Biology 154, 65–80.
Joughin, I., Howat, I.M., Fahnestock, M., Smith, B., Krabill, W., Alley, R.B., Stern, H., Truffer, M., 2008. Continued evolution of Jakobshavn Isbrae following its rapid speedup. Journal of Geophysical Research-Earth Surface 113, 1–14.
Keller, K., Tan, K., Morel, F.M.M., Bradford, D.F., 2000. Preserving the Ocean Circulation: Implications for Climate Policy. National Bureau of Economic Research Cambridge, MA, USA.
Kelly, A.E., Goulden, M.L., 2008. Rapid shifts in plant distribution with recent climate change. Proceedings of the National Academy of Sciences of the United States of America 105, 11823–11826.
Kerr, R.A., 2009. Galloping glaciers of greenland have reined themselves. Science 323, 458.
Khan, S.A., Wahr, J., Bevis, M., Velicogna, I., Kendrick, E., 2010. Spread of ice mass loss into northwest Greenland observed by GRACE and GPS. Geophysical Research Letters 37, 1–5.
Kleypas, J.A., Yates, K.K., 2009. Coral reefs and ocean acidification. Oceanography 22, 108–117.
Kniveton, D., Smith, C., Wood, S., 2011. Agent-based model simulations of future changes in migration flows for Burkina Faso. Global Environmental Change 21 (Suppl. 1), S34–S40.
Köhler, P., Joos, F., Gerber, S., Knutti, R., 2005. Simulated changes in vegetation distribution, land carbon storage, and atmospheric $CO_2$ in response to a collapse of the North Atlantic thermohaline circulation. Climate Dynamics 25, 689–708.
Kriegler, E., Hall, J.W., Held, H., Dawson, R., Schellnhuber, H.J., 2009. Imprecise probability assessment of tipping points in the climate system. Proceedings of the National Academy of Sciences of the United States of America 106, 5041–5046.
Kripalani, R.H., Oh, J.H., Kulkarni, A., Sabade, S.S., Chaudhari, H.S., 2007. South Asian summer monsoon precipitation variability: coupled climate model simulations and projections under IPCC AR4. Theoretical and Applied Climatology 90, 133–159.
Kuhlbrodt, T., Rahmstorf, S., Zickfeld, K., Vikebø, F., Sundby, S., Hofmann, M., Link, P., Bondeau, A., Cramer, W., Jaeger, C.,

