The Copenhagen Diagnosis

Updating the World on the Latest Climate Science

2009

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PREFACE

It is over three years since the drafting of text was completed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In the meantime, many hundreds of papers have been published on a suite of topics related to human-induced climate change. The purpose of this report is to synthesize the most policy-relevant climate science published since the close-off of material for the last IPCC report. The rationale is two-fold. Firstly, this report serves as an interim evaluation of the evolving science midway through an IPCC cycle – IPCC AR5 is not due for completion until 2013. Secondly, and most importantly, the report serves as a handbook of science updates that supplements the IPCC AR4 in time for Copenhagen in December, 2009, and any national or international climate change policy negotiations that follow.

This report covers the range of topics evaluated by Working Group I of the IPCC, namely the Physical Science Basis. This includes:

- an analysis of greenhouse gas emissions and their atmospheric concentrations, as well as the global carbon cycle;
- coverage of the atmosphere, the land-surface, the oceans, and all of the major components of the cryosphere (land-ice, glaciers, ice shelves, sea-ice and permafrost);
- paleoclimate, extreme events, sea level, future projections, abrupt change and tipping points;
- separate boxes devoted to explaining some of the common misconceptions surrounding climate change science.

The report has been purposefully written with a target readership of policy-makers, stakeholders, the media and the broader public. Each section begins with a set of key points that summarises the main findings. The science contained in the report is based on the most credible and significant peer-reviewed literature available at the time of publication. The authors primarily comprise previous IPCC lead authors familiar with the rigor and completeness required for a scientific assessment of this nature.

This report is freely available on the web at:

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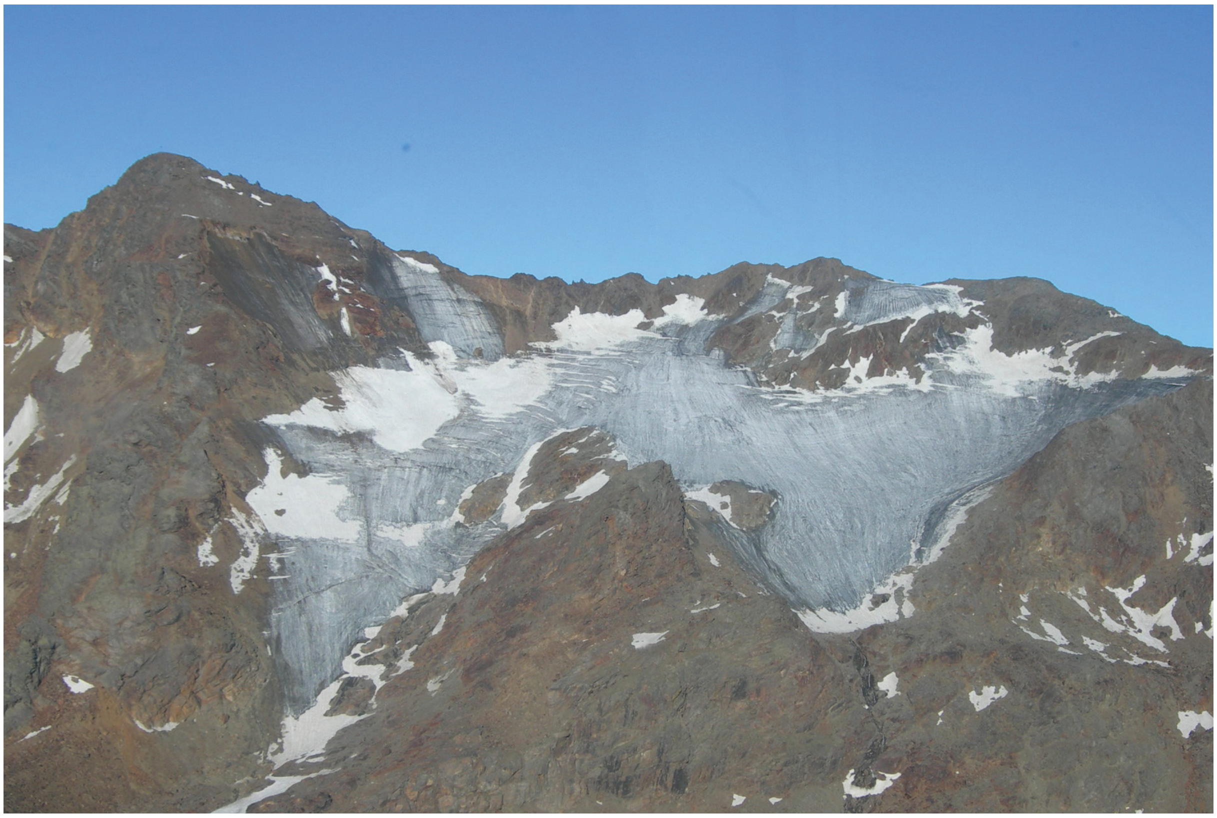


^ Weissbrunnferner, Italian Alps, 18 July 2006, showing a glacier that has lost its firm body. Extended dark ice surfaces accelerate the melt rate.

EXECUTIVE SUMMARY

The most significant recent climate change findings are:

Surging greenhouse gas emissions: Global carbon dioxide emissions from fossil fuels in 2008 were nearly 40% higher than those in 1990. Even if global emission rates are stabilized at present-day levels, just 20 more years of emissions would give a 25% probability that warming exceeds 2°C, even with zero emissions after 2030. Every year of delayed action increases the chances of exceeding 2°C warming.

Recent global temperatures demonstrate human-induced warming: Over the past 25 years temperatures have increased at a rate of 0.19°C per decade, in very good agreement with predictions based on greenhouse gas increases. Even over the past ten years, despite a decrease in solar forcing, the trend continues to be one of warming. Natural, short-term fluctuations are occurring as usual, but there have been no significant changes in the underlying warming trend.

Acceleration of melting of ice-sheets, glaciers and ice-caps: A wide array of satellite and ice measurements now demonstrate beyond doubt that both the Greenland and Antarctic ice-sheets are losing mass at an increasing rate. Melting of glaciers and ice-caps in other parts of the world has also accelerated since 1990.

Rapid Arctic sea-ice decline: Summer-time melting of Arctic sea-ice has accelerated far beyond the expectations of climate models. The area of sea-ice melt during 2007-2009 was about 40% greater than the average prediction from IPCC AR4 climate models.

Current sea-level rise underestimated: Satellites show recent global average sea-level rise (3.4 mm/yr over the past 15 years) to be ~80% above past IPCC predictions. This acceleration in sea-level rise is consistent with a doubling in contribution from melting of glaciers, ice caps, and the Greenland and West-Antarctic ice-sheets.

Sea-level predictions revised: By 2100, global sea-level is likely to rise at least twice as much as projected by Working Group 1 of the IPCC AR4; for unmitigated emissions it may well exceed 1 meter. The upper limit has been estimated as ~ 2 meters sea level rise by 2100. Sea level will continue to rise for centuries after global temperatures have been stabilized, and several meters of sea level rise must be expected over the next few centuries.

Delay in action risks irreversible damage: Several vulnerable elements in the climate system (e.g. continental ice-sheets, Amazon rainforest, West African monsoon and others) could be pushed towards abrupt or irreversible change if warming continues in a business-as-usual way throughout this century. The risk of transgressing critical thresholds ("tipping points") increases strongly with ongoing climate change. Thus waiting for higher levels of scientific certainty could mean that some tipping points will be crossed before they are recognized.

The turning point must come soon: If global warming is to be limited to a maximum of 2 °C above pre-industrial values, global emissions need to peak between 2015 and 2020 and then decline rapidly. To stabilize climate, a decarbonized global society – with near-zero emissions of CO_2 and other long-lived greenhouse gases – needs to be reached well within this century. More specifically, the average annual per-capita emissions will have to shrink to well under 1 metric ton CO_2 by 2050. This is 80-95% below the per-capita emissions in developed nations in 2000.

GREENHOUSE GASES AND THE CARBON CYCLE

- *Global carbon dioxide (CO_2) emissions from fossil fuel burning in 2008 were 40% higher than those in 1990, with a three-fold acceleration over the past 18 years.*
- *Global CO_2 emissions from fossil fuel burning are tracking near the highest scenarios considered so far by the IPCC.*
- *The fraction of CO_2 emissions absorbed by the land and ocean CO_2 reservoirs has likely decreased by ~5% (from 60 to 55%) in the past 50 years, though interannual variability is large.*

Global Carbon Dioxide Emissions

In 2008, combined global emissions of carbon dioxide (CO_2) from fossil fuel burning, cement production and land use change (mainly deforestation) were 27% higher than in the year 1990 (Le Quéré et al. 2009). Of this combined total, the CO_2 emissions from fossil fuel burning and cement production were 40% higher in 2008 compared to 1990. The global rate of increase of fossil fuel CO_2 emissions has accelerated three-fold over the last 18 years, increasing from 1.0% per year in the 1990s to 3.4% per year between 2000-2008 (Figure 1). The accelerated growth in fossil fuel CO_2 emissions since 2000 was primarily caused by fast growth rates in developing countries (particularly China) in part due to increased international trade of goods (Peters and Hertwich 2008), and by the slowdown of previous improvements in the CO_2 intensity of the global economy (Raupach et al. 2007). The observed acceleration in fossil fuel CO_2 emissions is tracking high-end emissions scenarios used by IPCC AR4 (Nakicenovic et al. 2000). In contrast, CO_2 emissions from land use change were relatively constant in the past few decades. Preliminary figures suggest total CO_2 emissions have dropped in 2009, but this is a temporary effect resulting from the global recession and no sign of the transformation required for stabilizing greenhouse gases in the atmosphere.

Carbon Dioxide

The concentration of CO_2 in the atmosphere reached 385 parts per million (ppm) in 2008 (Figure 2). The atmospheric CO_2 concentration is more than 105 ppm above its natural pre-industrial level. The present concentration is higher than at any time in the last 800,000 years, and potentially the last 3 to 20 million years (Luthi et al. 2008; Tripati et al. 2009; Raymo et al. 1996). CO_2 levels increased at a rate of 1.9 ppm/year between 2000 and 2008, compared to 1.5 ppm/yr in the 1990s. This rate of increase of atmospheric CO_2 is more than ten times faster than the highest rate that has been detected in ice core data; such high rates would be discernable in ice cores if they had occurred at any time in the last 22,000 years (Joos and Spahni 2008).

Methane

The concentration of methane (CH_4) in the atmosphere increased since 2007 to 1800 parts per billion (ppb) after almost a decade of little change (Figure 2). The causes of the recent increase in CH_4 have not yet been determined. The spatial distribution of the CH_4 increase shows that an increase in Northern Hemisphere CH_4 emissions has played a role and could dominate the signal

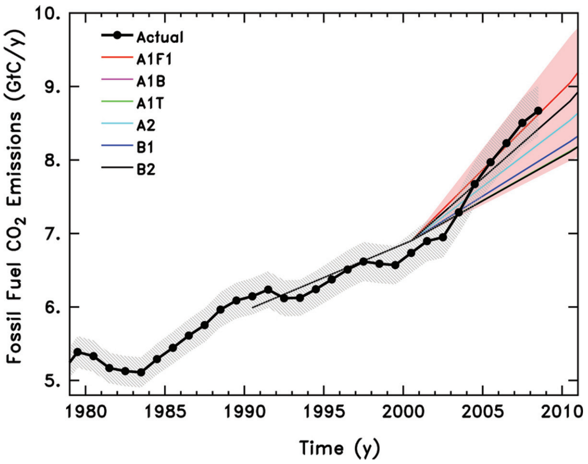


Figure 1. Observed global CO_2 emissions from fossil fuel burning and cement production compared with IPCC emissions scenarios (Le Quéré et al. 2009). Observations are from the US Department of Energy Carbon Dioxide Information Center (CDIAC) up to 2006. 2007 and 2008 are based on BP economic data. The emission scenarios are averaged over families of scenarios presented in Nakicenovic et al (2000). The shaded area covers all scenarios used to project climate change by the IPCC. Emissions in 2009 are projected to be ~3% below 2008 levels, close to the level of emissions in 2007. This reduction is equivalent to a temporary halt in global emissions for a period of only 2-4 weeks.

(Rigby et al. 2008), but the source of the increase is unknown. CH_4 is emitted by many industrial processes (ruminant farming, rice agriculture, biomass burning, coal mining, and gas & oil industry) and by natural reservoirs (wetlands, permafrost and peatlands). Annual industrial emissions of CH_4 are not available as they are difficult to quantify. CH_4 emissions from natural reservoirs can increase under warming conditions. This has been observed from permafrost thawing in Sweden (see Permafrost section), but no large-scale evidence is available to clearly connect this process to the recent CH_4 increase. If the CH_4 increase is caused by the response of natural reservoirs to warming, it could continue for decades to centuries and enhance the greenhouse gas burden of the atmosphere.

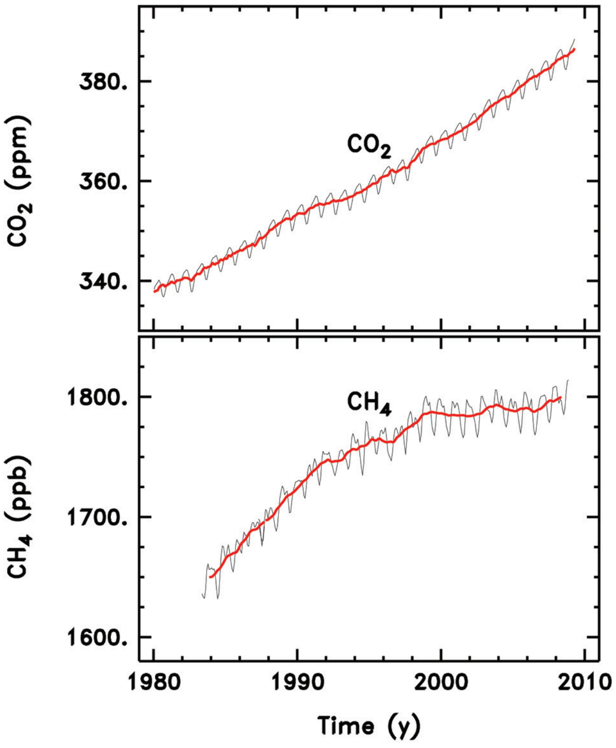


Figure 2. Concentration of CO_2 (top) and CH_4 (bottom) in the atmosphere. The trends with seasonal cycle removed are shown in red. CO_2 and CH_4 are the two most important anthropogenic greenhouse gases. Data are from the Earth System Laboratory of the US National Oceanic and Atmospheric Administration. CO_2 is averaged globally. CH_4 is shown for the Mauna Loa station only.

Carbon Sinks and Future Vulnerabilities

The oceanic and terrestrial CO_2 reservoirs – the 'CO_2 sinks'– have continued to absorb more than half of the total emissions of CO_2. However the fraction of emissions absorbed by the reservoirs has likely decreased by ~5% (from 60 to 55%) in the past 50 years (Canadell et al. 2007). The uncertainty in this estimate is large because of the significant background interannual variability and because of uncertainty in CO_2 emissions from land use change.

The response of the land and ocean CO_2 sinks to climate variability and recent climate change can account for the decrease in uptake efficiency of the sinks suggested by the observations (Le Quéré et al. 2009). A long-term decrease in the efficiency of the land and ocean CO_2 sinks would enhance climate change via an increase in the amount of CO_2 remaining in the atmosphere. Many new studies have shown a recent decrease in the efficiency of the oceanic carbon sink at removing anthropogenic CO_2 from the atmosphere. In the Southern Ocean, the CO_2 sink has not increased since 1981 in spite of the large increase in atmospheric CO_2 (Le Quéré et al. 2007; Metzl 2009; Takahashi et al. 2009). The Southern Ocean trends have been attributed to an increase in winds, itself a likely consequence of ozone depletion (Lovenduski et al. 2008). Similarly, in the North Atlantic, the CO_2 sink decreased by ~50% since 1990 (Schuster et al. 2009), though part of the decrease has been associated with natural variability (Thomas et al. 2008).

