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An updated assessment of the risks from climate change based on research published since the IPCC Fourth Assessment Report

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Abstract The IPCC Fourth Assessment Report (AR4) published in 2007 presents the most complete and authoritative assessment of the status of scientific knowledge on all aspects of climate change. This paper presents an updated assessment of the risks from anthropogenic climate change, based on a comprehensive review of the pertinent scientific literature published since finalization of the AR4. Many risks are now assessed as stronger than in the AR4, including the risk of large sea-level rise already in the current century, the amplification of global warming due to biological and geological carbon-cycle feedbacks, a large magnitude of "committed warming" currently concealed by a strong aerosol mask, substantial increases in climate variability and extreme weather events, and the risks to marine ecosystems from climate change and ocean acidification. Some topics remain the subject of intense scientific debate, such as past and future changes in tropical cyclone activity and the risk of large-scale Amazon forest dieback. The rise in greenhouse gas emissions and concentrations has accelerated recently, and it is expected to accelerate further in the absence of targeted policy interventions. Taken together, these findings point to an increased urgency of implementing mitigation policies as well as comprehensive and equitable adaptation policies.

1 Introduction

The IPCC Fourth Assessment Report (AR4) published in 2007 (IPCC 2007) presents the most complete and authoritative assessment of the scientific knowledge on anthropogenic climate change, on associated impacts and vulnerabilities, and on options for reducing climatic risks through mitigation and adaptation. The complex writing and review process of IPCC assessment reports implies that the cutoff date

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for the inclusion of literature was between mid-2006 and early 2007, depending on the particular Working Group. This paper presents a comprehensive review of the scientific literature on climate change and climate impacts published between the finalization of the AR4 and September 2008. The literature selection focuses on studies that may substantially affect the assessment of the risks from global climate change. For that reason, publications with a more regional focus and studies that primarily confirm earlier findings generally have not been included. Section 2 reviews new knowledge on the science of climate change, and Section 3 reviews new scientific findings on the impacts of climate change.

2 Climate change

Scientific understanding of climate change has substantially progressed since finalization of the Working Group 1 contribution to the AR4. New knowledge includes updated observations of recent climate change, better attribution of the causes of observed climate change to anthropogenic and natural factors, improved analysis of prehistoric climate shifts, improved understanding of carbon cycle feedbacks, and new projections of future changes in extreme weather events.

2.1 New observations

2007 was another exceptionally warm year that tied with 1998 for Earth's second warmest year on record (i.e., since 1850). The eight warmest years on record have all occurred since 1998, and the 14 warmest years have all occurred since 1990 (GISS 2008). The last 2 years have also established several all-time records in terms of glacier and sea-ice melting. According to a new global database on glacier fluctuations from 1803 glaciers as far back as the 19th century, 2006 established a new record annual mass loss of the reference glaciers under long-term observation. The average annual melting rate of mountain glaciers has doubled after 2000, in comparison with the already accelerated melting rates observed in the two decades before (UNEP/WGMS 2008).

Melting of the Greenland ice sheet in summer 2007 established a new record. The seasonal melt departure, a sum of the departures from average melt extent each day from 1 June to 31 August, was 60% greater in 2007 than the previous high in 1998. The most recent 11 summers have all experienced melting greater than the average of the available time series (1973 to 2007) (Mote 2007). The current and future contribution to sea level rise from Antarctica has been subject to large uncertainties. A recent analysis of extensive satellite observations from 1992 to 2006 provides a spatially explicit assessment of the mass flux and mass change covering 85% of Antarctica's coastline. The study finds near-zero ice loss in East Antarctica, substantial losses in West Antarctica, and smaller but still significant ice loss on the Antarctic peninsula. The authors conclude that during the 1992–2006 period, "the ice sheet as a whole was certainly losing mass, and that the mass loss increased by 75% in 10 years" (Rignot et al. 2008). Increases in glacier flow were identified as the main cause of increased ice loss. Satellite laser altimeter elevation profiles reveal a wide spread, dynamic subglacial water system in West Antarctica (Fricker et al. 2007). Observed acceleration and deceleration of ice flow on a large East Antarctic outlet glacier has been linked to the discharge from subglacial lakes upstream of the groundling line, providing direct evidence that an active lake drainage system can cause large and rapid changes in glacier dynamics (Stearns et al. 2008). Other studies have also found that mass losses in the Greenland and the West Antarctic ice sheets are accelerating, and that Antarctica as a whole is losing mass, mostly from West Antarctica (Velicogna and Wahr 2006a, b; Shepherd and Wingham 2007).