2009. An Integrated Assessment of changes in the thermohaline circulation. Climatic Change 96, 489–537.
Kundzewicz, Z.W., Giannakopoulos, C., Schwarb, M., Stjernquist, I., Schlyter, P., Szwed, M., Palutikof, J., 2008. Impacts of climate extremes on activity sectors – stakeholders' perspective. Theoretical and Applied Climatology 93, 117–132.
Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., Shiklomanov, I.A., 2007. Freshwater resources and their management. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 173–210.
Kurihara, H., Asai, T., Kato, S., Ishimatsu, A., 2009. Effects of elevated pCO(2) on early development in the mussel *Mytilus galloprovincialis*. Aquatic Biology 4, 225–233.
Kurihara, H., Kato, S., Ishimatsu, A., 2007. Effects of increased seawater pCO(2) on early development of the oyster *Crassostrea gigas*. Aquatic Biology 1, 91–98.
Lal, R., Islam, K., 2010. Climate Change and Food Security in South Asia. Springer.
Lambo, A.L., Ormond, R.F.G., 2006. Continued post-bleaching decline and changed benthic community of a Kenyan coral reef. Marine Pollution Bulletin 52, 1617–1624.
Langley, J.A., McKee, K.L., Cahoon, D.R., Cherry, J.A., Megonigal, J.P., 2009. Elevated $CO_2$ stimulates marsh elevation gain, counterbalancing sea-level rise. Proceedings of the National Academy of Sciences of the United States of America 106, 6182–6186.
Lapola, D.M., Oyama, M.D., Nobre, C.A., 2009. Exploring the range of climate biome projections for tropical South America: the role of $CO_2$ fertilization and seasonality. Global Biogeochemical Cycles 23, 1–16.
Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R., 2009. Elevated $CO_2$ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. Journal of Experimental Botany 60, 2859–2876.
Lenton, T.M., 2011. Early warning of climate tipping points. Nature Climate Change 1, 201–209.
Levermann, A., Bamber, J., Drijfhout, S., Ganopolski, A., Haeberli, W., Harris, N., Huss, M., Krüger, K., Lenton, T., Lindsay, R., Notz, D., Wadhams, P., Weber, S., 2012. Potential climatic transitions with profound impact on Europe. Climatic Change 110, 845–878.
Lieberman, V., 2003. Strange Parallels: Southeast Asia in Global Context, c 800–1830. Cambridge University Press.
Link, P.M., Tol, R.S.J., 2009. Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation. Global Environmental Change 19, 422–433.
Link, P., Tol, R., 2011. Estimation of the economic impact of temperature changes induced by a shutdown of the thermohaline circulation: an application of FUND. Climatic Change 104, 287–304.
Loeb, V., Siegel, V., HolmHansen, O., Hewitt, R., Fraser, W., Trivelpiece, W., Trivelpiece, S., 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature 387, 897–900.
Lonsdale, K., Downing, T., Nicholls, R., Parker, D., Vafeidis, A., Dawson, R., Hall, J., 2008. Plausible responses to the threat of rapid sea-level rise in the Thames Estuary. Climatic Change 91, 145–169.
Loomis, M.J., Craft, C.B., 2010. Carbon sequestration and nutrient (nitrogen, phosphorus) accumulation in river-dominated tidal marshes, Georgia, USA. Soil Science Society of America Journal 74, 1028–1036.
Lough, J.M., 2008. 10th anniversary review: a changing climate for coral reefs. Journal of Environmental Monitoring 10, 21–29.
Lowe, J.A., Gregory, J.M., 2010. A sea of uncertainty. Nature Reports Climate Change 4, 42–43.
Lunt, D.J., de Noblet-Ducoudre, N., Charbit, S., 2004. Effects of a melted greenland ice sheet on climate, vegetation, and the cryosphere. Climate Dynamics 23, 679–694.
Luyssaert, S., Schulze, E.D., Borner, A., Knohl, A., Hessenmoller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.
Lythe, M.B., Vaughan, D.G., Consortium, B., 2001. BEDMAP: a new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research-Solid Earth 106, 11335–11351.
Malhi, Y., Aragão, L.E.O.C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., Meir, P., 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. Proceedings of the National Academy of Sciences of the United States of America 106, 20610–20615.
Mall, R.K., Singh, R., Gupta, A., Srinivasan, G., Rathore, L.S., 2007. Impact of climate change on Indian agriculture: a review. Climatic Change 82, 225–231.
Marengo, J., 2006. On the hydrological cycle of the Amazon Basin: a historical review and current state-of-the-art. Revista Brasileira de Meteorologia 21, 1–19.
Mazaris, A.D., Matsinos, G., Pantis, J.D., 2009. Evaluating the impacts of coastal squeeze on sea turtle nesting. Ocean Coastal Management 52, 139–145.
McClanahan, T.R., 2000. Bleaching damage and recovery potential of Maldivian coral reefs. Marine Pollution Bulletin 40, 587–597.
McKee, K.L., 2011. Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. Estuarine, Coastal and Shelf Science 91, 475–483.
McLeod, E., Hinkel, J., Vafeidis, A., Nicholls, R., Harvey, N., Salm, R., 2010a. Sea-level rise vulnerability in the countries of the Coral Triangle. Sustainability Science 5, 207–222.
McLeod, E., Moffitt, R., Timmermann, A., Salm, R., Menviel, L., Palmer, M.J., Selig, E.R., Casey, K.S., Bruno, J.F., 2010b. Warming seas in the coral triangle: coral reef vulnerability and management implications. Coastal Management 38, 518–539.
McNeall, D., Halloran, P.R., Good, P., Betts, R.A., 2011. Analyzing abrupt and nonlinear climate changes and their impacts. Wiley Interdisciplinary Reviews: Climate Change 2, 663–686.
McPhaden, M.J., Zhang, D., 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. Nature 415, 603–608.
MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being. Synthesis. Island Press, Washington, DC.
Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Moline, M.A., Karnovsky, N.J., Brown, Z., Divoky, G.J., Frazer, T.K., Jacoby, C.A., Torrese, J.J., Fraser, W.R., 2008. High latitude changes in ice dynamics and their impact on polar marine ecosystems. Year in Ecology and Conservation Biology 1134, 267–319.
Moreno, A., Amelung, B., 2009. Climate change and tourist comfort on Europe's beaches in summer: a reassessment. Coastal Management 37, 550–568.

Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Doving, K.B., 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. Proceedings of the National Academy of Sciences of the United States of America 106, 1848–1852.
Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., Chivers, D.P., 2010. Replenishment of fish populations is threatened by ocean acidification. Proceedings of the National Academy of Sciences of the United States of America 107, 12930–12934.
Nakićenović, N., Alcamo, J., Davis, G., De Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T., Kram, T., 2000. IPCC Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge.
Nicholls, R., Tol, R., Vafeidis, A., 2008. Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. Climatic Change 91, 171–191.
Nicholls, R.J., 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Global Environmental Change-Human and Policy Dimensions 14, 69–86.
Nicholls, R.J., Wong, P.P., Burkett, V.P., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 315–356.
Notz, D., 2009. The future of ice sheets and sea ice: between reversible retreat and unstoppable loss. Proceedings of the National Academy of Sciences of the United States of America 106, 20590–20595.
Olsthoorn, X., van der Werff, P., Bouwer, L., Huitema, D., 2008. Neo-Atlantis: The Netherlands under a 5-m sea level rise. Climatic Change 91, 103–122.
Overpeck, J., Rind, D., Lacis, A., Healy, R., 1996. Possible role of dust-induced regional warming in abrupt climate change during the last glacial period. Nature 384, 447–449.
Overpeck, J.T., Cole, J.E., 2007. Climate change – lessons from a distant monsoon. Nature 445, 270–271.
Phillips, O.L., Aragao, L.E.O.C., Lewis, S.L., Fisher, J.B., Lloyd, J., Lopez-Gonzalez, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C.A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T.R., Banki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A.C.A., Cardozo, N.D., Czimczik, C.I., Feldpausch, T.R., Freitas, M.A., Gloor, E., Higuchi, N., Jimenez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D.A., Nepstad, D., Patino, S., Penuela, M.C., Prieto, A., Ramirez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A.S., Steege, H., Stropp, T., Vasquez, J., Zelazowski, R., Davila, P., Andelman, E.A., Andrade, S., Chao, A., Erwin, K.-J., Di Fiore, T.A.C., Keeling, E.H., Killeen, H., Laurance, T.J., Cruz, W.F., Pitman, A.P., Vargas, N.C.A., Ramirez-Angulo, P.N., Rudas, H., Salamao, A., Silva, R., Terborgh, N., Torres-Lezama, J.A., 2009. Drought sensitivity of the Amazon rainforest. Science 323, 1344–1347.
Phillips, O.L., Martinez, R.V., Arroyo, L., Baker, T.R., Killeen, T., Lewis, S.L., Malhi, Y., Mendoza, A.M., Neill, D., Vargas, P.N., Alexiades, M., Ceron, C., Di Fiore, A., Erwin, T., Jardim, A., Palacios, W., Saldias, M., Vinceti, B., 2002. Increasing dominance of large lianas in Amazonian forests. Nature 418, 770–774.
Post, E., Forchhammer, M.C., 2008. Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 2367–2373.