Future vulnerabilities of the global CO_2 sinks (ocean and land) have not been revised since the IPCC AR4. Our current understanding indicates that the natural CO_2 sinks will decrease in efficiency during this century, and the terrestrial sink could even start to emit CO_2 (Friedlingstein et al. 2006). The response of the sinks to elevated CO_2 and climate change is shown in models to amplify global warming by 5-30%. The observations available so far are insufficient to provide greater certainty, but they do not exclude the largest global warming amplification projected by the models (Le Quéré et al. 2009).

Is the greenhouse effect already saturated, so that adding more CO_2 makes no difference?

No, not even remotely. It isn't even saturated on the runaway greenhouse planet Venus, with its atmosphere made up of 96% CO_2 and a surface temperature of 467 °C, hotter even than Mercury (Weart and Pierrehumbert 2007). The reason is simple: the air gets ever thinner when we go up higher in the atmosphere. Heat radiation escaping into space mostly occurs higher up in the atmosphere, not at the surface – on average from an altitude of about 5.5 km. It is here that adding more CO_2 does make a difference. When we add more CO_2, the layer near the surface where the CO_2 effect is largely saturated gets thicker – one can visualize this as a layer of fog, visible only in the infrared. When this "fog layer" gets thicker, radiation can only escape to space from higher up in the atmosphere, and the radiative equilibrium temperature of -18 °C therefore also occurs higher up. That upward shift heats the surface, because temperature increases by 6.5 °C per kilometer as one goes down through the atmosphere due to the pressure increase. Thus, adding 1 km to the "CO_2 fog layer" that envelopes our Earth will heat the surface climate by about 6.5 °C.

THE ATMOSPHERE

☐ *Global air temperature, humidity and rainfall trend patterns exhibit a distinct fingerprint that cannot be explained by phenomena apart from increased atmospheric greenhouse gas concentrations.*

☐ *Every year this century (2001-2008) has been among the top 10 warmest years since instrumental records began, despite solar irradiance being relatively weak over the past few years.*

☐ *Global atmospheric temperatures maintain a strong warming trend since the 1970s (~0.6°C), consistent with expectations of greenhouse induced warming.*

Global Temperature Trends

IPCC AR4 presented "an unambiguous picture of the ongoing warming of the climate system." The atmospheric warming trend continues to climb despite 2008 being cooler than 2007 (Figure 3). For example, the IPCC gave the 25-year trend as 0.177 ± 0.052 °C per decade for the period ending 2006 (based on the HadCRUT data). Updating this by including the last two years (2007 and 2008), the trend becomes 0.187 ± 0.052 °C per decade for the period ending 2008. The recent observed climate trend is thus one of ongoing warming, in line with IPCC predictions.

Year-to-year differences in global average temperatures are unimportant in evaluating long-term climate trends. During the warming observed over the 20th century, individual years lie above or below the long-term trend line due to internal climate variability (like 1998); this is a normal and natural phenomenon. For example, in 2008 a La Niña occurred, a climate pattern which naturally causes a temporary dip in the average global temperature. At the same time, solar output was also at its lowest level of the satellite era, another temporary cooling influence. Without anthropogenic warming these two factors should have resulted in the 2008 temperature being among the coolest in the instrumental era, while in fact 2008 was the 9th warmest on record. This underpins the strong greenhouse warming that has occurred in the atmosphere over the past century. The most recent ten-year period is warmer than the previous ten-year period, and the longer-term warming trend is clear and unambiguous (Figure 3).

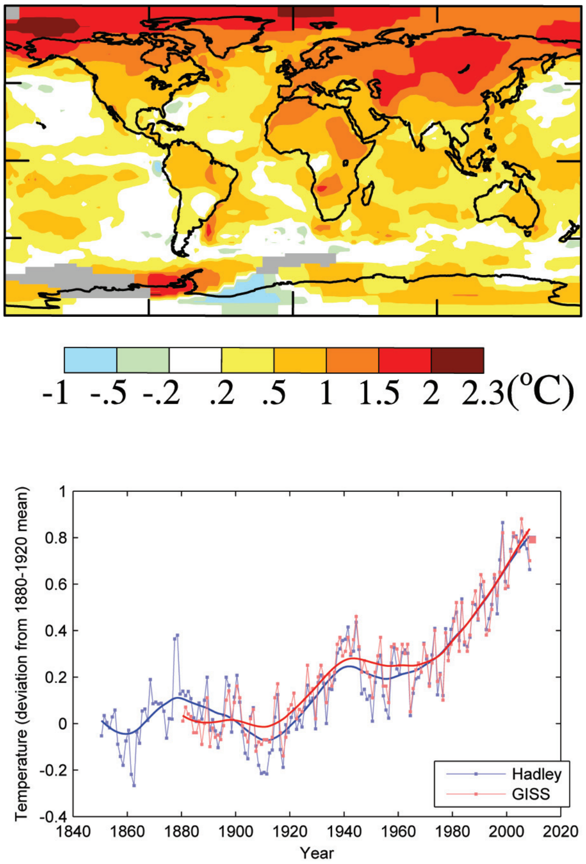


Figure 3. (top) Mean surface temperature change (°C) for 2001-2007 relative to the baseline period of 1951-1980 and (bottom) global average temperature 1850-2009 relative to the baseline period 1880-1920 estimated from the (top) NASA/GISS data set and (bottom) NASA/GISS and Hadley data. Data from the NOAA reconstructed sea surface temperature show similar results. In the lower panel the final bold-face points (they lie on top of each other) are the preliminary values for 2009 based on data up to and including August.

Is the Warming Natural or Human-Induced?

Our understanding of the causes of the recent century-scale trend has improved further since the IPCC AR4. By far the greatest part of the observed century-scale warming is due to human factors. For example, Lean and Rind (2008) analyzed the role of natural factors (e. g., solar variability, volcanoes) versus human influences on temperatures since 1889. They found that the sun contributed only about 10% of surface warming in the last century and a negligible amount in the last quarter century, less than in earlier assessments. No credible scientific literature has been published since the AR4 assessment that supports alternative hypotheses to explain the warming trend.

Is Warming Occurring Higher up in the Atmosphere?

The IPCC AR4 noted a remaining uncertainty in temperature trends in the atmosphere above the lowest layers near the Earth's surface. Most data sets available at that time showed weaker than expected warming in the atmospheric region referred to as the tropical upper troposphere, ten to fifteen kilometers above the surface. However, the observations suffered from significant stability issues especially in this altitude region. Researchers have since performed additional analyses of the same data using more rigorous techniques, and developed a new method of assessing temperature trends from wind observations (Allen and Sherwood 2008). The new observational estimates show greater warming than the earlier ones, and the new, larger set of estimates taken as a whole now bracket the trends predicted by the models (Thorne 2008). This resolves a significant ambiguity expressed in AR4 (Santer et al. 2008).

Water Vapor, Rainfall and the Hydrological Cycle

New research and observations have resolved the question of whether a warming climate will lead to an atmosphere containing more water vapor, which would add to the greenhouse effect and enhance the warming. The answer is yes, this amplifying feedback has been detected: water vapor does become more plentiful in a warmer atmosphere (Dessler et al. 2008). Satellite data show that atmospheric moisture content over the oceans has increased since 1998, with greenhouse emissions being the cause (Santer at al. 2007).

No studies were cited in IPCC AR4 linking observed rainfall trends on a fifty-year time scale to anthropogenic climate change. Now such trends can be linked. For example, Zhang et al. (2007) found that rainfall has reduced in the Northern Hemisphere subtropics but has increased in middle latitudes, and that this can be attributed to human-caused global warming. Models project that such trends will amplify as temperatures continue to rise.

Recent research has also found that rains become more intense in already-rainy areas as atmospheric water vapor content increases (Wentz et al. 2007; Allan and Soden 2008). Their conclusions strengthen those of earlier studies. However, recent changes have occurred even faster than predicted, raising the possibility that future changes could be more severe than predicted. This is a common theme from the recent science: uncertainties existing in AR4, once resolved, point to a more rapidly changing and more sensitive climate than we previously believed.

Has global warming recently slowed down or paused?

No. There is no indication in the data of a slowdown or pause in the human-caused climatic warming trend. The observed global temperature changes are entirely consistent with the climatic warming trend of ~0.2 °C per decade predicted by IPCC, plus superimposed short-term variability (see Figure 4). The latter has always been – and will always be – present in the climate system. Most of these short-term variations are due to internal oscillations like El Niño – Southern Oscillation, solar variability (predominantly the 11-year Schwabe cycle) and volcanic eruptions (which, like Pinatubo in 1991, can cause a cooling lasting a few years).

If one looks at periods of ten years or shorter, such short-term variations can more than outweigh the anthropogenic global warming trend. For example, El Niño events typically come with global-mean temperature changes of up to 0.2 °C over a few years, and the solar cycle with warming or cooling of 0.1 °C over five years (Lean and Rind 2008). However, neither El Niño, nor solar activity or volcanic eruptions make a significant contribution to longer-term climate trends. For good reason the IPCC has chosen 25 years as the shortest trend line they show in the global temperature records, and over this time period the observed trend agrees very well with the expected anthropogenic warming.

Nevertheless global cooling has not occurred even over the past ten years, contrary to claims promoted by lobby groups and picked up in some media. In the NASA global temperature data, the past ten 10-year trends (i.e. 1990-1999, 1991-2000 and so on) have all been between 0.17 and 0.34 °C warming per decade, close to or above the expected anthropogenic trend, with the most recent one (1999-2008) equal to 0.19 °C per decade. The Hadley Center data most recently show smaller warming trends (0.11 °C per decade for 1999-2008) primarily due to the fact that this data set is not fully global but leaves out the Arctic, which has warmed particularly strongly in recent years.

It is perhaps noteworthy that despite the extremely low brightness of the sun over the past three years (see next page); temperature records have been broken during this time (see NOAA, State of the Climate, 2009). For example, March 2008 saw the warmest global land temperature of any March ever measured in the instrumental record. June and August 2009 saw the warmest land and ocean temperatures in the Southern Hemisphere ever recorded for those months. The global ocean surface temperatures in 2009 broke all previous records for three consecutive months: June, July and August. The years 2007, 2008 and 2009 had the lowest summer Arctic sea ice cover ever recorded, and in 2008 for the first time in living memory the Northwest Passage and the Northeast Passage were simultaneously ice-free. This feat was repeated in 2009. Every single year of this century (2001-2008) has been among the top ten warmest years since instrumental records began.

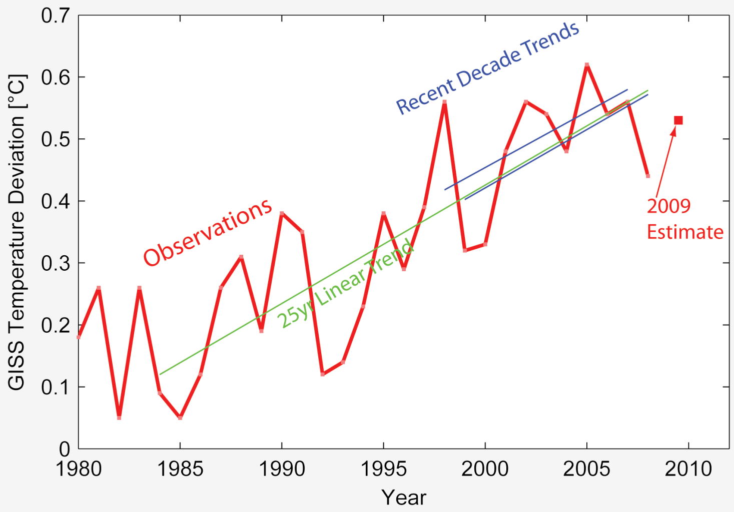


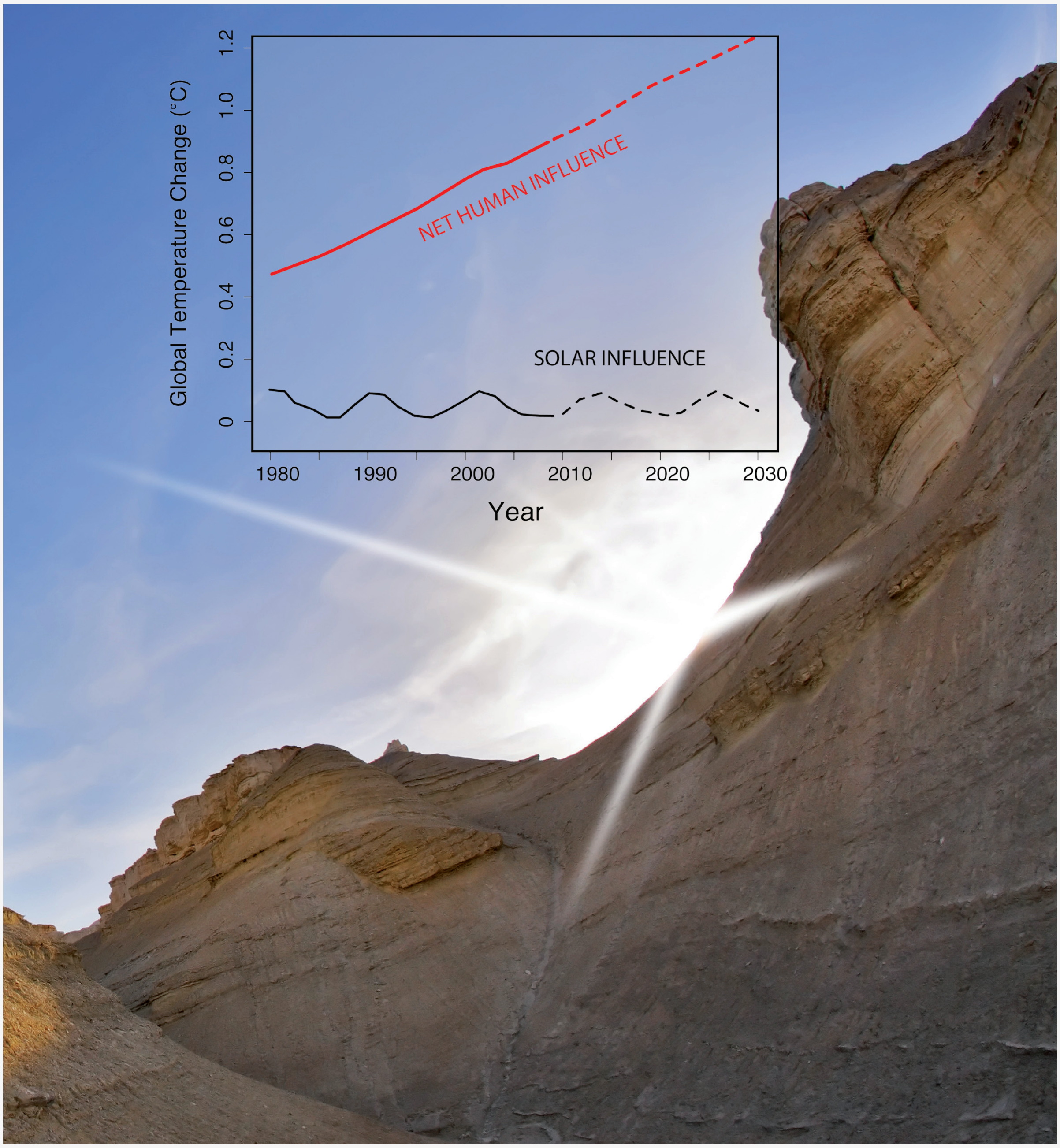
Figure 4. Global temperature according to NASA GISS data since 1980. The red line shows annual data, the red square shows the preliminary value for 2009, based on January-August. The green line shows the 25-year linear trend (0.19 °C per decade). The blue lines show the two most recent ten-year trends (0.18 °C per decade for 1998-2007, 0.19 per decade for 1999-2008) and illustrates that these recent decadal trends are entirely consistent with the long-term trend and IPCC predictions. Misunderstanding about warming trends can arise if only selected portions of the data are shown, e.g. 1998 to 2008, combined with the tendency to focus on extremes or end points (e.g. 2008 being cooler than 1998) rather than an objective trend calculation. Even the highly "cherry-picked" 11-year period starting with the warm 1998 and ending with the cold 2008 still shows a warming trend of 0.11 °C per decade.