Arctic sea ice area reached a new all-time minimum in September 2007 at 3.6 Mio km^2, which is 27% lower than the previous record low reached in 2005. The decline in ice cover has accelerated substantially, from about −3.0% per decade in 1979–1996 to about −10.7% per decade in the last 10 years (Comiso et al. 2008).

2.2 Comparison of observed and projected changes

Comparison of the most recent observed trends for carbon dioxide concentration, global-mean surface temperature and sea level with the projections in the IPCC Third Assessment Report (TAR) shows that previous IPCC projections have not exaggerated, but in some respects underestimated, the change in global climate. The observed increase in global mean surface temperature since 1990 is 0.33°C; this is in the upper part of the range set by the IPCC. Sea level data from tide gauges and satellite data show a linear trend of 3.3 mm/year for the 1993–2006 period (which was already reported in the AR4) whereas the IPCC TAR projected a best-estimate rise of less than 2 mm/year (Rahmstorf et al. 2007). The observed decline of Arctic sea ice extent from 1953–2006 is about three times faster than the mean of climate models participating in the IPCC AR4 and larger than any of these models (Stroeve et al. 2007). About half of current climate models already display an ice-free Arctic Ocean in late summer by the end of the 21st century for the SRES A1B scenario (Arzel et al. 2006) but this estimate may be too conservative in the light of the new observations.

2.3 New analyses of recent climate change

One of the remaining gaps in understanding 20th century climate change appears to have been resolved. The weak cooling trend observed in global surface temperatures between 1940 and 1970 is partly due to a previously overlooked abrupt temperature drop of 0.3°C in summer 1945. This drop is the apparent result of uncorrected instrumental biases in the sea surface temperature record caused by different measurement techniques on US ships (which provided most sea surface temperature measurements during World War II) and British ships (which provided most observations after summer 1945). The results do not alter estimates of the century-long trend in global mean temperatures (Thompson et al. 2008). Past temperature observations from radiosonde and (some) satellite measurements have not supported a result from climate model simulations suggesting that the upper troposphere should warm faster than the surface. A new analysis of radiosonde data, however, shows a warming trend in the upper troposphere that agrees well with predictions from global climate models (Allen and Sherwood 2008). The validity of the Mann et al. “hockeystick curve” (a Northern Hemisphere temperature reconstruction for 1400–1980) has caused substantial political and scientific debate concerning the nature and processing of included climate proxy data. A recent study has produced the most comprehensive reconstruction of that curve utilizing both indirect analyses via exclusion of proxies and processing steps subject to criticism, and direct analyses of principal component processing methods in question. The authors conclude that the hockeystick curve is robust against the criticisms addressed, and that several 'corrections' to this curve which suggest 15th century temperatures could have been as high as those of the late-20th century are without statistical and climatological merit (Wahl and Ammann 2007).

The question whether terrestrial temperature observations over the 20th century have been substantially contaminated by anthropogenic surface processes such as the urban heat island effect has been the subject of intense debate. One study found that trends in daily minimum and maximum air temperatures for the period 1950–2000 at a worldwide selection of land stations were almost identical for windy and calm conditions, supporting earlier results regarding the minimal influence of urban warming on global and regional temperature trends of the 20th century (Parker 2006). A contrary study has interpreted (nominally highly significant) correlations between observed gridded climate data and various socio-economic variables as indication of a strong contamination of the temperature record by local socio-economic processes. The authors concluded "that the data contamination likely leads to an overstatement of actual [temperature] trends over land", and that "nonclimatic effects reduce the estimated 1980–2002 global average temperature trend over land by about half" (McKitrick and Michaels 2007). A recent reanalysis of these results, however, suggests that the correlations between recent warming and indices of local economic activity are spurious because they rely on a very restricted set of locations which project strongly onto naturally occurring patterns of climate variability, and the statistical analysis did not account for strong spatial auto-correlation in the underlying datasets. The study concludes that "previous conclusions that there must be a large bias to the surface temperature record are unsupported" (Schmidt 2009).