Post, E., Forchhammer, M.C., Bret-Harte, M.S., Callaghan, T.V., Christensen, T.R., Elberling, B., Fox, A.D., Gilg, O., Hik, D.S., Hoye, T.T., Ims, R.A., Jeppesen, E., Klein, D.R., Madsen, J., McGuire, A.D., Rysgaard, S., Schindler, D.E., Stirling, I., Tamstorf, M.P., Tyler, N.J.C., van der Wal, R., Welker, J., Wookey, P.A., Schmidt, N.M., Aastrup, P., 2009. Ecological dynamics across the Arctic associated with recent climate change. Science 325, 1355–1358.
Poumadère, M., Mays, C., Pfeifle, G., Vafeidis, A., 2008. Worst case scenario as stakeholder decision support: a 5- to 6-m sea level rise in the Rhone delta. France. Climatic Change 91, 123–143.
Rammig, A., Jupp, T., Thonicke, K., Tietjen, B., Heinke, J., Ostberg, S., Lucht, W., Cramer, W., Cox, P., 2010. Estimating the risk of Amazonian forest dieback. New Phytologist 187, 694–706.
Regehr, E.V., Lunn, N.J., Amstrup, S.C., Stirling, L., 2007. Effects of earlier sea ice breakup on survival and population size of polar bears in western Hudson bay. Journal of Wildlife Management 71, 2673–2683.
Reid, K., Croxall, J.P., 2001. Environmental response of upper trophic-level predators reveals a system change in an Antarctic marine ecosystem. Proceedings of the Royal Society of London Series B: Biological Sciences 268, 377–384.
Richards, J., Mokrech, M., Berry, P., Nicholls, R., 2008. Regional assessment of climate change impacts on coastal and fluvial ecosystems and the scope for adaptation. Climatic Change 90, 141–167.
Ridley, J., Gregory, J.M., Huybrechts, P., Lowe, J., 2010. Thresholds for irreversible decline of the Greenland ice sheet. Climate Dynamics 35, 1065–1073.
Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E., Morel, F.M.M., 2000. Reduced calcification of marine plankton in response to increased atmospheric $CO_2$. Nature 407, 364–367.
Ries, J.B., Cohen, A.L., McCorkle, D.C., 2009. Marine calcifiers exhibit mixed responses to $CO_2$-induced ocean acidification. Geology 37, 1131–1134.
Rockstrom, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resources Research 45.
Saatchi, S.S., Houghton, R.A., Dos Santos AlvalÁ, R.C., Soares, J.V., Yu, Y., 2007. Distribution of aboveground live biomass in the Amazon basin. Global Change Biology 13, 816–837.
Salazar, L.F., Nobre, C.A., Oyama, M.D., 2007. Climate change consequences on the biome distribution in tropical South America. Geophysical Research Letters 34, L09708.
Schellnhuber, H.J., 2009. Tipping elements in the earth system. Proceedings of the National Academy of Sciences of the United States of America 106, 20561.
Schmittner, A., 2005. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. Nature 434, 628–633.
Schneider, S.H., 2004. Abrupt non-linear climate change, irreversibility and surprise. Global Environmental Change 14, 245–258.
Selig, E.R., Casey, K.S., Bruno, J.F., 2010. New insights into global patterns of ocean temperature anomalies: implications for coral reef health and management. Global Ecology and Biogeography 19, 397–411.
Sheffield, J., Wood, E., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Climate Dynamics 31, 79–105.
Shen, C., Wang, W.C., Hao, Z., Gong, W., 2007. Exceptional drought events over eastern China during the last five centuries. Climatic Change 85, 453–471.