Can solar activity or other natural processes explain global warming?

No. The incoming solar radiation has been almost constant over the past 50 years, apart from the well-known 11-year solar cycle (Figure 5). In fact it has slightly decreased over this period. In addition, over the past three years the brightness of the sun has reached an all-time low since the beginning of satellite measurements in the 1970s (Lockwood and Fröhlich 2007, 2008). But this natural cooling effect was more than a factor of ten smaller than the effect of increasing greenhouse gases, so it has not noticeably slowed down global warming. Also, winters are warming more rapidly than summers, and overnight minimum temperatures have warmed more rapidly than the daytime maxima – exactly the opposite of what would be the case if the sun were causing the warming.

Other natural factors, like volcanic eruptions or El Niño events, have only caused short-term temperature variations over time spans of a few years, but cannot explain any longer-term climatic trends (e.g., Lean and Rind 2008).

Figure 5. (below) Time-series of solar irradiance alongside the net effect of greenhouse gas emissions (the latter relative to the year 1880; using Meehl et al. 2004) calculated in terms of total estimated impact on global air temperatures; observed from 1970-2008; and projected from 2009-2030 (adapted from Lean and Rind 2009).



EXTREME EVENTS

- ☐ *Increases in hot extremes and decreases in cold extremes have continued and are expected to amplify further.*
- ☐ *Anthropogenic climate change is expected to lead to further increases in precipitation extremes, both increases in heavy precipitation and increases in drought.*
- ☐ *Although future changes in tropical cyclone activity cannot yet be modeled, new analyses of observational data confirm that the intensity of tropical cyclones has increased in the past three decades in line with rising tropical ocean temperatures.*

Many of the impacts of climate variations and climate change on society, the environment and ecosystems arise through changes in the frequency or intensity of extreme weather and climate events. The IPCC Fourth Assessment Report (IPCC 2007) concluded that many changes in extremes had been observed since the 1970s as part of the warming of the climate system. These included more frequent hot days, hot nights and heat waves; fewer cold days, cold nights and frosts; more frequent heavy precipitation events; more intense and longer droughts over wider areas; and an increase in intense tropical cyclone activity in the North Atlantic but no trend in total numbers of tropical cyclones.

Temperature extremes

Recent studies have confirmed the observed trends of more hot extremes and fewer cold extremes and shown that these are consistent with the expected response to increasing greenhouse gases and anthropogenic aerosols at large spatial scales (CCSP 2008a; Meehl et al. 2007a; Jones et al. 2008; Alexander and Arblaster 2009). However, at smaller scales, the effects of land-use change and variations of precipitation may be more important for changes in temperature extremes in some locations (Portmann et al. 2009). Continued marked increases in hot extremes and decreases in cold extremes are expected in most areas across the globe due to further anthropogenic climate change (CCSP 2008a; Kharin et al. 2007; Meehl et al. 2007a; Jones et al. 2008; Alexander and Arblaster 2009).

Precipitation extremes and drought

Post IPCC AR4 research has also found that rains become more intense in already-rainy areas as atmospheric water vapor content increases (Pall et al. 2007; Wentz et al. 2007; Allan and Soden 2008). These conclusions strengthen those of earlier studies and are expected from considerations of atmospheric thermodynamics. However, recent changes have occurred faster than predicted by some climate models, raising the possibility that future changes will be more severe than predicted.

An example of recent increases in heavy precipitation is found in the United States, where the area with a much greater than normal proportion of days with extreme rainfall amounts has increased markedly (see Figure 6). While these changes in precipitation extremes are consistent with the warming of the climate system, it has not been possible to attribute them to anthropogenic climate change with high confidence due to the very large variability of precipitation extremes (CCSP 2008a; Meehl et al. 2007b; Alexander and Arblaster 2009).

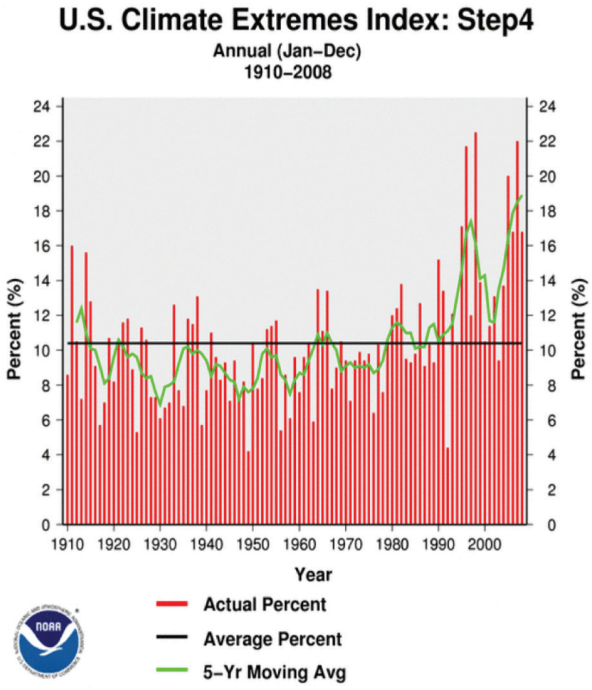


Figure 6. An increasing area of the US is experiencing very heavy daily precipitation events. Annual values of the percentage of the United States with a much greater than normal proportion of precipitation due to very heavy (equivalent to the highest tenth percentile) 1-day precipitation amounts. From Gleason et al. (2008) updated by NOAA at /www.ncdc.noaa.gov/oa/climate/research/cei/cei.html.

In addition to the increases in heavy precipitation, there have also been observed increases in drought since the 1970s (Sheffield and Wood 2008), consistent with the decreases in mean precipitation over land in some latitude bands that have been attributed to anthropogenic climate change (Zhang et al. 2007).

The intensification of the global hydrological cycle with anthropogenic climate change is expected to lead to further increases in precipitation extremes, both increases in very heavy precipitation in wet areas and increases in drought in dry areas. While precise figures cannot yet be given, current studies suggest that heavy precipitation rates may increase by 5% - 10% per °C of warming, similar to the rate of increase of atmospheric water vapor.

Tropical cyclones

The IPCC Fourth Assessment found a substantial upward trend in the severity of tropical cyclones (hurricanes and typhoons) since the mid-1970s, with a trend towards longer storm duration and greater storm intensity, strongly correlated with the rise in tropical sea surface temperatures. It concluded that a further increase in storm intensity is likely.

Several studies since the IPCC report have found more evidence for an increase in hurricane activity over the past decades. Hoyos et al. (2006) found a global increase in the number of hurricanes of the strongest categories 4 and 5, and they identified rising sea surface temperatures (SST) as the leading cause. Warming tropical SST has also been linked to increasingly intense tropical cyclone activity – and an increasing number of tropical cyclones – in the case of certain basins such as the North Atlantic (Mann and Emanuel 2006; Emanuel et al. 2008; Mann et al. 2009). Scientific debate about data quality has continued, especially on the question of how many tropical cyclones may have gone undetected before satellites provided a global coverage of observations. Mann et al. (2007) concluded that such an undercount bias would not be large enough to question the recent rise in hurricane activity and its close connection to sea surface warming. A complete reanalysis of satellite data since 1980 (Elsner et al. 2008) confirms a global increase of the number of category 4 and 5 (i.e., the strongest) tropical cyclones: they found a 1°C global warming corresponding to a 30% increase in these storms. While evidence has thus firmed up considerably that recent warming has been associated with stronger tropical cyclones, modeling studies (e.g. Emanuel et al. 2008; Knutson et al. 2008, Vecchi et al. 2008) have shown that we have as yet no robust capacity to project future changes in tropical cyclone activity.

Other severe weather events

The IPCC Fourth Assessment concluded that there were insufficient studies available to make an assessment of observed changes in small-scale severe weather events or of expected future changes in such events. However, recent research has shown an increased frequency of severe thunderstorms in some regions, particularly the tropics and south-eastern US, is expected due to future anthropogenic climate change (Trapp et al. 2007; Aumann et al. 2008; Marsh et al. 2009; Trapp et al. 2009). In addition, there have been recent increases in the frequency and intensity of wildfires in many regions with Mediterranean climates (e.g. Spain, Greece, southern California, south-east Australia) and further marked increases are expected due to anthropogenic climate change (Westerling et al. 2006; Pitman et al. 2008).

LAND SURFACE

- ☐ *Land cover change, particularly deforestation, can have a major impact on regional climate, but at the global scale its biggest impact comes from the CO_2 released in the process.*
- ☐ *Observations through the 2005 drought in Amazonia suggest that the tropical forests could become a strong carbon source if rainfall declines in the future.*
- ☐ *Carbon dioxide changes during the Little Ice Age indicate that warming may in turn lead to carbon release from land surfaces, a feedback that could amplify 21st century climate change.*
- ☐ *Avoiding tropical deforestation could prevent up to 20% of human-induced CO_2 emissions and help to maintain biodiversity.*

How does land-use change affect climate?

Earth's climate is strongly affected by the nature of the land-surface, including the vegetation and soil type and the amount of water stored on the land as soil moisture, snow and groundwater. Vegetation and soils affect the surface albedo, which determines the amount of sunlight absorbed by the land. The land surface also affects the partitioning of rainfall into evapotranspiration (which cools the surface and moistens the atmosphere) and runoff (which provides much of our freshwater). This partitioning can affect local convection and therefore rainfall. Changes in land-use associated with the spread of agriculture and urbanization and deforestation can alter these mechanisms. Land use change can also change the surface roughness, affect emissions of trace gases, and some volatile organic compounds such as isoprene. Despite the key role of land cover change at regional scales, climate model projections from IPCC AR4 excluded anthropogenic land-cover change.

There has been significant progress on modeling the role of land cover change since the IPCC AR4 (Piekle et al. 2007), with the first systematic study demonstrating that large-scale land cover change directly and significantly affects regional climate (Pitman et al. 2009). This has important implications for understanding future climate change; climate models need to simulate land cover change to capture regional changes in regions of intense land cover change. However, failing to account for land cover change has probably not affected global-scale projections (Pitman et al. 2009), noting that emissions from land cover change are included in projections.

Land-cover change also affects climate change by releasing CO_2 to the atmosphere and by modifying the land carbon sink (Bondeau et al. 2007; Fargione et al. 2008). The most obvious example of this is tropical deforestation which contributes about a fifth of global CO_2 emissions and also influences the land-to-atmosphere fluxes of water and energy (Bala et al. 2007). Avoiding deforestation therefore eliminates a significant fraction of anthropogenic CO_2 emissions, and maintains areas like the Amazon rainforest which supports high biodiversity and plays a critically important role in the climate system (Malhi et al. 2008).

Climate Change and the Amazon Rainforest

The distribution and function of vegetation depends critically on the patterns of temperature and rainfall across the globe. Climate change therefore has the potential to significantly alter land-cover even in the absence of land-use change. A key area of concern has been the remaining intact Amazonian rainforest which is susceptible to 'dieback' in some climate models due to the combined effects of increasing greenhouse gases and reducing particulate or 'aerosol' pollution in the northern hemisphere (Cox et al. 2008). However, these projections are very dependent on uncertain aspects of regional climate change, most notably the sign and magnitude of rainfall change in Amazonia in the 21st century (Malhi et al. 2008, 2009).

There have also been some doubts raised as to whether the Amazonian rainforest is as sensitive to rainfall reductions as large-scale models suggest. The drought in Western Amazonia in 2005 provided a test of this hypothesis using long-term monitoring of tree growth in the region (Phillips et al. 2009), and a massive carbon source was detected in the region in 2005 against the backdrop of a significant carbon sink in the decades before. The forests of Amazonia are therefore sensitive to '2005-like' droughts and these are expected to become more common in the 21st century (Cox et al. 2008).

A similar story emerges from the analysis of satellite and CO_2 flux measurements during the European drought of 2003 (Reichstein et al. 2007). The IPCC AR4 tentatively suggested a link between global warming and the 2003 drought, and this analysis showed that the drought had an enormous impact on the health and functioning of both natural and managed landscapes in the region.

How large are feedbacks linking land-surface and climate?

The response of the land-surface to climatic anomalies feeds back on the climate by changing the fluxes of energy, water and CO_2 between the land and the atmosphere. For example, it seems likely that changes in the state of the land-surface, which in turn changed the energy and water fluxes to the atmosphere, played an important part in the severity and length of the 2003 European drought (Fischer et al. 2007). In some regions, such as the Sahel, land-atmosphere coupling may be strong enough to support two alternative climate-vegetation states; one wet and vegetated, the other dry and desert-like. There may be other "hot-spot" regions where the land-atmosphere coupling significantly controls the regional climate; indeed it appears that the land is a strong control on climate in many semi arid and Mediterranean-like regions.

However, the strongest feedbacks on global climate in the 21st century are likely to be due to changes in the land carbon sink. The climate-carbon cycle models reported in the IPCC AR4 (Friedlingstein et al. 2006) reproduced the historical land carbon sink predominantly through `CO_2 fertilization'. There is evidence of CO_2 fertilization being limited in nitrogen-limited ecosystems (Hyvonen et al. 2007), but the first generation coupled climate-carbon models did not include nutrient cycling.

The IPCC AR4 climate-carbon cycle models also represented a counteracting tendency for CO_2 to be released more quickly from the soils as the climate warms, and as a result these models predicted a reducing efficiency of the land carbon sink under global warming. There is some suggestion of a slow-down of natural carbon sinks in the recent observational record (Canadell et al. 2007), and strong amplifying land carbon-climate feedback also seems to be consistent with records of the little ice-age period (Cox and Jones 2008).

Does the land-surface care about the causes of climate change?

Yes. Vegetation is affected differently by different atmospheric pollutants, and this means that the effects of changes in atmospheric composition cannot be understood purely in terms of their impact on global warming.

CO_2 increases affect the land through climate change, but also directly through CO_2-fertilization of photosynthesis, and 'CO_2-induced stomatal closure' which tends to increase plant water-use efficiency. Observational studies have shown a direct impact of CO_2 on the stomatal pores of plants, which regulate the fluxes of water vapor and CO_2 at the leaf surface. In a higher CO_2 environment, stomata reduce their opening since they are able to take up CO_2 more efficiently. By transpiring less, plants increase their water-use efficiency, which consequently affects the surface energy and water balance. If transpiration is suppressed via higher CO_2, the lower evaporative cooling may also lead to higher temperatures (Cruz et al. 2009). There is also the potential for significant positive impacts on freshwater resources, but this is still an area of active debate (Gedney et al. 2006, Piao et al. 2007, Betts et al. 2007).

By contrast, increases in near surface ozone have strong negative impacts on vegetation by damaging leaves and their photosynthetic capacity. As a result historical increases in near surface ozone have probably suppressed land carbon uptake and therefore increased the rate of growth of CO_2 in the 20th century. Sitch et al. (2007) estimate that this indirect forcing of climate change almost doubles the contribution that near-surface ozone made to 20th century climate change.

Atmospheric aerosol pollution also has a direct impact on plant physiology by changing the quantity and nature of the sunlight reaching the land-surface. Increasing aerosol loadings from around 1950 to 1980, associated predominantly with the burning of sulphurous coal, reduced the amount of sunlight at the surface, which has been coined 'global dimming' (Wild et al. 2007). Since plants need sunlight for photosynthesis, we might have expected to see a slow-down of the land carbon sink during the global dimming period, but we didn't. Mercado et al. (2009) offer an explanation for this based on the fact that plants are more light-efficient if the sunlight is 'diffuse'. Aerosol pollution would certainly have scattered the sunlight, making it more diffuse, as well as reducing the overall quantity of sunlight reaching the surface. It seems that 'diffuse radiation fertilization' won this battle, enhancing the global land-carbon sink by about a quarter from 1960 to 2000 (Mercado et al. 2009). This implies that the land carbon sink will decline if we reduce the amount of potentially harmful particulates in the air.

These recent studies since IPCC AR4 argue strongly for metrics to compare different atmospheric pollutants that go beyond radiative forcing and global warming, to impacts on the vital ecosystem services related to the availability of food and water.