2.4 Detection and attribution of recent climate change

The AR4 states that the human influence on climate has been detected in surface air temperature, sea level pressure, free atmospheric temperature, tropopause height and ocean heat content. Several recent publications have identified the anthropogenic signal also in precipitation and the moisture content of Earth's atmosphere. Comparison of observed changes in land precipitation during the twentieth century averaged over latitudinal bands with changes simulated by 14 climate models shows that anthropogenic forcing has had a detectable influence on observed changes in average precipitation within latitudinal bands, and that these changes cannot be explained by internal climate variability or natural forcing (Zhang et al. 2007). Other studies found that the substantial increase in total atmospheric moisture content over land and over oceans observed during the last decades is primarily due to human caused increases in greenhouse gases (GHGs) (Santer et al. 2007; Willett et al. 2007). Furthermore, the effect of anthropogenic forcing can now be clearly detected in 20th-century temperature changes at global through regional scales, and the effect of GHGs can be separated from that of sulfate aerosols at continental and regional scales (Zhang et al. 2006). A new analysis of trends in solar activity and global mean surface temperature over the last 40 years that includes the effects of the various time constants with which the Earth's climate system might react to solar forcing could not detect any correspondence between the Earth's air surface temperature and the pattern of solar cycles. In conclusion, the rapid rise in global mean temperatures since 1985 cannot be ascribed to solar activity, whichever mechanism of solar forcing is invoked (Lockwood and Froehlich 2008).

2.5 Changes in sea level

Recent studies have improved our understanding of the rate of sea-level rise in Earth's history. Melting of the Laurentide ice sheet on Greenland is estimated to have contributed around 6.6 m of sea level rise at about 1.3 m per century between 9,000 and 8,500 years ago (Carlson et al. 2008). The average rate of sea-level rise during the last interglacial period, around 120,000 years ago, has been estimated at about 1.6 m per century (Rohling et al. 2008). Both studies suggest that climatic conditions in these periods (in terms of the increase in summer surface air temperatures and global mean temperature, respectively) were comparable to those projected for the 21st century under business-as-usual emission scenarios. Combining climate modeling and paleoclimatic data, total sea-level rise of about 2.0 m by 2100 has been estimated as the maximum that could occur under physically possible glaciological conditions, with a best estimate of about 0.8 m (Pfeffer et al. 2008). Independently, a semi-empirical model of sea-level rise, which reveals a highly significant correlation between the magnitude of warming and sea-level rise for the period 1880–2001 calculates a best estimate of sea-level rise of 55 to 125 cm by 2100 for the TAR climate scenarios and of 54 to 89 cm for the AR4 climate scenarios (which exclude the highest emission scenario, SRES A1FI) (Rahmstorf 2007; Horton et al. 2008). All these figures are substantially higher than the model-based estimates in the IPCC AR4, which did not include ice-sheet dynamics. Hence, the risk of large sea-level rise already in the 21st century is now estimated to be much greater than in the AR4.

2.6 Carbon cycle feedbacks

Most climate simulations in the IPCC AR4 did not include physical or biological carbon-cycle feedbacks. Recent studies have found that the oceanic carbon sink has already weakened (Le Quere et al. 2007; Canadell et al. 2007). Several studies have substantiated the risks of a positive carbon cylce feedback from melting permafrost by showing that (1) the warming signal of a rapid loss of Arctic sea ice may penetrate up to 1,500 km inland (Lawrence et al. 2008), (2) methane emission levels from Arctic thaw lakes are about five times greater than previous estimates (Walter et al. 2006), and (3) the majority of the highly labile carbon deposits from East Siberia's permafrost may be released within a period of 100 years (Khvorostyanov et al. 2008). Hence, future CO_2 and CH_4 releases from decaying Arctic permafrost may create a new significant positive climate feedback that has not been considered by climate modellers yet.