Sikka, D., 2003. Evaluation of monitoring and forecasting of summer monsoon over India and a review of monsoon drought of 2002. Proceedings of the Indian National Science Academy Part A 69, 479–504.

Simelton, E., Fraser, E., Termansen, M., Benton, T., Gosling, S.N., South, A., Arnell, N.W., Challinor, A., Dougill, A., Forster, P., 2012. The socioeconomics of food crop production and climate change vulnerability: a global scale quantitative analysis of how grain crops are sensitive to drought. Food Security 1–17, http://dx.doi.org/10.1007/s12571-012-0173-4.

Simmonds, M.P., Isaac, S.J., 2007. The impacts of climate change on marine mammals: early signs of significant problems. Oryx 41, 19–26.

Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C., Woodward, F.I., 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). Global Change Biology 14, 2015–2039.

Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Füssel, H.-M., Pittock, A.B., Rahman, A., Suarez, A., van Ypersele, J.-P., 2009. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) ''reasons for concern''. Proceedings of the National Academy of Sciences of the United States of America 106, 4133–4137.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R., Maretti, C., 2010. Role of Brazilian Amazon protected areas in climate change mitigation. Proceedings of the National Academy of Sciences of the United States of America 107, 10821–10826.

Stott, P.A., Jones, G.S., Christidis, N., Zwiers, F.W., Hegerl, G., Shiogama, H., 2011. Single-step attribution of increasing frequencies of very warm regional temperatures to human influence. Atmospheric Science Letters 12, 220–227.

Suhrke, A., 1994. Environmental degradation and population flows. Journal of International Affairs 47, 473–496.

Tanzil, J.T.I., Brown, B.E., Tudhope, A.W., Dunne, R.P., 2009. Decline in skeletal growth of the coral Porites lutea from the Andaman Sea, South Thailand between 1984 and 2005. Coral Reefs 28, 519–528.

Thibault, K.M., Brown, J.H., 2008. Impact of an extreme climatic event on community assembly. Proceedings of the National Academy of Sciences of the United States of America 105, 3410–3415.

Tian, B., Zhang, L., Wang, X., Zhou, Y., Zhang, W., 2010. Forecasting the effects of sea-level rise at Chongming Dongtan Nature Reserve in the Yangtze Delta, Shanghai, China. Ecological Engineering 36, 1383–1388.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B., Zhai, P., 2007. Observations: surface and atmospheric climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51, 807–815.

van de Wal, R.S.W., Boot, W., van den Broeke, M.R., Smeets, C., Reijmer, C.H., Donker, J.J.A., Oerlemans, J., 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. Science 321, 111–113.

van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W.J., van Meijgaard, E., Velicogna, I., Wouters, B., 2009. Partitioning recent greenland mass loss. Science 326, 984–986.

van der Werf, G.W., Sass-Klaassen, U.G.W., Mohren, G.M.J., 2007. The impact of the 2003 summer drought on the intra-annual growth pattern of beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L.) on a dry site in the Netherlands. Dendrochronologia 25, 103–112.

Velicogna, I., 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophysical Research Letters 36, 1–4.

Vellinga, M., Wood, R., 2008. Impacts of thermohaline circulation shutdown in the twenty-first century. Climatic Change 91, 43–63.

Verbeeck, H., Samson, R., Granier, A., Montpied, P., Lemeur, R., 2008. Multi-year model analysis of GPP in a temperate beech forest in France. Ecological Modelling 210, 85–103.

Veron, J.E.N., Hoegh-Guldberg, O., Lenton, T.M., Lough, J.M., Obura, D.O., Pearce-Kelly, P., Sheppard, C.R.C., Spalding, M., Stafford-Smith, M.G., Rogers, A.D., 2009. The coral reef crisis: the critical importance of $<$350 ppm $CO_2$. Marine Pollution Bulletin 58, 1428–1436.

Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.

Wahl, E.R., Morrill, C., 2010. Climate change: toward understanding and predicting monsoon patterns. Science 328, 437–438.

Watkinson, A.R., Nicholls, R.J., Sear, D.A., Ledoux, L., 2007. Environmental impacts of future flood risk. In: Thorne, C., Evans, E., Penning-Rowsell, E. (Eds.), Future Flooding and Coastal Erosion Risks. Thomas Telford, London, UK, pp. 29–44.

Weishampel, J., Bagley, D., Ehrhart, L., Weishampel, A., 2010. Nesting phenologies of two sympatric sea turtle species related to sea surface temperatures. Endangered Species Research 12, 41–47.

Wilson, R.J., Gutierrez, D., Gutierrez, J., Monserrat, V.J., 2007. An elevational shift in butterfly species richness and composition accompanying recent climate change. Global Change Biology 13, 1873–1887.

WoS, W.o.S., 2012. Web of Science. Thomson Reuters.

Zickfeld, K., Levermann, A., Morgan, M.G., Kuhlbrodt, T., Rahmstorf, S., Keith, D.W., 2007. Expert judgements on the response of the Atlantic meridional overturning circulation to climate change. Climatic Change 82, 235–265.

**Simon N. Gosling** is Lecturer in Physical Geography at The University of Nottingham, UK. He is a Fellow of the Royal Meteorological Society, a Fellow of the Royal Geographical Society and a Fellow of the Higher Education Academy. Simon's main interests are in understanding the impacts of climate change on natural and human systems and linking physical science with national and international policy. A key element throughout all of his research is exploring the inherent uncertainties in climate change impacts projections, due to, for instance, uncertainties associated with the current state of science on climate modelling.