PERMAFROST AND HYDRATES

- ❏ *New insights into the Northern Hemisphere permafrost (permanently frozen ground) suggest a large potential source of CO_2 and CH_4 that would amplify atmospheric concentrations if released.*
- ❏ *A recent increase in global methane levels cannot yet be attributed to permafrost degradation.*
- ❏ *A separate and significant source of methane exists as hydrates beneath the deep ocean floor and in permafrost. It has recently been concluded that release of this type of methane is very unlikely to occur this century.*

As noted in the IPCC AR4 and more recent studies, the southern boundary of the discontinuous permafrost zone has shifted northward over North America in recent decades. Rapid degradation and upward movement of the permafrost lower limit has continued on the Tibetan plateau (Jin et al. 2008, Cui and Graf 2009). In addition, observations in Europe (Åkerman and Johansson 2008; Harris et al. 2009) have noted permafrost thawing and a substantial increase in the depth of the overlying active layer exposed to an annual freeze/thaw cycle, especially in Sweden.

As permafrost melts and the depth of the active layer deepens, more organic material can potentially start to decay. If the surface is covered with water, methane-producing bacteria break down the organic matter. But these bacteria cannot survive in the presence of oxygen. Instead, if the thawed soils are exposed to air, carbon dioxide-producing bacteria are involved in the decay process. Either case is an amplifying feedback to global warming. In fact, the magnitude of the feedback represents an important unknown in the science of global warming; this feedback has not been accounted for in any of the IPCC projections. The total amount of carbon stored in permafrost has been estimated to be around 1672 Gt (1 Gt = 10^9 tons), of which ~277 Gt are contained in peatlands (Schuur et al. 2008; Tarnocai et al. 2009). This represents about twice the amount of carbon contained in the atmosphere. A recent analysis by Dorrepaal et al. (2009) has found strong direct observational evidence for an acceleration of carbon emissions in association with climate warming from a peat bog overlying permafrost at a site in northern Sweden. Whether or not recent observations of increasing atmospheric methane concentration (Rigby et al. 2008), after nearly a decade of stable levels, are caused by enhanced northern hemisphere production associated with surface warming is still uncertain.

Another amplifying feedback to warming that has recently been observed in high northern latitudes involves the microbial transformation of nitrogen trapped in soils to nitrous oxide. By measuring the nitrous oxide emissions from bare peat surfaces, Repo et al. (2009) inferred emissions per square meter of the same magnitude as those from croplands and tropical soils. They point out that as the Arctic warms, regions of bare exposed peat will increase, thereby amplifying total nitrous oxide emissions.

Between 500 and 10,000 Gt of carbon are thought to be stored under the sea floor in the form methane hydrates (or clathrates), a crystalline structure of methane gas and water molecules (Brook et al. 2008). Another 7.5 to 400 Gt of carbon are stored in the form of methane hydrates trapped in permafrost (Brook et al. 2008). Some have argued that anthropogenic warming could raise the possibility of a catastrophic release of methane from hydrates to the atmosphere. In a recent assessment by the US Climate Change Science Program (CCSP 2008b), it was deemed to be very unlikely that such a release would occur this century, although the same assessment deemed it to be very likely that methane sources from hydrate and wetland emissions would increase as the climate warmed. This is supported by a recent analysis that found that the observed increase in atmospheric methane 11,600 years ago had a wetland, as opposed to hydrate, origin (Petrenko et al. 2009); as was also found in studies using Earth models of intermediate complexity (Fyke and Weaver 2006; Archer et al. 2009).

Few studies with AR4-type climate models have been undertaken. One systematic study used the Community Climate System Model, version 3 (CCSM3) with explicit treatment of frozen soil processes. The simulated reduction in permafrost reached 40% by ~2030 irrespective of emission scenario (a reduction from ~10 million km^2 to 6 million km^2). By 2050, this reduces to 4 million km^2 (under B1 emissions) and 3.5 million km^2 (under A2 emissions). Permafrost declines to ~1 million km^2 by 2100 under A2. In each case, the simulations did not include additional feedbacks triggered by the collapse of permafrost including out-gassing of methane, a northward expansion of shrubs and forests and the activation of the soil carbon pool. These would each further amplify warming.

GLACIERS AND ICE-CAPS

- *There is widespread evidence of increased melting of glaciers and ice-caps since the mid-1990s.*
- *The contribution of glaciers and ice-caps to global sea-level has increased from 0.8 millimeters per year in the 1990s to be 1.2 millimeters per year today.*
- *The adjustment of glaciers and ice caps to present climate alone is expected to raise sea level by ~18 centimeters. Under warming conditions they may contribute as much as ~55 centimeters by 2100*

Glaciers and mountain ice-caps can potentially contribute a total of approximately 0.7 meters to global sea-level. Glaciers and mountain ice-caps also provide a source of freshwater in many mountain regions worldwide. The IPCC AR4 assessed the contribution from worldwide shrinking glaciers and ice caps to sea level rise at the beginning of the 21st Century at about 0.8 millimeters per year (Lemke et al. 2007, Kaser et al. 2006). Since then, new estimates of the contribution from glaciers and ice caps have been made using new data and by exploring new assessment methods.

These new assessments are shown in Figure 7. They show glacier and ice cap contributions to sea level rise that are generally slightly higher than those reported in IPCC AR4. They also extend from 1850 up to 2006. These new estimates show that the mass loss of glaciers and ice caps has increased considerably since the beginning of the 1990s and now contribute about 1.2 millimeters per year to global sea level rise.

Glaciers and ice caps are not in balance with the present climate. Recent estimates show that adjustment to that alone will cause a mass loss equivalent to ~18 centimeters sea level rise (Bahr et al. 2009) within this century. Under ongoing changes consistent with current warming trends, a mass loss of up to ~55 centimeters sea level rise is expected by 2100 (Pfeffer et al. 2008).

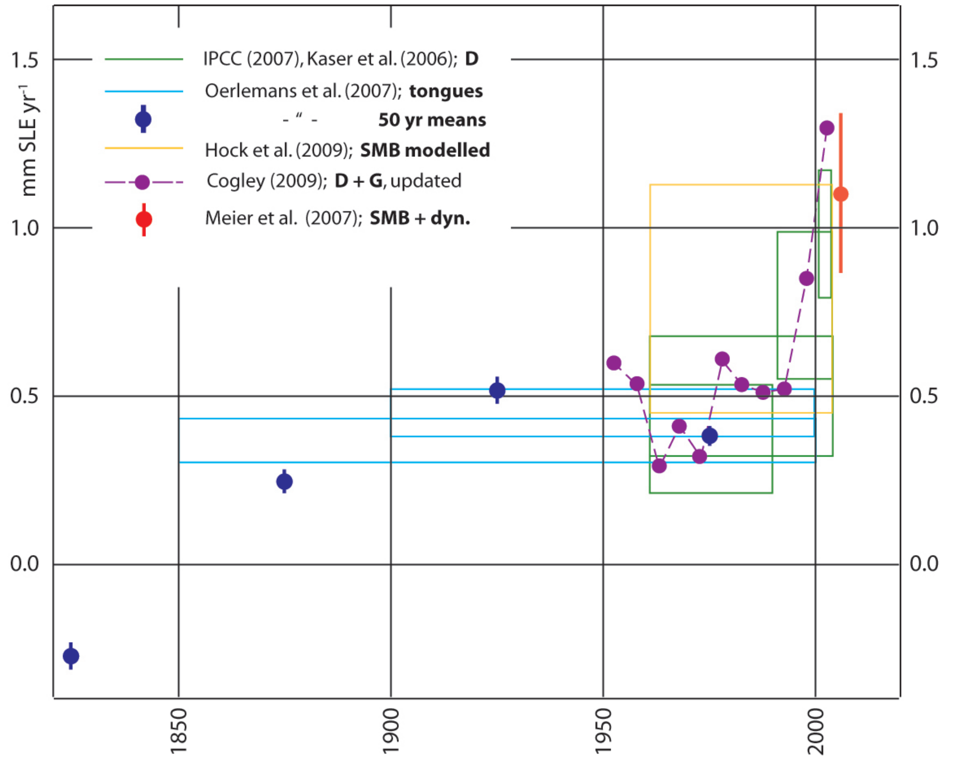


Figure 7. Estimates of the contribution of glaciers and ice-caps to global change in sea-level equivalent (SLE), in millimeters SLE per year.

ICE-SHEETS OF GREENLAND AND ANTARCTICA

- *The surface area of the Greenland ice sheet which experiences summer melt has increased by 30% since 1979, consistent with warming air temperatures. Melt covered 50% of the ice sheet during the record season in 2007.*
- *The net loss of ice from the Greenland ice sheet has accelerated since the mid-1990s and is now contributing as much as 0.7 millimeters per year to sea level rise due to both increased melting and accelerated ice flow.*
- *Antarctica is also losing ice mass at an increasing rate, mostly from the West Antarctic ice sheet due to increased ice flow. Antarctica is currently contributing to sea level rise at a rate nearly equal to Greenland.*

Antarctica and Greenland maintain the largest ice reservoirs on land. If completely melted, the Antarctic ice-sheet would raise global sea-level by 52.8 meters, while Greenland would add a further 6.6 meters. Loss of only the most vulnerable parts of West Antarctica would still raise sea level by 3.3 meters (Bamber et al,. 2009). IPCC AR4 concluded that net ice loss from the Greenland and Antarctic ice sheets together contributed to sea level rise over the period 1993 to 2003 at an average rate estimated at 0.4 millimeters per year. Since IPCC AR4, there have been a number of new studies observing and modelling ice-sheet mass budget that have considerably enhanced our understanding of ice-sheet vulnerabilities (Allison et al. 2009). These assessments reinforce the conclusion that the ice sheets are contributing to present sea level rise, and show that the rate of loss from both Greenland and Antarctica has increased recently. Furthermore, recent observations have shown that changes in the rate of ice discharge into the sea can occur far more rapidly than previously suspected (e.g. Rignot 2006).

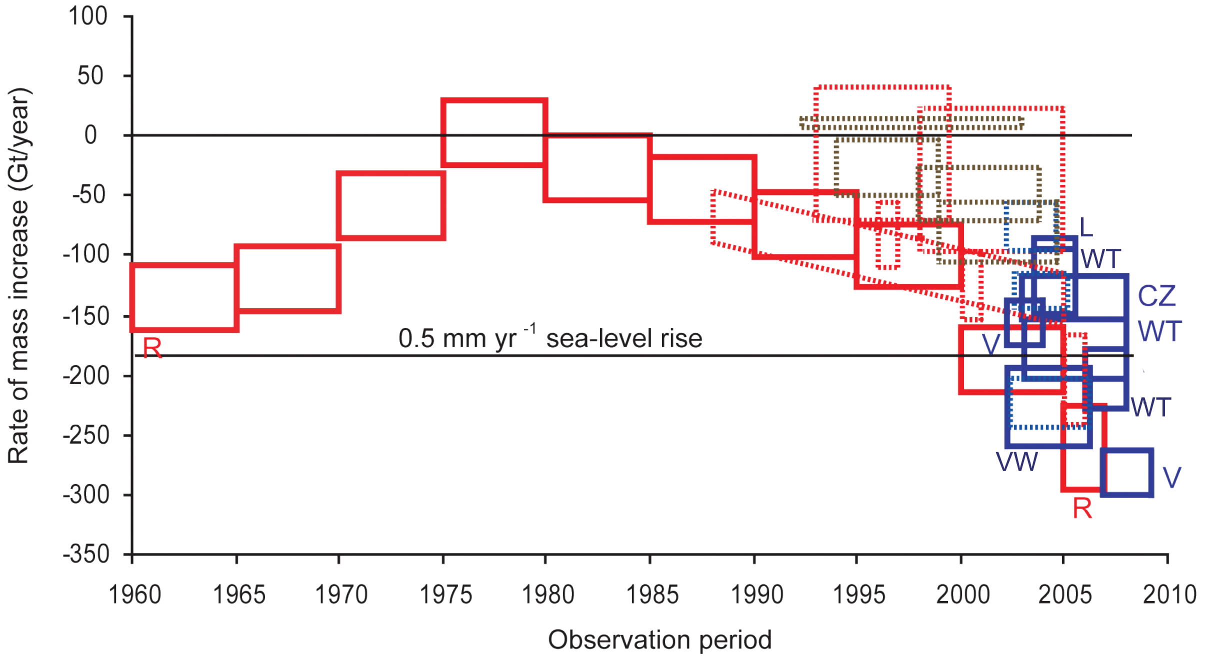


Figure 8. Estimates of the net mass budget of the Greenland Ice Sheet since 1960. A negative mass budget indicates ice loss and sea level rise. Dotted boxes represent estimates used by IPCC AR4 (IPCC, 2007). The solid boxes are post-AR4 assessments (R = Rignot et al. 2008a; VW = Velicogna & Wahr 2006; L = Luthcke et al. 2006; WT = Wouters et al. 2008; CZ = Cazenave et al. 2009; V = Velicogna 2009).

Greenland

Figure 8 shows estimates of the mass budget of the Greenland Ice Sheet since 1960. In this representation, the horizontal dimension of the boxes shows the time period over which the estimate was made, and the vertical dimension shows the upper and lower limits of the estimate. The colors represent the different methods that were used: estimates derived from satellite or aircraft altimeter measurements of height change of the ice sheet surface are brown; estimates of mass loss from satellite gravity measurements are blue; and estimates derived from the balance between mass influx and discharge are red.

The data in Figure 8 indicate that net ice mass loss from Greenland has been increasing since at least the early 1990s, and that in the 21st Century, the rate of loss has increased significantly. Multiple observational constraints and the use of several different techniques provide confidence that the rate of mass loss from the Greenland ice-sheet has accelerated. Velicogna (2009) used GRACE satellite gravity data to show that the rate of Greenland mass loss doubled over the period from April 2002 to February 2009.

Near-coastal surface melt and run-off have increased significantly since 1960 in response to warming temperature, but total snow precipitation has also increased (Hanna et al. 2008). The average Greenland surface temperature rose by more than 1.5°C over the period 2000 to 2006 and mass loss estimated from GRACE gravity data occurred within 15 days of the initiation of surface melt, suggesting that the water drains rapidly from the ice sheet (Hall et al. 2008). Passive microwave satellite measurements of the area of the Greenland ice sheet subject to surface melt indicate that the melt area has been increasing since 1979 (Steffen et al. 2008; Figure 9). There is a good correlation between total melt area extent and the number of melt days with total volume of run off, which has also increased.

The pattern of ice sheet change in Greenland is one of near-coastal thinning, primarily in the south along fast-moving outlet glaciers. Accelerated flow and discharge from some major outlet glaciers (also called dynamic thinning) is responsible for much of the loss (Rignot & Kanagaratnam 2006; Howat et al. 2007). In southeast Greenland many smaller drainage basins, especially the catchments of marine-terminating outlet glaciers, are also contributing to ice loss (Howat et al. 2008). Pritchard et al. (2009) used high resolution satellite laser altimetry to show that dynamic thinning of fast-flowing coastal glaciers is now widespread at all latitudes in Greenland. Greenland glaciers flowing faster than 100 meters per year thinned by an average of 0.84 meters per year between 2003 and 2007.