Various recent studies have shown that consideration of carbon-cycle feedbacks in simulations of future climate change leads to substantial increases in future warming estimates. Using different methods, they estimate that (1) warming of 1.5–4.5°C associated with anthropogenic doubling of CO_2 is amplified to 1.6–6.0°C warming due to the feedback for CO_2 and CH_4 (Torn and Harte 2006), (2) the biological carbon cycle feedback could increase warming over the next century by an additional 15–78% (Scheffer et al. 2006), and (3) consideration of carbon-cycle feedbacks increases the probability of exceeding 2°C warming by 2100 from 10 to 23% and the probability of exceeding 2°C warming by 2200 from 23 to 41% for a given emissions scenario (Matthews and Keith 2007). In summary, all studies conclude it is likely that the future will be substantially warmer than estimated in the AR4.

2.7 Changes in temperature and precipitation extremes

While changes in climate extremes remain uncertain, knowledge on recent and future changes in extreme events has improved due to improved analysis techniques and better climate models. Extremely cold and warm daily temperatures in most land regions have increased much faster than the change in average temperature since 1950 (Brown et al. 2008). Anthropogenic GHG emissions have been identified as the dominant cause of the observed warming in almost every region of the Northern hemisphere, which has led to a rapidly increasing risk of extremely hot summers over the last decades (Jones et al. 2008). Modelling studies suggest that extremely high temperatures will continue to increase faster than the average temperatures, due to increasing climate variability. New simulations with the global climate model ECHAM5/ MPI-OM suggest that for the SRES A1B emissions scenario, 100-year return temperature values at the end of this century exceed 50°C in Australia, India, the Middle East, North Africa, the Sahel and equatorial and subtropical South America. Hence, dangerously high temperatures in several densely populated areas may already occur in the 21st century (Sterl et al. 2008). Other studies found significant increases in indices of extreme precipitation in most regions, especially in those that are relatively wet already. Conversely those regions which are presently dry are projected to become drier because of longer dry spells (Sillmann and Roeckner 2008). The spatial extent of severe soil moisture deficits and frequency of short-term drought is expected to double until late 21st century, and long-term droughts become three times more common. The increases in drought are strongest in Mediterranean, west African, central Asian and central American regions (Sheffield and Wood 2008).

2.8 Changes in tropical cyclones

Current global climate models are rather poor in simulating tropical cyclones, due in part to the coarse spatial resolution of these models and to uncertainties regarding the quality of observational cyclone datasets for the 20th century. Most recent studies suggest that the frequency of strong tropical cyclones has increased globally in recent decades in association with increases in sea-surface temperature (SST) (Saunders and Lea 2008), and that anthropogenic GHG emissions are the main driver of observed changes in SST in tropical cyclogenesis regions (Santer et al. 2006). A comprehensive reanalysis of satellite records has found significant upward trends in the strongest cyclones in all world regions during the last 30 years, with the largest increase occurring over the North Atlantic (Elsner et al. 2008). Another study has shown that the trend of increasing numbers of category 4 and 5 hurricanes for the period 1970–2004 is directly linked to the SST trend (Hoyos et al. 2006). These results are qualitatively consistent with the hypothesis that as the seas warm, the ocean has more energy to convert to tropical cyclone wind. Several reviews of past reconstructions of tropical cyclone activity, however, have suggested that improved satellite coverage, new analysis methods, and operational changes at the various tropical cyclone warning centres contributed to discontinuities in tropical cyclone intensity estimates and to more frequent identification of extreme tropical cyclones after 1990 (Landsea et al. 2006; Chang and Guo 2007; Kossin et al. 2007). These findings question the reliability of trend analyses. Simulations with a regional climate model find that Atlantic hurricane and tropical storm frequencies may be reduced in the 21st century, which is apparently due to higher levels of vertical wind shear, whereas near-storm rainfall rates increase substantially (Knutson et al. 2008; Vecchi and Soden 2007). A study based on downscaling of the IPCC AR4 climate simulations suggests that global warming will decrease tropical cyclone frequency in the Southern hemisphere, but that an increase in the frequency of the most intense events is to be expected (Emanuel et al. 2008). Similar results have been obtained by simulations with a high-resolution version of the ECHAM5 global climate model (Bengtsson et al. 2007). In summary, substantial uncertainties about past and future changes in cyclone activity remain, and the scientific debate on this subject is expected to remain very active.