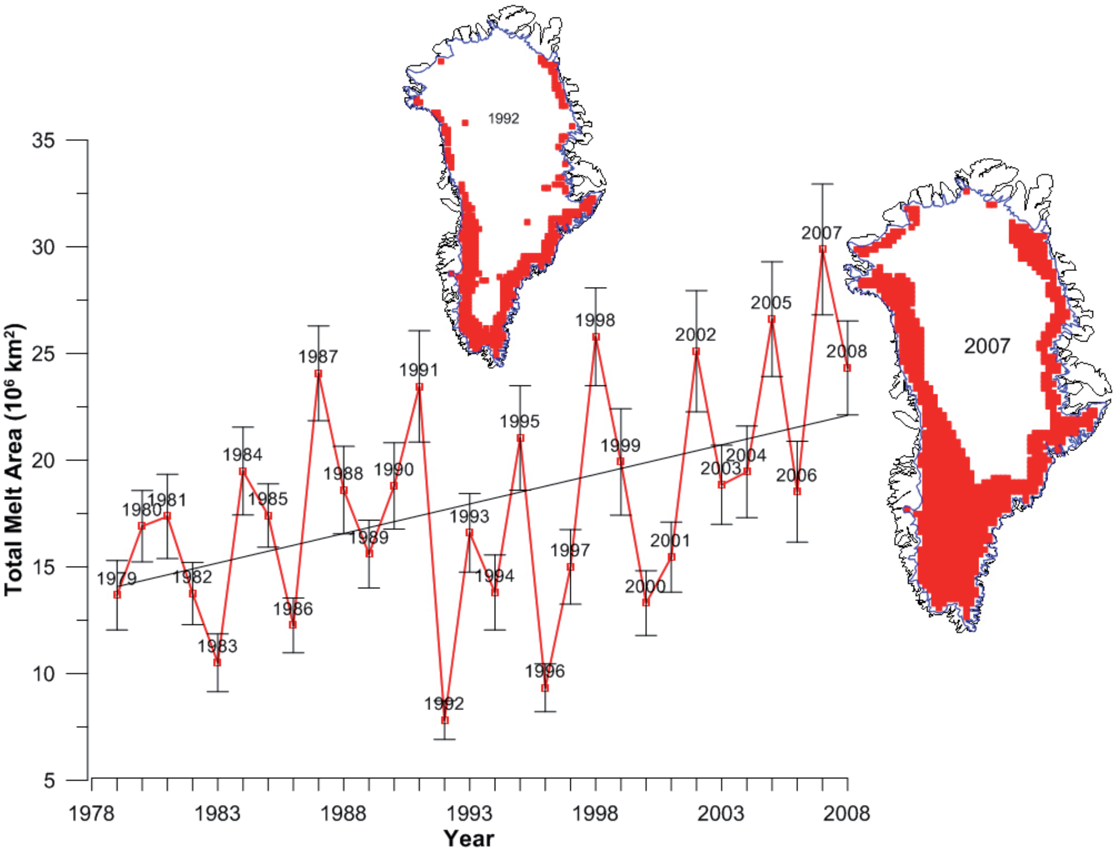


Figure 9. The total melt area of the Greenland ice sheet increased by 30% between 1979 and 2008 based on passive microwave satellite data, with the most extreme melt in 2007. In general 33-55% of the total mass loss from the Greenland ice sheet is caused by surface melt and runoff. For 2007, the area experiencing melt was around 50% of the total ice sheet area. The low melt year in 1992 was caused by the volcanic aerosols from Mt. Pinatubo causing a short-lived global cooling (updated from Steffen et al. 2008).

Antarctica

New estimates of the mass budget of the Antarctic Ice Sheet are shown in Figure 10. Comprehensive estimates for Antarctica are only available since the early 1990s. Several new studies using the GRACE satellite gravity data (blue boxes in Figure 10) all show net loss from the Antarctic since 2003 with a pattern of near balance for East Antarctica, and greater mass loss from West Antarctica and the Antarctic Peninsula (e.g. Chen et al. 2006; Cazenave et al. 2009). The GRACE assessment of Velicogna (2009) indicates that, like Greenland, the rate of mass loss from the Antarctic ice sheet is accelerating, increasing from 104 Gt per year for 2002-2006 to 246 Gt per year for 2006-2009 (the equivalent of almost 0.7 millimeters per year of sea level rise). Gravity and altimeter observations require correction for uplift of the Earth's crust under the ice sheets (glacial isostatic adjustment): this is poorly known for Antarctica.

The largest losses occurred in the West Antarctic basins draining into the Bellingshausen and Amundsen Seas. Satellite glacier velocity estimates from 1974 imagery show that the outlet glaciers of the Pine Island Bay region have accelerated since then, changing a region of the ice sheet that was in near-balance to one of considerable loss (Rignot 2008). Rignot et al. (2008b) show that the ice discharge in this region further increased between 1996 and 2006, increasing the net mass loss over the period by 59%, and Pritchard et al. (2009) show from laser altimetry that dynamic thinning in some parts of the Amundsen Sea embayment has exceeded 9 meters per year. The recent acceleration of ice streams in West Antarctica explains much of the Antarctic mass loss, but narrow fast-moving ice streams in East Antarctica are also contributing to the loss (Pritchard et al. 2009).

The Antarctic Peninsula region has experienced much greater warming than the continent as a whole. This has led to widespread retreat (Cook et al. 2005) and acceleration (Pritchard & Vaughan 2007) of the tidewater glaciers in that region.

The Risk of Ice-Sheet Collapse

The largest unknown in the projections of sea level rise over the next century is the potential for rapid dynamic collapse of ice sheets. The most significant factor in accelerated ice discharge in both Greenland and Antarctica over the last decade has been the un-grounding of glacier fronts from their bed, mostly due to submarine ice melting. Changes to basal lubrication by melt water, including surface melt draining through moulins (vertical conduits) to the bottom of the ice sheet, may also affect the ice sheet dynamics in ways that are not fully understood. The major dynamic ice sheet uncertainties are largely one-sided: they can lead to a faster rate of sea-level rise, but are unlikely to significantly slow the rate of rise. Although it is unlikely that total sea level rise by 2100 will be as high as 2 meters (Pfeffer et al. 2008), the probable upper limit of a contribution from the ice sheets remains uncertain.

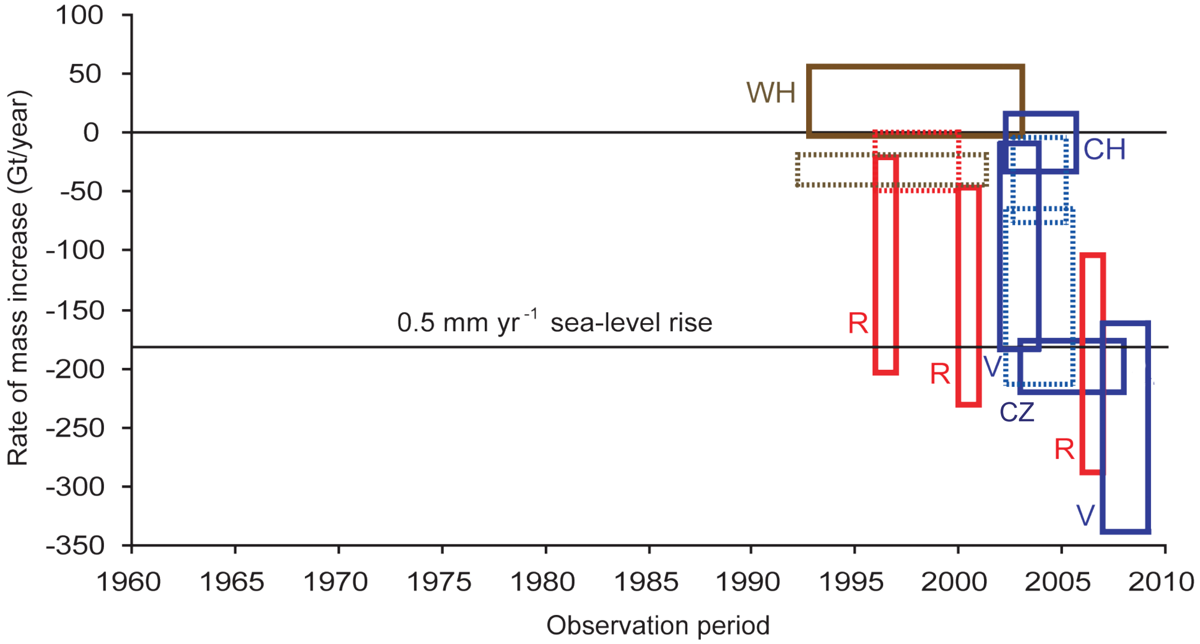


Figure 10. Estimates of the net mass budget of the Antarctic Ice Sheet since 1992. Dotted boxes represent estimates used by IPCC AR4 (IPCC 2007). The solid boxes are more recent estimates (CH = Chen et al. 2006; WH = Wingham et al. 2006; R = Rignot et al. 2008b; CZ = Cazenave et al. 2009; V = Velicogna 2009).

ICE SHELVES

- ❏ *Ice-shelves connect continental ice-sheets to the ocean. Destabilization of ice-shelves along the Antarctic Peninsula has been widespread with 7 collapses over the past 20 years.*
- ❏ *Signs of ice shelf weakening have been observed elsewhere than in the Antarctic Peninsula, e.g. in the Bellingshausen and Amundsen seas, indicating a more widespread influence of atmospheric and oceanic warming than previously thought.*
- ❏ *There is a strong influence of ocean warming on ice sheet stability and mass balance via the melting of ice-shelves.*

Ice shelves are floating sheets of ice of considerable thickness that are attached to the coast. They are mostly composed of ice that has flowed from the interior ice sheet, or that has been deposited as local snowfall. They can be found around 45% of the Antarctic coast, in a few bays off the north coast of Ellesmere Island near Greenland, and in a few fiords along the northern Greenland coast (where they are termed ice tongues). Over the last few years, the six remaining ice shelves (Serson, Petersen, Milne, Ayles, Ward Hunt and Markham) off Ellesmere Island have either collapsed entirely (Ayles on August 13, 2005 and Markham during the first week of August, 2008) or undergone significant disintegration.

Along the coast of Greenland, the seaward extent of the outlet glacier Jakobshavn Isbrae provides a striking example of a floating ice tongue in retreat (Figure 11). Holland et al. (2008) suggest

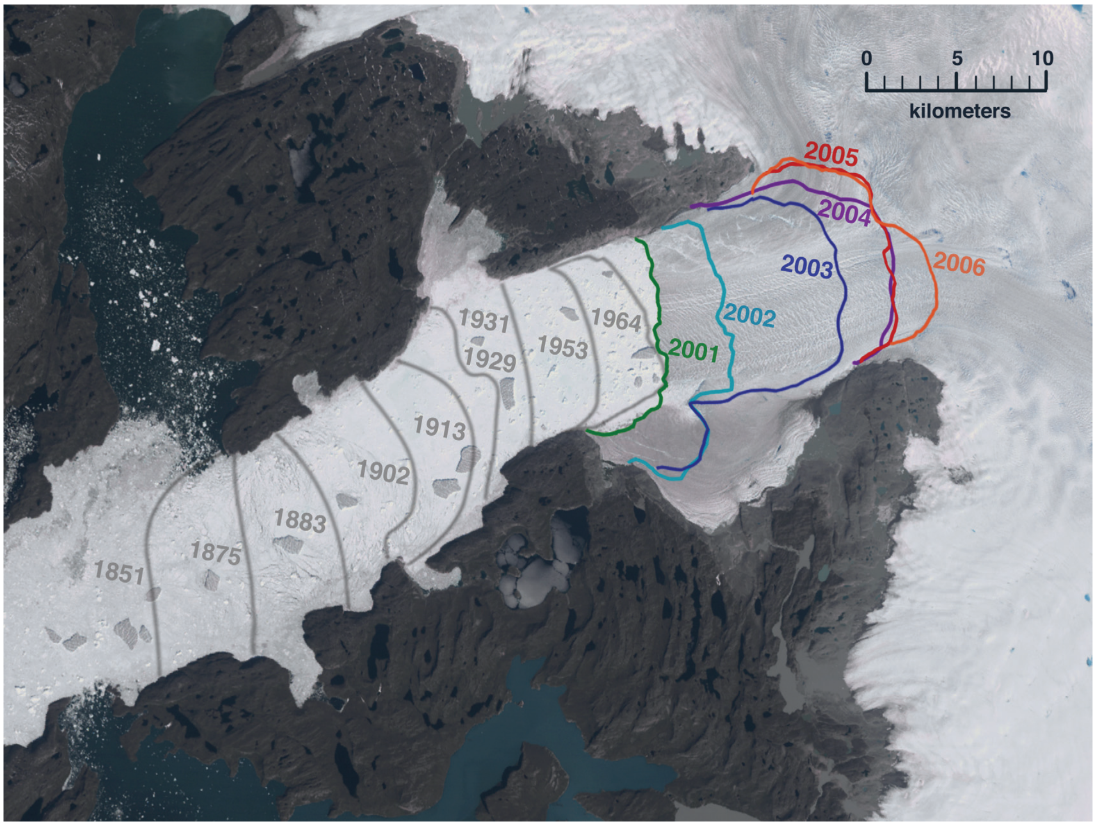


Figure 11. The floating ice tongue representing the seaward extent of Jakobshavn Isbræ on July 7, 2001. Changes in the position of the calving front from 1851 to 2006 are indicated. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio (http://svs.gsfc.nasa.gov/vis/a000000/a003300/a003395/).

that the observed recent acceleration (Rignot and Kanagaratnam 2006) of Jakobshavn Isbrae may be attributed to thinning from the arrival of warm waters in the region.

Destabilization of floating ice shelves has been widespread along the Antarctic Peninsula with seven collapsing in the last 20 years. Warming along the Peninsula has been dramatic, and on the western side has been substantially above the global average. Most recently, in March 2009, more than 400 square kilometers collapsed off the Wilkins Ice Shelf on the western side of the Antarctic Peninsula. A number of mechanisms are thought to play important roles in destabilizing floating Antarctic ice shelves. These include: surface warming leading to the creation of melt ponds and subsequent fracturing of existing crevasses (van den Broeke 2005); subsurface ice shelf melting from warming ocean waters (Rignot et al. 2008b); and internal ice shelf stresses (Bruan and Humbert 2009). While the collapse of a floating ice shelf does not itself raise sea level, its collapse is followed by rapid acceleration of glacier outflow – which does raise sea level – due to the removal of the ice shelf buttressing effect (e.g. Rignot et al. 2004; Scambos et al. 2004).

There is evidence for the melting of ice shelves in the Amundsen Sea, with impacts on the flow speed of glaciers draining this part of West Antarctica. A recent modeling study has suggested that the West Antarctic Ice Sheet would begin to collapse when ocean temperatures in the vicinity of any one of the ice shelves that surround it warm by about 5°C (Pollard and DeConto 2009). There is also evidence that these changes are not limited to West Antarctica and may also affect the coastline of East Antarctica, for example in Wilkes Land (Pritchard et al. 2009; Shepherd and Wingham 2007). The widespread thinning and acceleration of glaciers along the Antarctic coast may indicate a significant impact of oceanic changes on glacier dynamics, a factor that has received little attention in past IPCC reports due to the lack of observational data on ice-ocean interactions and how climate change might influence coastal ocean waters.

SEA-ICE

❏ *The observed summer-time melting of Arctic sea-ice has far exceeded the worst-case projections from climate models of IPCC AR4.*

❏ *The warming commitment associated with existing atmospheric greenhouse gas levels means it is very likely that in the coming decades the summer Arctic Ocean will become ice-free, although the precise timing of this remains uncertain.*

❏ *Satellite observations show a small increase of Antarctic sea-ice extent and changes to seasonality, although there is considerable regional variability. This is most likely due to changes in Southern Ocean winds associated with stratospheric ozone-depletion.*

Arctic Sea Ice

Perhaps the most stunning observational change since the IPCC AR4 has been the shattering of the previous Arctic summer minimum sea ice extent record – something not predicted by climate models. Averaged over the five-day period leading up to September 16, 2007, the total extent of sea ice in the Arctic was reduced to an area of only 4.1 million square kilometers (see Figure 12), surpassing the previous minimum set in 2005 by 1.2 million square kilometers (about the same size as France, Spain, Portugal, Belgium and Netherlands combined). The median September minimum sea ice extent since observations with the current generation of multi-frequency passive microwave sensors commenced in 1979 to 2000 was 6.7 million square kilometers. Compared to the median, the 2007 record involved melting 2.6 million square kilometers more ice (~40% of the median).

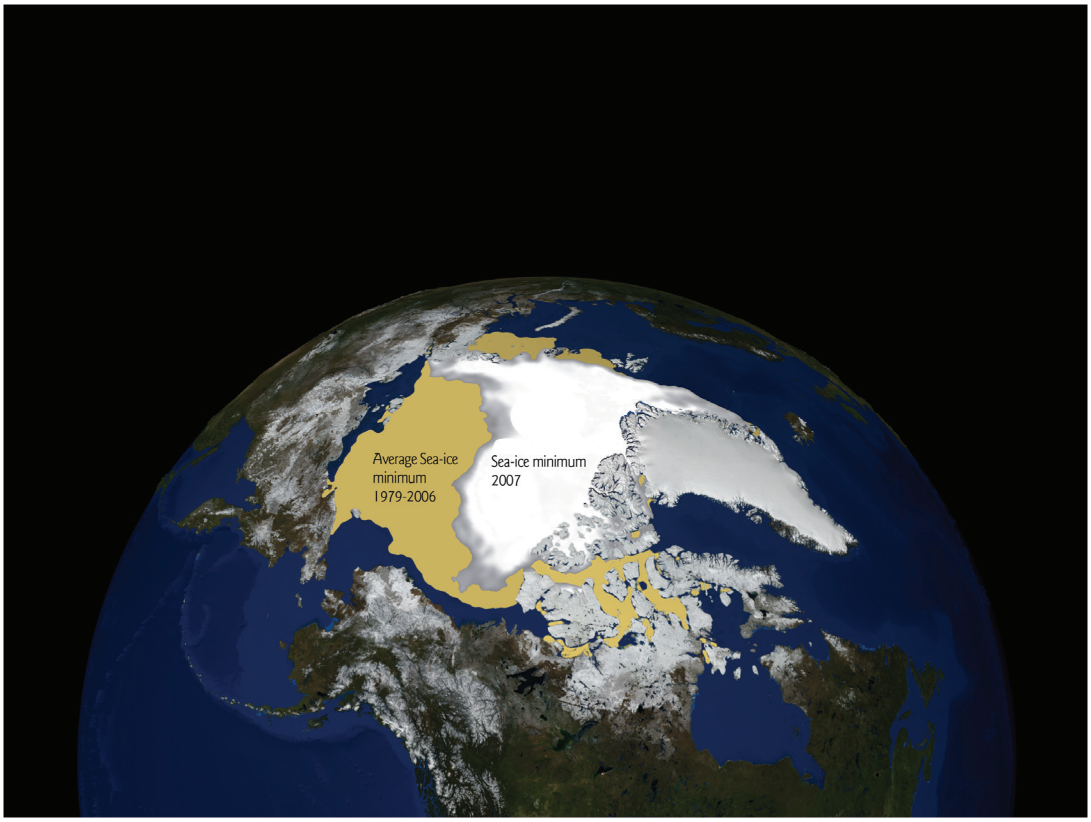


Figure 12. Arctic sea ice extent over the five days leading up to and including September 16, 2007 compared to the average sea-ice minimum extent for the period 1979- 2006. Sourced from the NASA/Goddard Space Flight Center Scientific Visualization Studio.

The September Arctic sea ice extent over the last several decades has decreased at a rate of 11.1 ± 3.3%/decade (NSIDC 2009). This dramatic retreat has been much faster than that simulated by any of the climate models assessed in the IPCC AR4 (Figure 13). This is likely due to a combination of several model deficiencies, including: 1) incomplete representation of ice albedo physics, including the treatment of melt ponds (e.g., Pedersen et al. 2009) and the deposition of black carbon (e.g. Flanner et al. 2007; Ramanathan and Carmichael 2008); and 2) incomplete representation of the physics of vertical and horizontal mixing in the ocean (e.g. Arzel et al. 2006). Winter Arctic sea ice extent has also decreased since 1979, but at a slower rate than in summer. The February extent has decreased at a rate of 2.9 ± 0.8%/decade (NSIDC 2009).

The thickness of Arctic sea ice has also been on a steady decline over the last several decades. For example, Lindsay et al. (2009) estimated that the September sea ice thickness has been decreasing at a rate of 57 centimeters per decade since 1987. Similar decreases in sea-ice thickness have been detected in winter. For example, within the area covered by submarine sonar measurements, Kwok and Rothrock (2009) show that the overall mean winter thickness of 3.64 meters in 1980 decreased to only 1.89 meters by 2008 — a net decrease of 1.75 meters, or 48%. By the end of February 2009, less than 10% of Arctic sea ice was more than two years old, down from the historic values of 30%.

When Will the Arctic Ocean be Ice-Free?

Due to the existence of natural variability within the climate system, it is not possible to predict the precise year that the Arctic Ocean will become seasonally ice free. Nevertheless, the warming commitment associated with existing atmospheric greenhouse gas levels very likely means that a summer ice-free Arctic is inevitable. Evidence is also emerging to suggest that the transition to an ice-free summer in the Arctic might be expected to occur abruptly, rather than slowly (Holland et al. 2006), because of amplifying feedbacks inherent within the Arctic climate system. In fact, in one of the simulations of the NCAR Climate System Model version 3 (CCSM3) discussed in Holland et al (2006), the Arctic summer became nearly ice-free by 2040. As noted by Lawrence et al. (2008), an abrupt reduction in Arctic summer sea ice extent also triggers rapid warming on land and subsequent permafrost degradation.

Antarctic Sea Ice

Unlike the Arctic, Antarctic sea-ice extent changes have been more subtle, with a net annual-mean area increase of ~1% per decade over the period 1979–2006 (Cavalieri and Parkinson 2008; Comiso and Nishio 2008). There have however been large regional changes in Antarctic sea-ice distribution: for example, the Weddell and Ross Sea areas have shown increased extent linked to changes in large-scale atmospheric circulation, while the western Antarctic Peninsula region and the coast of West Antarctica (Amundsen and Bellingshausen Seas) show a significant decline consistent with more northerly winds and surface warming observed there (Lefebvre et al. 2004; Turner et al. 2009; Steig et al. 2009). These regional changes are linked to a major change in the seasonality of the ice; that is, its duration and the timing of the annual advance and retreat (Stammerjohn et al. 2008).

Since Antarctica is a land mass surrounded by the vast Southern Ocean, whereas the Arctic is a small ocean surrounded by vast amounts of land, and as oceans respond less rapidly than land to warming because of their thermal stability, one would expect, and indeed climate models show, a delayed

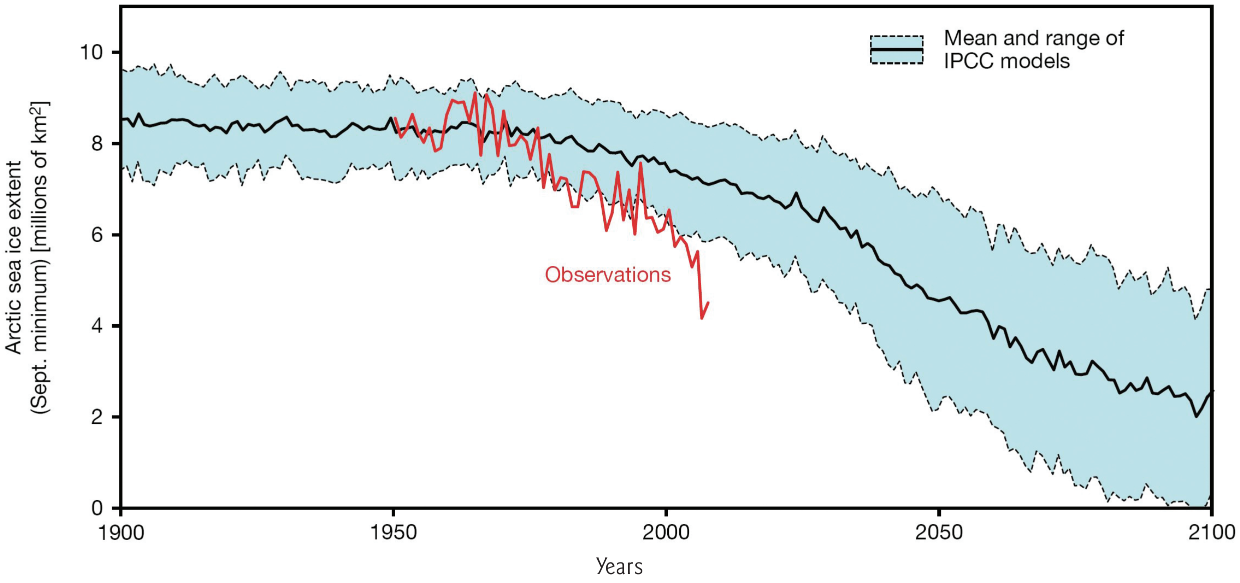


Figure 13. Observed (red line) and modeled September Arctic sea ice extent in millions of square kilometers. The solid black line gives the ensemble mean of the 13 IPCC AR4 models while the dashed black lines represent their range. From Stroeve et al. (2007) updated to include data for 2008. The 2009 minimum has recently been calculated at 5.10 million km^2, the third lowest year on record, and still well below the IPCC worst case scenario.

warming response around Antarctica. In addition, Turner et al. (2009) note that stratospheric ozone depletion arising from the anthropogenic release of chlorofluorocarbons (CFCs) has led to the strengthening of surface winds around Antarctica during December to February (summer). They argue that these strengthened winds are in fact the primary cause for the slight positive trend in Antarctic sea ice extent observed over the last three decades. However, as CFCs are regulated under the Montreal Protocol and have declining atmospheric concentrations, the ozone hole over Antarctica is expected to recover and hence one anticipates an acceleration of sea ice melt in the Southern Hemisphere in the decades ahead.

There are few data available on the thickness distribution of Antarctic pack ice, and no information on any changes in the thickness of Antarctic sea ice.

Isn't Antarctica cooling and Antarctic sea ice increasing?

Antarctica is not cooling: it has warmed overall over at least the past 50 years. Although the weather station at the South Pole shows cooling over this period, this single weather station is not representative. For example, there is a warming trend at Vostok, the only other long-term monitoring station in the interior of the continent. Several independent analyses (Chapman and Walsh 2008; Monaghan et al. 2008; Goosse et al. 2009; Steig et al. 2009) show that on average, Antarctica has warmed by about 0.5°C since wide-scale measurements began in the 1957 International Geophysical Year, with particularly rapid warming around the Antarctic Peninsula region and over the West Antarctic Ice Sheet (Figure 14 shows the mean trend from 1957-2006). Furthermore, there is direct evidence from borehole measurements that warming in West Antarctica began no later than the 1930s (Barrett et al. 2009).

Since the development of the Antarctic ozone hole in the late 1970s, there has been a strengthening of the circumpolar winds around Antarctica, which tends to reduce the amount of warmer air reaching the interior of the continent. The stronger winds are due to cooling in the upper atmosphere, which are in turn a result of ozone depletion caused by chlorofluorocarbons. As a consequence, much of East Antarctica has cooled in the summer and autumn seasons since the late 1970s. Ironically, human emissions of CFCs are thus helping to partly offset interior Antarctic warming, analogous to the global dimming due to sulphate aerosols. As the ozone hole gradually repairs over the coming century, the cooling offset is likely to diminish.

The factors that determine sea ice extent around Antarctica are very different from those in the Arctic, because Antarctica is a continent sited around the pole and surrounded by water, just the opposite of the Arctic geography. The extent of sea ice around Antarctica is strongly determined by the circumpolar winds which spread the ice out from the continent, and by the position of the polar front where the ice encounters warmer ocean waters. Sea ice cover in Antarctica shows a slight upward trend, consistent with the increase in circumpolar winds mentioned above. In West Antarctica, where the temperature increases are the greatest, sea ice has declined at a statistically significant rate since at least the 1970s.

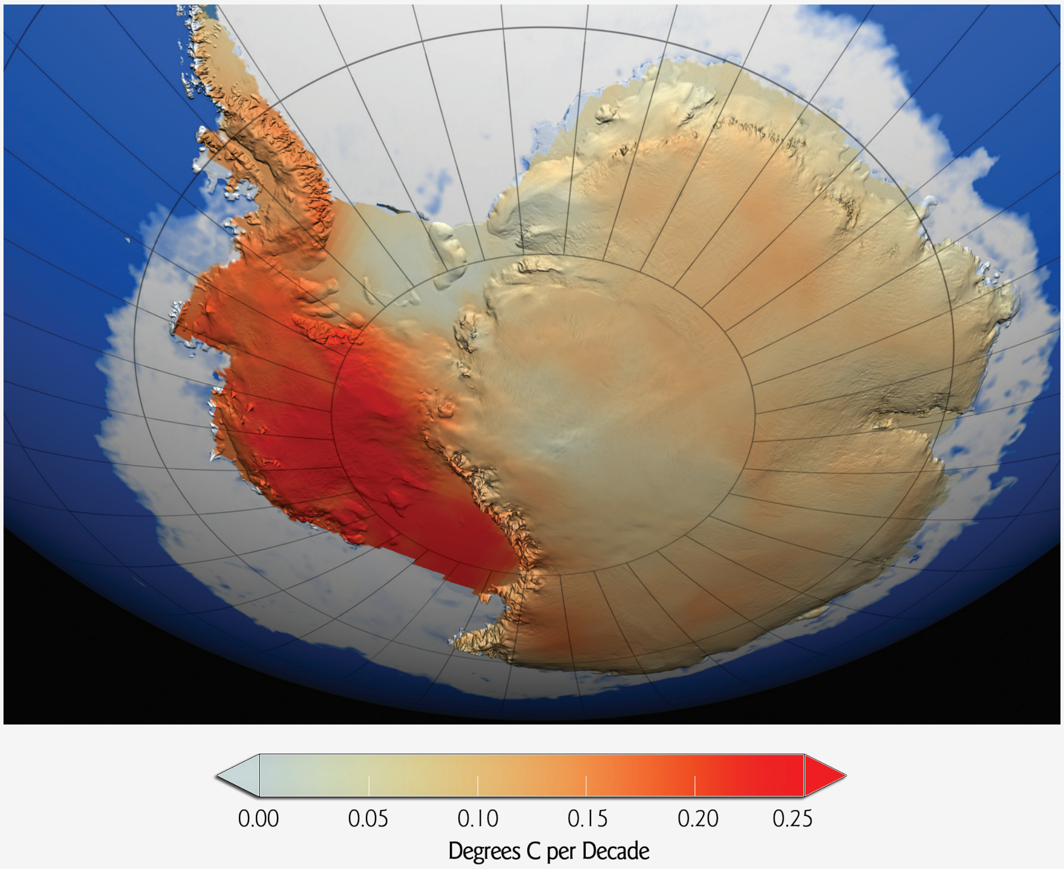


Figure 14. Annual mean air temperature trend in °C/decade during 1957-2006 from Steig et al. [2009].

THE OCEANS

- ☐ *Estimates of ocean heat uptake have converged and are found to be 50% higher than previous calculations.*
- ☐ *Global ocean surface temperature reached the warmest ever recorded for each of June, July and August 2009.*
- ☐ *Ocean acidification and ocean de-oxygenation have been identified as potentially devastating for large parts of the marine ecosystem.*

Detection of how climate change is impacting the oceans has improved markedly since the IPCC AR4. Significant changes in temperature, salinity and biogeochemical properties have been measured. These changes are consistent with the observed 50-year warming, rainfall and CO_2 trends in the atmosphere. There have also been important new analyses of the trends in a broader range of properties since the IPCC AR4, including acidification and oxygen. This has improved our understanding of the changing state of the oceans and also identified new issues. Where new estimates of ocean change exist since IPCC AR4, they tend to be larger and also more consistent with projections of climate change (e.g., global heat content).

Ocean Warming

There has been a long-term sustained warming trend in ocean surface temperatures over the past 50 years (Figure 15). Satellite measurements for the surface ocean showed 2007 to be the warmest year ever recorded, despite the extremely strong El Niño of 1997/1998. The year 2008 was cooler due to an intense temporary La-Niña event, whereas ocean temperatures up until the time of publication are tracking toward record warmth in 2009. For example, global ocean surface temperature was the warmest ever recorded for June, for July and for August in 2009.

Increases in oceanic heat content in the upper ocean (0-700m) between 1963 and 2003 have been found to be 50% higher than previous estimates (Domingues et al. 2008, Bindoff et al. 2007). The higher estimates of heat content change are now consistent with observations of sea-level rise over the last 50 years, resolving a long standing scientific problem in understanding the contribution of thermal expansion to sea-level (Domingues et al. 2008). Observations also show deep-ocean warming that is much more widespread in the Atlantic and Southern Oceans (Johnson et al. 2008a, Johnson et al. 2008b) than previously appreciated.