2.9 Abrupt climate change and tipping elements

Human activities have the potential to push the Earth's system beyond critical thresholds where the climate system switches rapidly to a new mode of operation. Such a mode would be unfamiliar for humankind and the predictive ability of climate models becomes highly questionable. A recent study compiled a short list of potential policy-relevant future tipping elements in the climate system. Based on a critical review of the literature, discussions at an expert workshop, and an expert elicitation, the authors suggest that global warming of 1–2.5°C and 1.5–2.5°C above preindustrial levels would trigger total loss of Arctic summer ice and radical shrinking or complete melting of the Greenland ice sheet, respectively. The threshold range for the Greenland ice sheet (1.5–2.5°C) is estimated smaller and narrower than in the AR4 (1.9–4.6°C) because of recent observations of rapid accelerating mass loss of the Greenland ice sheet, melting and thinning of the coastal margins, and surging of outlet glaciers, which cannot be explained by recent ice-sheet models. Direct comparison of these ranges, however, is problematic because the authors of this review study do not associate any likelihood or confidence statement with their temperature ranges. Global warming of 3.5°C above preindustrial levels is suggested as the lower temperature threshold for six additional tipping elements: collapse of the West Antarctic ice sheet, shutoff of the Atlantic thermohaline circulation, substantial increase in the amplitude of the El Nino–Southern Oscillation, large-scale dieback of the Amazon rainforest and of the boreal forest, and disruption of the West African monsoon (Lenton et al. 2008). The last process is a rare example of a beneficial tipping element as it may lead to a greening of the Sahara and Sahel. Another tipping element that has attracted considerable attention is accelerated melting of the Himalayan–Tibetan glaciers caused by a combination of global warming and black carbon deposition (Ramanathan and Carmichael 2008).

An analysis of the geological records of eight ancient abrupt climate shifts shows that they were all preceded by a characteristic slowing down of the fluctuations starting well before the actual shift. Because such slowing down can be mathematically shown to be a hallmark of tipping points, these results imply independent empirical evidence for the idea that past abrupt shifts were associated with the passing of critical thresholds (Dakos et al. 2008). Further evidence on the risks of abrupt climate change is provided by a new extremely detailed record of the Younger Dryas cooling, one of the most abrupt changes in climate observed in Northern Hemisphere palaeoclimate records. This record indicates an abrupt increase in storminess occurring from one year to the next at 12,679 year BP, which is broadly coincident with other climatic changes in this region. These findings imply that the substantial cooling in Europe associated with the younger Dryas event occurred very abruptly, largely within a single year (Brauer et al. 2008). Similar results have been reported for other abrupt climate shifts (Steffensen et al. 2008).

2.10 Climate stabilization

Several recent studies have assessed the long-term implications of current GHG emissions and the implications for reaching different climate stabilization targets. A review study finds that a significant fraction of the CO_2 from fossil fuel emissions, ranging in published models in the literature from 20–60%, remains in the atmosphere for more than thousand years (Archer and Brovkin 2008). This finding reemphasizes that current emissions have a substantial impact on the Earth's climate for many millennia. One study investigated the relationship between the timing of emissions reductions and the ability to reach different stabilization targets for GHG concentrations. Assuming that global emissions can decline at 1% per year, postponing mitigation causes stabilization options to disappear at a rate of 9 ppm per year. This value is much larger than the recent annual increase in atmospheric CO_2 concentrations of around 2 ppm per year because it considers the inertia in the energy and climate system. These results suggest that delaying mitigation further impedes reaching a given stabilization level much faster than generally assumed (Mignone et al. 2008).