Salinity and the Hydrological Cycle

More comprehensive analyses of ocean salinity show a freshening of high latitudes, while regions of excess evaporation over precipitation have become saltier. The salinity changes are consistent with a strengthening of the hydrological cycle. The patterns of salinity change are also consistent with regional circulation and inter-basin exchanges. We now have increased evidence that the long-term trends in patterns of rainfall over the global ocean, as reflected in salinity, can be attributed to human influence (Stott et al. 2008).

Climate Change and Ocean Circulation

Surprising salinity changes in Antarctic bottom waters provide additional evidence of increased melt from the ice-sheets and ice shelves (Rintoul 2007). The Arctic shows strong evidence for increased precipitation and river run-off. Intermediate layers in the Arctic Ocean have warmed notably (Polyakov et al. 2004). Consistent with current model results, observations are yet to detect any indication of a sustained change in the North Atlantic Ocean circulation (e.g. Hansen and Østerhus 2007).

Regional climate change is often organized and expressed around the main patterns of variation such as the North Atlantic Oscillation, El Niño, and the Southern Annular Mode. These patterns themselves may be affected by greenhouse gases, leading to either larger fluctuations, or a preferred state in coming decades (e.g., a trend toward a different type of El Niño event, Yeh et al. 2009; Latif and Keenlyside 2009). Currently the influence of regional climate modes on ocean circulation is larger than the underlying trends attributable to anthropogenic climate change.

The stability of the North Atlantic Ocean circulation is vitally important for North American and European climate. For example, a slowdown of these ocean currents could lead to a more rapid rise of regional sea level along the northeast US coast (Yin et al. 2009). The IPCC AR4 concluded that there is greater than 90% probability of a slowdown of this ocean current system, and less than 10% risk of a "large abrupt transition" by the year 2100. As noted in the Synthesis and Assessment Project 3.4 of the US Climate Change Science Program (Delworth et al. 2008), no comprehensive climate model projects such a transition within this century. However, given uncertainty in our ability to model nonlinear threshold behaviour, and the recent suggestion that models may be too stable (Hoffman and Rahmstorf 2009) we cannot completely exclude the possibility of such an abrupt transition.

Ocean Acidification, Carbon Uptake and Ocean De-oxygenation

The CO_2 content of the oceans increased by 118 ± 19 Gt (1 Gt = 10^9 tons) between the end of the pre-industrial period (about 1750) and 1994, and continues to increase by about 2 Gt each year (Sabine et al. 2004). The increase in ocean CO_2 has caused a direct decrease in surface ocean pH by an average of 0.1 units since 1750 and an increase in acidity by more than 30% (Orr et al. 2005: McNeil and Matear 2007; Riebesell, et al. 2009). Calcifying organisms and reefs have been shown to be particularly vulnerable to high CO_2, low pH waters (Fabry et al. 2008).

New in-situ evidence shows a tight dependence between calcification and atmospheric CO_2, with smaller shells evident during higher CO_2 conditions over the past 50,000 years (Moy et al. 2009). Furthermore, due to pre-existing conditions, the polar regions of the Arctic and Southern Oceans are expected to start dissolving certain shells once the atmospheric levels reach 450ppm (~2030 under business-as-usual; McNeil and Matear 2008: Orr et al. 2009).

There is new evidence for a continuing decrease in dissolved oxygen concentrations in the global oceans (Oschlies et al. 2008), and there is for the first time significant evidence that the large equatorial oxygen minimum zones are already expanding in a warmer ocean (Stramma et al. 2008). Declining oxygen is a stress multiplier that causes respiratory issues for large predators (Rosa and Seibel 2008) and significantly compromises the ability of marine organisms to cope with acidification (Brewer 2009). Increasing areas of marine anoxia have profound impacts on the marine nitrogen cycle, with yet unknown global consequences (Lam et al. 2009). A recent modeling study (Hofmann and Schellnhuber 2009) points to the risk of a widespread expansion of regions lacking in oxygen in the upper ocean if increases in atmospheric CO_2 continue.

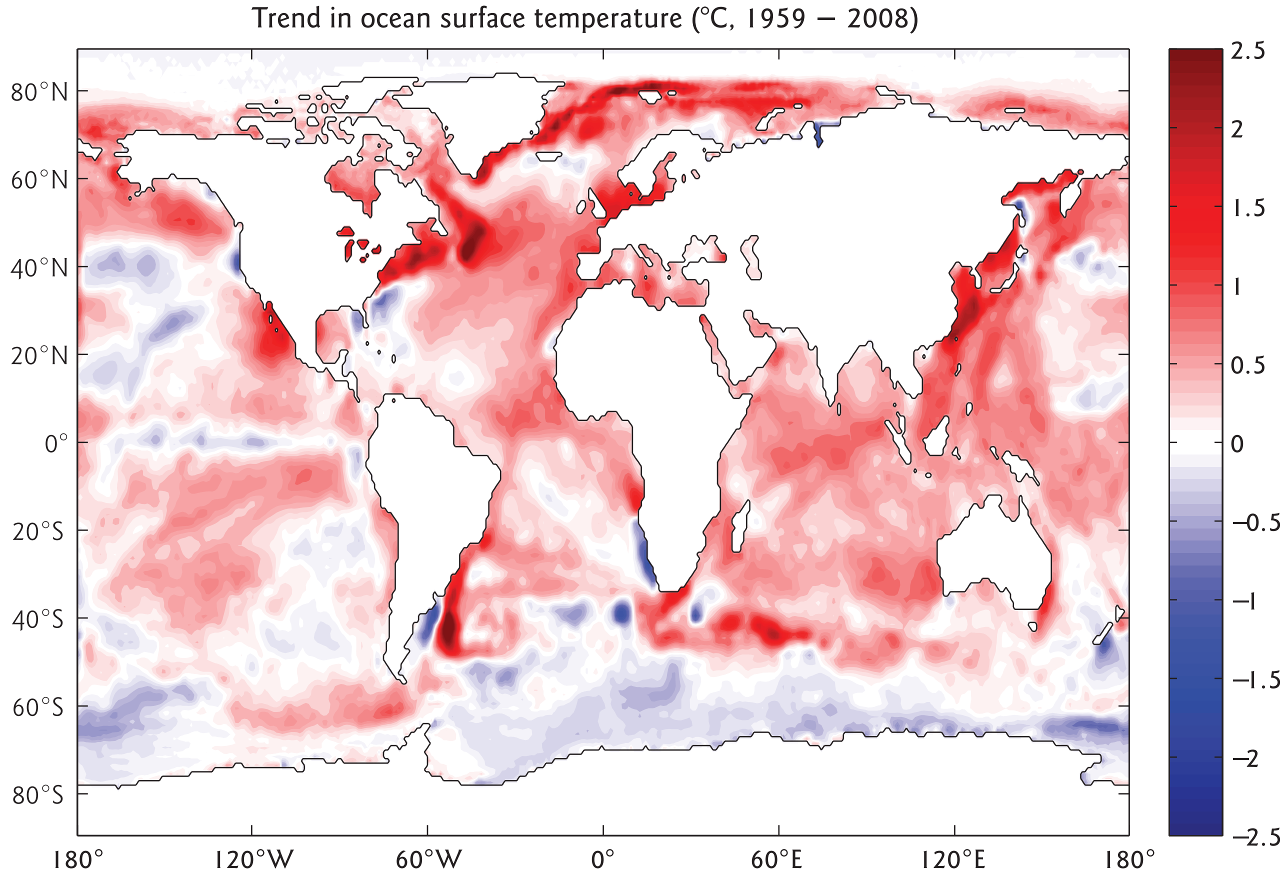


Figure 15. Long-term 50-year change in sea surface temperature (SST) during 1959-2008 calculated by fitting a linear trend to 50 years of monthly SST data at each grid point. The SST fields are from the Hadley Centre data set as described by Rayner et al. (2006).

GLOBAL SEA LEVEL

- ❑ *Satellite measurements show sea-level is rising at 3.4 millimeters per year since these records began in 1993. This is 80% faster than the best estimate of the IPCC Third Assessment Report for the same time period.*
- ❑ *Accounting for ice-sheet mass loss, sea-level rise until 2100 is likely to be at least twice as large as that presented by IPCC AR4, with an upper limit of ~2m based on new ice-sheet understanding.*

Population densities in coastal regions and on islands are about three times higher than the global average. Currently 160 million people live less than 1 meter above sea level. This allows even small sea level rise to have significant societal and economic impacts through coastal erosion, increased susceptibility to storm surges and resulting flooding, ground-water contamination by salt intrusion, loss of coastal wetlands, and other issues.

Since 1870, global sea level has risen by about 20 centimeters (IPCC AR4). Since 1993, sea level has been accurately measured globally from satellites. Before that time, the data come from tide gauges at coastal stations around the world. Satellite and tide-gauge measurements show that the rate of sea level rise has accelerated. Statistical analysis reveals that the rate of rise is closely correlated with temperature: the warmer it gets, the faster sea level rises (Rahmstorf 2007).

Sea level rise is an inevitable consequence of global warming for two main reasons: ocean water expands as it heats up, and additional water flows into the oceans from the ice that melts on land. For the period 1961-2003, thermal expansion contributed ~40% to the observed sea level rise, while shrinking mountain glaciers and ice sheets have contributed ~60% (Domingues et al. 2008).

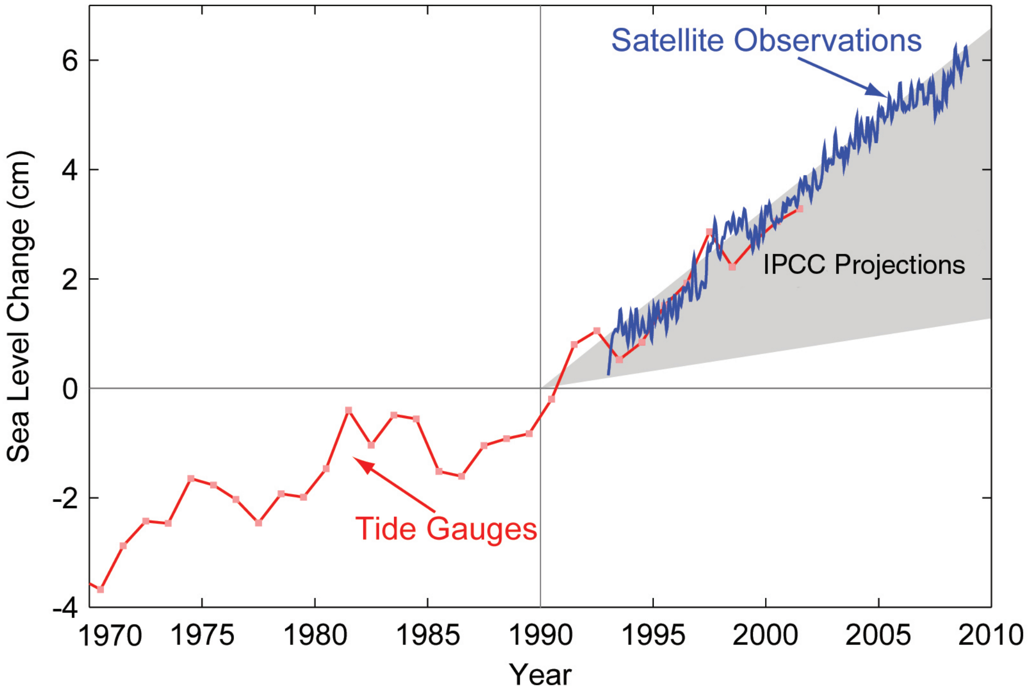


Figure 16. Sea level change during 1970-2010. The tide gauge data are indicated in red (Church and White 2006) and satellite data in blue (Cazenave et al. 2008). The grey band shows the projections of the IPCC Third Assessment report for comparison.

Sea level has risen faster than expected (Rahmstorf et al. 2007), see Figure 16. The average rate of rise for 1993-2008 as measured from satellite is 3.4 millimeters per year (Cazenave et al. 2008), while the IPCC Third Assessment Report (TAR) projected a best estimate of 1.9 millimeters per year for the same period. Actual rise has thus been 80% faster than projected by models. (Note that the more recent models of the 2007 IPCC report still project essentially the same sea level rise as those of the TAR, to within 10%.)

Future sea level rise is highly uncertain, as the mismatch between observed and modeled sea level already suggests. The main reason for the uncertainty is in the response of the big ice sheets of Greenland and Antarctica.

Sea level is likely to rise much more by 2100 than the often-cited range of 18-59 centimeters from the IPCC AR4. As noted in the IPCC AR4, the coupled models used in developing the 21st century sea level projections did not include representations of dynamic ice sheets. As such, the oft-cited 18-59 centimeters projected sea level rise only included simple mass balance estimates of the sea level contribution from the Greenland and Antarctic ice sheets. As a consequence of an assumed positive mass balance over the Antarctic ice sheet in the AR4, Antarctica was estimated to have contributed to global sea level decline during the 21st century in that report. However, the Antarctic Ice Sheet is currently losing mass as a consequence of dynamical processes (see Figure 10 in this report). Based on a number of new studies, the synthesis document of the 2009 Copenhagen Climate Congress (Richardson et al. 2009) concluded that "updated estimates of the future global mean sea level rise are about double the IPCC projections from 2007."

Sea level will continue to rise for many centuries after global temperature is stabilized, since it takes that much time for the oceans and ice sheets to fully respond to a warmer climate. Some recent estimates of future rise are compiled in Figure 17. These estimates highlight the fact that unchecked global warming is likely to raise sea level by several meters in coming centuries, leading to the loss of many major coastal cities and entire island states.

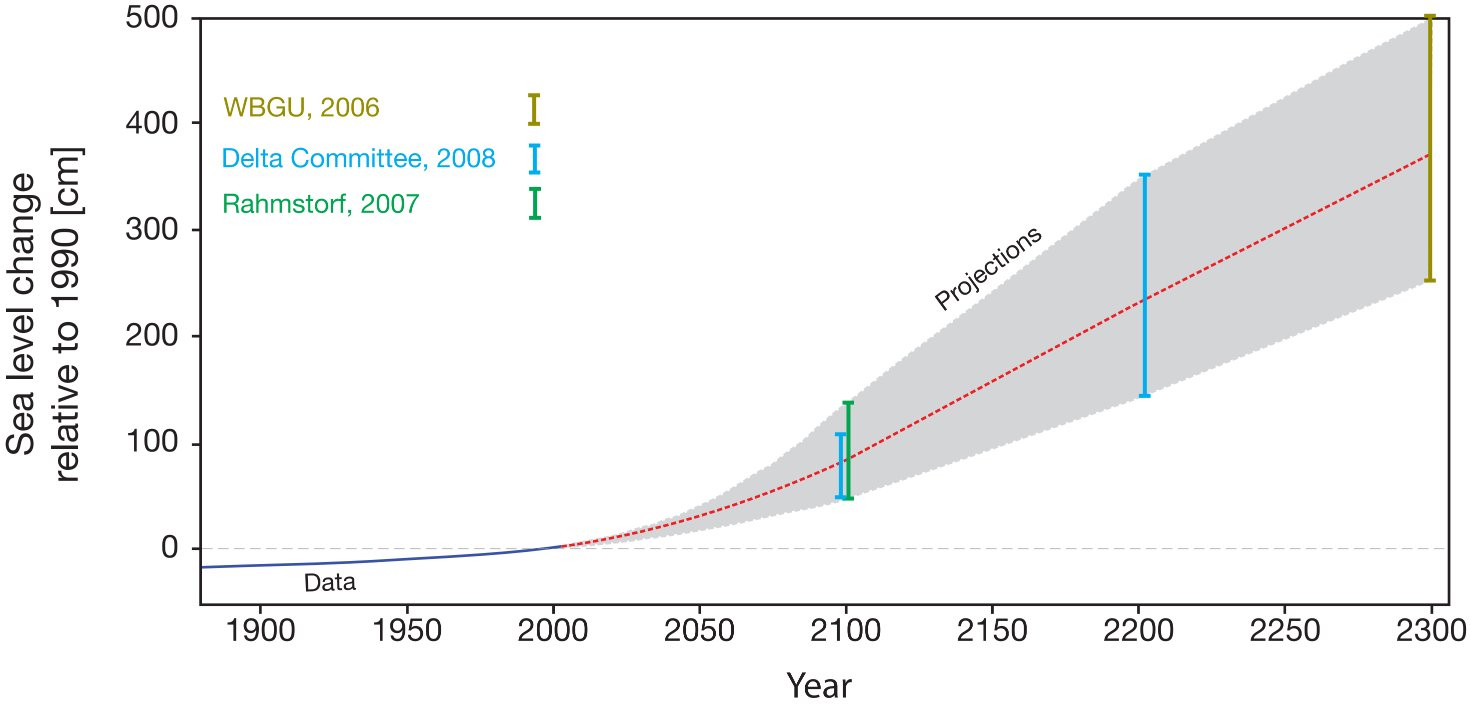


Figure 17. Some recent projections of future sea level rise. Historical data from Church and White (2006). Future projections are from Rahmstorf (2007) and WBGU (2006), while those projections represented here as 'Delta Committee' are from Vellinga et al., (2008).