Comprehensive coupled atmosphere-ocean general circulation models have typically examined the climatic consequences of specified atmospheric CO_2 concentration stabilization pathways without including dynamic carbon cycle subcomponents. It has therefore not been possible to assess the internal consistency of proposed global emissions pathways with targets for climate stabilization. A recent study has addressed this knowledge gap by using the UVic earth system model of intermediate complexity, which combines an atmospheric model, an ocean general circulation model, a sea-ice model, and a dynamic terrestrian carbon model. This model has an equilibrium climate sensitivity of 3.5°C. The study finds that even when emissions are stabilized at 90% below present levels at 2050, global mean temperature would eventually increase by more than 2°C above preindustrial levels. This result implies that if a 2°C warming is to be avoided in the long term, direct CO_2 capture from the air, together with subsequent sequestration, would eventually have to be introduced in addition to sustained 90% global carbon emissions reductions by 2050 (Weaver et al. 2007). Another study has come to similar conclusions (Matthews and Caldeira 2008).

The magnitude of committed warming from past GHG emissions is now estimated to be higher than in the AR4. The observed increase in GHG concentrations has most likely committed the world to a warming of 2.4°C (range 1.4 to 4.3°C) above preindustrial levels if the aerosol mask is completely removed, due to higher estimates of the positive radiative forcing from black carbon and the negative radiative forcing from other aerosols (Ramanathan and Feng 2008; Ramanathan and Carmichael 2008). These estimates are based on a recent probability density function of climate sensitivity (Roe and Baker 2007). A slower selective aerosol unmasking in combination with an overshoot GHG scenario possibly including biosequestration, however, may still be able to keep global warming within 2°C above preindustrial levels (Schellnhuber 2008).

The most recent data on GHG emissions show that the increase in CO_2 emissions and concentrations has accelerated substantially, from 1.3% per year in the 1990s to 3.3% per year in 2000–2006. Two thirds of this acceleration have been attributed to an accelerated growth of the world economy but one sixth each is caused by the recent increase in the carbon intensity of the world economy and a decline in the efficiency of the oceanic CO_2 sink in absorbing anthropogenic emissions (Raupach et al. 2007; Canadell et al. 2007). The first factor may fluctuate in response to multi-year economic cycles but the observed trend in the second factor is likely to persist in the absence of targeted policy interventions. The multi-decadal trend in the third factor suggests that allowable emissions to reach a given stabilization target may be lower than previously expected. While forecasts of global economic development are inherently uncertain, a continuation of the economic growth path observed from 2000–2007 would lead to further acceleration of CO_2 emissions growth in the absence of stringent mitigation policies (Sheehan et al. 2008).

3 Climate impacts

Any selection of key advances in knowledge on climate impacts is necessarily subjective. This review focuses on studies that are relevant beyond individual sectors or regions. Key advances in knowledge are related to observed climate impacts and to the impacts of climate change and ocean acidification on biodiversity hotspots (e.g., coral reefs and the Amazon rainforest).

3.1 Observed climate impacts

Recent climate change has already affected physical, biological, and human systems in many ways. Many observed changes, from the global to the continental scale can now be attributed to anthropogenic climate change (Rosenzweig et al. 2008). A new statistical analysis has estimated the global-scale net effect of climate change on crop yields for the world's six most widely grown crops. According to this study, "the historical temperature–yield relationships indicate that, at the global scale, warming from 1981 to 2002 very likely offset some of the yield gains [for wheat, maize and barley] from technological advances, rising CO_2 and other non-climatic factors". Yields for rice, soy and sorghum were less affected (Lobell and Field 2007). A recent study has updated mortality estimates for the European record heat wave in summer 2003, which has been partly attributed to anthropgenic climate change. Comprehensive analysis of daily mortality numbers at the regional level from 16 European countries found that more than 70,000 additional deaths occurred in Europe during this heat wave, which is much higher than previous estimates. Furthermore, mortality levels after the heat wave were not lower than during the reference period, which is in contrast to wide-held beliefs that most of the deceased were at the brink of dying anyway (Robine et al. 2008).

3.2 Climate impacts on biodiversity hotspots

Projections of a large-scale Amazon dieback in the 21st century were based on the output of a single global climate model in the AR4 but similar results have recently been simulated with other climate and vegetation models. Most of the 23 climate models used in the IPCC AR4 project a substantial reduction in dry-season rainfall in parts of the Amazon basin. In southeastern Amazonia, a rainfall decline of at least 20% and 50% is projected by 70% and 50% of the models, respectively (Malhi et al. 2008). Those models that are better able to reproduce the observed drying trend in recent decades show an even stronger drying trend than the unweighted ensemble average (Li et al. 2008). A modelling study that coupled a potential vegetation model with a regional atmospheric model nested in the CCC GCM projects a 70% reduction in the extent of the Amazon rain forest by the end of the 21st century for the SRES A2 emissions scenario. Rain forest vegetation disappears entirely from Bolivia, Paraguay and Argentina and most of Brazil and Peru (Cook and Vizy 2008). The direct human influence on vegetation (mostly from deforestation) has not been included in these modelling studies. One study utilizing the HadCM3LC climate model found that aerosol forcing has delayed greenhouse gas-induced reductions in Amazonian rainfall but is unlikely to do so for much longer. As a result, the likelihood of severe droughts in Western Amazonia, such as the one that occurred in 2005 is simulated to increase from an approximately 1-in-20-year event currently to a 1-in-2-year event by 2025 and a 9-in-10-year event by 2060 under the SRES A2 scenario (Cox et al. 2008). In summary, there is still large uncertainty on the future of the Amazon forest under scenarios of climate (and land-use) change but the risks are now assessed stronger than in the AR4.

Regional warming is predicted to generally increase with latitude. New studies suggest, however, that warming in the tropics, although relatively small in magnitude, is likely to have the most deleterious consequences on ecosystems because tropical species are relatively sensitive to temperature change and are currently living very close to their optimal temperature (Deutsch et al. 2008; Calosi et al. 2008). These results imply that the greatest extinction risks from global warming may be in the tropics, where biological diversity is also greatest (Williams et al. 2007).

Coral reefs are among the most important biodiversity hotspots, and they provide important services to society, including for coastal protection and coastal tourism. Several recent studies have strengthened the evidence of very substantial risks to coral reefs and other marine ecosystems from climate change and ocean acidification. Most coral species (77% out of 442 species assessed) do not change their symbiotic algae over time, even when a coral colony is transplanted to different environments or subjected to increased temperatures. Thus, without stringent mitigation measures coral reefs will undergo a substantial reduction in biodiversity during the 21st century because most coral species are unable to adapt to rising temperatures (Goulet 2006). Atmospheric carbon dioxide concentration in exceedance of 500 ppm and a global temperature rise of more than 2°C above current levels significantly exceeds conditions of at least the past 420,000 years during which most extant marine organisms evolved. As a result, corals will become increasingly rare on reef systems (Hoegh-Guldberg et al. 2007). Another study showed the potential for major damage to at least some ocean ecosystems at atmospheric CO_2 stabilization levels as low as 450 ppm. At this stabilization level, only 8% of existing coral reefs will be surrounded by water that is >3.5 times saturated with respect to their skeleton materials compared to more than 98% before the industrial revolution (Cao and Caldeira 2008). Experimental studies have shown that ocean acidification will also decrease calcification rates of mussels and oysters but that these organisms are less sensitive to acidification than corals (Gazeau et al. 2007). A recent review study identified carbon cycle changes in general and ocean chemistry in particular as the primary causes of the five known mass extinction events, each of which has left the Earth without living reefs for at least four million years. The author suggests that ocean acidification has the potential to trigger a sixth mass extinction event (Veron 2008).

4 Conclusions

This review has shown that several key risks from anthropogenic climate change and ocean acidification are now assessed substantially stronger than in the IPCC AR4, including risks that might be termed as “dangerous anthropogenic interference with the climate system” in the language of the United Nations Framework Convention on Climate Change. This stronger assessment is based on new observations of recent climate change and its impacts, improved analysis of recent climate change, and new modelling studies. At the same time, the increase in CO_2 concentrations has accelerated recently, and it is expected to accelerate further in the absence of stringent mitigation policies. As a result, we find ourselves in an increasingly uncomfortable situation where estimates of the risks from climate change continue to increase whereas the time for effective mitigation action is running out quickly. These findings point to an increased urgency to implement mitigation policies as well as comprehensive and equitable adaptation policies.

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