ABRUPT CHANGE AND TIPPING POINTS

❑ *There are several elements in the climate system that could pass a tipping point this century due to human activities, leading to abrupt and/or irreversible change.*

❑ *1 °C global warming (above 1980-1999) carries moderately significant risks of passing large-scale tipping points, and 3 °C global warming would give substantial or severe risks.*

❑ *There are prospects for early warning of approaching tipping points, but if we wait until a transition begins to be observed, in some cases it would be unstoppable.*

What is a tipping point?

A tipping point is a critical threshold at which the future state of a system can be qualitatively altered by a small change in forcing (Lenton et al. 2008; Schellnhuber 2009). A tipping element is a part of the Earth system (at least sub-continental in scale) that has a tipping point (Lenton et al. 2008). Policy-relevant tipping elements are those that could be forced past a tipping point this century by human activities. Abrupt climate change is the subset of tipping point change which occurs faster than its cause. Tipping point change also includes transitions that are slower than their cause (in both cases the rate is determined by the system itself). In either case the change in state may be reversible or irreversible. Reversible means that when the forcing is returned below the tipping point the system recovers its original state, either abruptly or gradually. Irreversible means that it does not (it takes a larger change in forcing to recover). Reversibility in principle does not mean that changes will be reversible in practice. A tipping element may lag anthropogenic forcing such that once a transition begins to be observed, a much larger change in state is already inevitable.

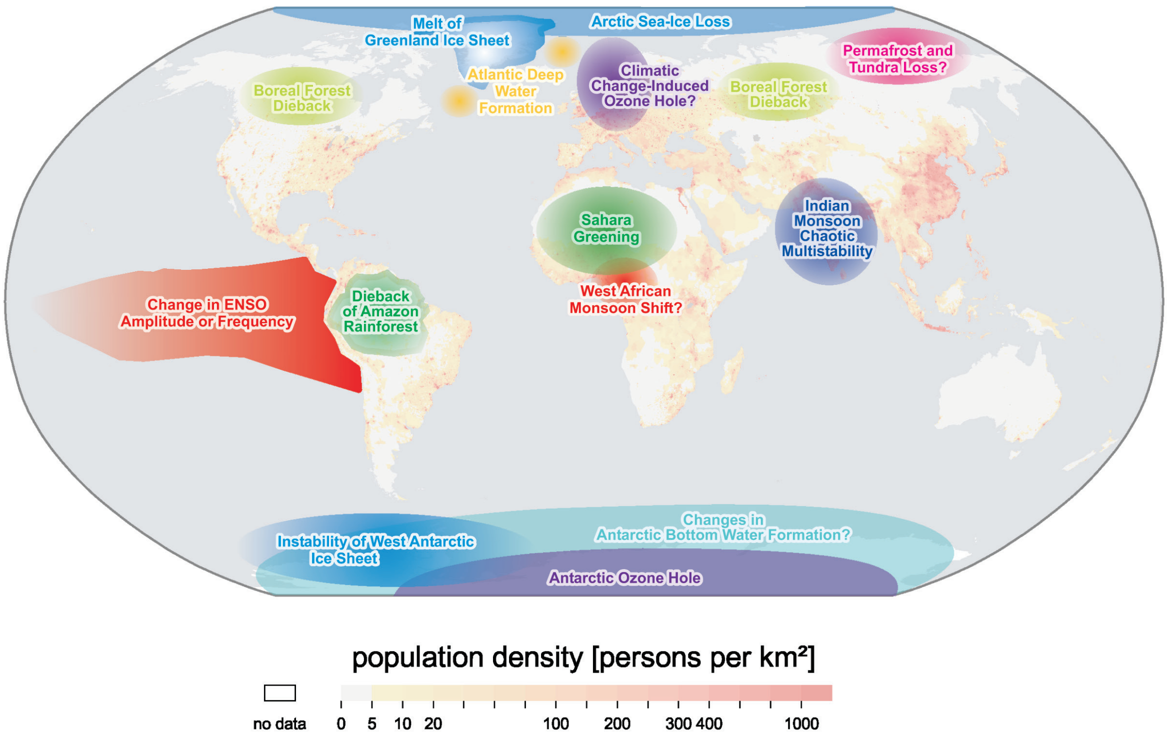


Figure 18. Map of some of the potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain. There are other potential tipping elements that are missing from the map, for example shallow-water coral reefs (Veron et al. 2009) threatened in part by ocean acidification (see Oceans chapter).

Are there tipping points in the Earth's climate system?

There are a number of tipping points in the climate system, based on understanding of its non-linear dynamics, and as revealed by past abrupt climate changes and model behavior (Pitman and Stouffer 2007; Schellnhuber 2009). Some models pass tipping points in future projections, and recent observations show abrupt changes already underway in the Arctic. Recent work has identified a shortlist of nine potential policy-relevant tipping elements in the climate system that could pass a tipping point this century and undergo a transition this millennium under projected climate change (Lenton et al. 2008). These are shown with some other candidates in Figure 18.

Which ones are of the greatest concern? How has this been assessed?

The tipping points of greatest concern are those that are the nearest (least avoidable) and those that have the largest negative impacts. Generally, the more rapid and less reversible a transition is, the greater its impacts. Additionally, any amplifying feedback to global climate change may increase concern, as can interactions whereby tipping one element encourages tipping another. The proximity of some tipping points has been assessed through expert elicitation (Lenton et al. 2008; Kriegler et al. 2009). Proximity, rate and reversibility have been also assessed through literature review (Lenton et al. 2008), but there is a need for more detailed consideration of impacts. Some of the most concerning regions and their tipping elements are now discussed:

Arctic: The Greenland ice sheet (GIS) may be nearing a tipping point where it is committed to shrink (Lenton et al. 2008; Kriegler et al. 2009). Striking amplification of seasonal melt was observed in 2007 associated with record Arctic summer sea-ice loss (Mote 2007). Once underway the transition to a smaller Greenland ice cap will have low reversibility, although it is likely to take several centuries (and is therefore not abrupt). The impacts via sea level rise will ultimately be large and global, but will depend on the rate of ice sheet shrinkage.

Antarctic: The West Antarctic ice sheet (WAIS) is currently assessed to be further from a tipping point than the GIS, but this is more uncertain (Lenton et al. 2008; Kriegler et al. 2009). The WAIS has the potential for more rapid change and hence greater impacts. The loss of ice-shelves around the Antarctic Peninsula, such as Larsen B, followed by the acceleration of glaciers they were buttressing, highlights a mechanism that could threaten parts of the WAIS. The main East Antarctic ice sheet (EAIS) is thought to be more stable than the WAIS. However, there is evidence that changes are taking place along its marine sector, which drains more ice than all of West Antarctica.

Amazonia: The Amazon rainforest experienced widespread drought in 2005 turning the region from a sink to a source (0.6 - 0.8 Gt C per year) of carbon (Phillips et al. 2009). If anthropogenic-forced lengthening of the dry season continues (Vecchi et al. 2006), and droughts increase in frequency or severity (Cox et al. 2008), the system could reach a tipping point resulting in dieback of up to ~80% of the rainforest (Cox et al. 2004; Scholze et al. 2006; Salazar et al. 2007; Cook and Vizy 2008), and its replacement by savannah. This could take a few decades, would have low reversibility, large regional impacts, and knock-on effects far away. Widespread dieback is expected in a >4 °C warmer world (Kriegler 2009), and it could be committed to at a lower global temperature, long before it begins to be observed (Jones et al. 2009).

West Africa: The Sahel and West African Monsoon (WAM) have experienced rapid but reversible changes in the past including devastating drought from the late 1960s through the 1980s. Forecast future weakening of the Atlantic thermohaline circulation contributing to 'Atlantic Niño' conditions, including strong warming in the Gulf of Guinea (Cook and Vizy 2006), could disrupt the seasonal onset of the WAM (Chang et al. 2008) and its later 'jump' northwards (Hagos 2007) into the Sahel. Perversely, if the WAM circulation collapses, this could lead to wetting of parts of the Sahel as moist air is drawn in from the Atlantic to the West (Cook and Vizy 2006; Patricola and Cook 2008), greening the region in what would be a rare example of a positive tipping point.

India: The Indian Summer Monsoon is probably already being disrupted (Ramanathan et al. 2005; Meehl et al. 2008) by an atmospheric brown cloud haze that sits over the sub-continent and, to a lesser degree, the Indian Ocean. This haze is comprised of a mixture of soot, which absorbs sunlight, and some reflecting sulfate. It causes heating of the atmosphere rather than the land surface, weakening the seasonal establishment of a land-ocean temperature gradient which is critical in triggering monsoon onset (Ramanathan 2005). In some future projections, brown cloud haze forcing could lead to a doubling of drought frequency within a decade (Ramanathan 2005) with large impacts, although transitions should be highly reversible.

Several other candidate tipping elements and mechanisms could become a major concern, for example, carbon loss from permafrost. Recently it has been suggested that a region of permafrost known as the Yedoma, which stores up to ~500 Gt C (Zimov et al. 2006) could be tipped into irreversible breakdown driven by internal, biochemical heat generation (Khvorostyanov et al. 2008a, 2008b). However, the tipping point is estimated to be relatively distant.

How do tipping points relate to amplifying feedbacks on climate change?

Tipping points are often confused with the phenomenon of amplifying feedbacks on climate change. All tipping elements must have some strong amplifying feedback – detailed elsewhere (Lenton et al. 2008) – in their own internal or regional climate dynamics in order to exhibit a threshold, but they need not have an amplifying feedback to global climate change. Tipping elements that could have an amplifying feedback to global climate change include the Amazon rainforest (dieback would make it a CO_2 source, which could ultimately release up to ~100 Gt C), the thermohaline circulation (weakening or collapse would lead to net out-gassing of CO_2), and the *Yedoma* permafrost (release of up to ~500 Gt C). Tipping elements that could have a diminishing feedback on global climate change include boreal forest (dieback would release CO_2 but this would be outweighed by cooling due to increased land surface albedo from unmasked snow cover; Betts 2000), and the Sahel/Sahara (greening would take up CO_2 and probably increase regional cloud cover).

Should we be concerned about global amplifying feedbacks?

Amplifying feedbacks from individual tipping elements are mostly fairly weak at the global scale. However, other (non tipping element) amplifying feedbacks, including a potential future switch in the average response of the land biosphere from a CO_2 sink to a CO_2 source, could significantly amplify CO_2 rise and global temperature on the century timescale (Friedlingstein et al. 2006). The Earth's climate system is already in a state of strong amplifying feedback from relatively fast physical climate responses (Bony et al. 2006) (e.g. water vapor feedback). In any system with strong amplifying feedback, relatively small additional feedbacks can have a disproportionate impact on the global state (in this case, temperature), because of the non-linear way in which amplifiers work together.

Is there a global tipping point?

A global tipping point can only occur if a net amplifying feedback becomes strong enough to produce a threshold whereby the global system is committed to a change in state, carried by its own internal dynamics. Despite much talk in the popular media about such 'runaway' climate change there is as yet no strong evidence that the Earth as a whole is near such a threshold. Instead 'amplified' climate change is a much better description of what we currently observe and project for the future.

Which anthropogenic forcing agents are dangerous?

The total cumulative emissions of CO_2 (and other long-lived greenhouse gases) determine long-term committed climate changes and hence the fate of those tipping elements that are sensitive to global mean temperature change, are slow to respond, and/or have more distant thresholds. Key examples are the large ice sheets (GIS and WAIS). Uneven sulfate (Rotstatyn and Lohmann 2002) and soot (Ramanathan 2005; Ramanathan and Carmichael 2008) aerosol forcing are most dangerous for monsoons. Soot deposition on snow and ice (Ramanathan and Carmichael 2008; Flanner et al. 2007) is a key danger to Arctic tipping elements as it is particularly effective at forcing melting (Flanner et al. 2007). Increasing soot aerosol, declining sulfate aerosol (Shindell and Faluvegi 2009), and increasing short-lived greenhouse gases (Hansen et al. 2007) (methane and tropospheric ozone) have also contributed to rapid Arctic warming, and together far outweigh the CO_2 contribution. The current mitigation of SO_2 emissions and hence sulfate aerosol is a mixed blessing for climate tipping elements, it may for example be benefiting the Sahel region (Rotstayn and Lohmann 2002) but endangering the Amazon (Cox et al. 2008) and the Arctic sea-ice (Shindell and Faluvegi 2009). Land cover change may also drive large areas of continents from being relatively robust to climate change to being highly vulnerable.

Is there any prospect for early warning of an approaching tipping point?

Recent progress has been made in identifying and testing generic potential early warning indicators of an approaching tipping point (Lenton et al. 2008; Livina and Lenton 2007; Dakos et al. 2008; Lenton et al. 2009; Scheffer et al. 2009). Slowing down in response to perturbation is a nearly universal property of systems approaching various types of tipping point (Dakos et al. 2008; Scheffer et al. 2009). This has been successfully detected in past climate records approaching different transitions (Livina and Lenton 2007; Dakos et al. 2008), and in model experiments (Livina and Lenton 2007; Dakos et al. 2008; Lenton et al. 2009). Flickering between states may also occur prior to a more permanent transition (Bakke et al. 2009). Other early warning indicators are being explored for ecological tipping points (Biggs et al. 2009), including increasing variance (Biggs et al. 2009), skewed responses (Biggs et al. 2009; Guttal and Jayaprakash 2008) and their spatial equivalents (Guttal and Jayaprakash 2009). These could potentially be applied to anticipating climate tipping points.

LESSONS FROM THE PAST

- *The reconstruction of past climate reveals that the recent warming observed in the Arctic, and in the Northern Hemisphere in general, are anomalous in the context of natural climate variability over the last 2000 years.*
- *New ice-core records confirm the importance of greenhouse gases for past temperatures on Earth, and show that CO_2 levels are higher now than they have ever been during the last 800,000 years.*

Reconstructing the last two millennia

Knowledge of climate during past centuries can help us to understand natural climate change and put modern climate change into context. There have been a number of studies to reconstruct trends in global and hemispheric surface temperature over the last millennium (e.g. Mann et al. 1998; Esper et al. 2002; Moberg et al. 2005), all of which show recent Northern Hemisphere warmth to be anomalous in the context of at least the past millennium, and likely longer (Jansen et al. 2007). The first of these reconstructions has come to be known as the 'hockey stick' reconstruction (Mann et al. 1998, 1999). Some aspects of the hockey stick reconstruction were subsequently questioned, e.g. whether the 20th century was the warmest at a hemispheric average scale (Soon and Baliunas 2003), and whether the reconstruction is reproducible, or verifiable (McIntyre and McKitrick 2003), or might be sensitive to the method used to extract information from tree ring records (McIntyre and McKitrick 2005a,b). Whilst these criticisms have been rejected in subsequent work (e.g. Rutherford et al. 2005; Wahl and Ammann 2006, 2007; Jansen et al. 2007) the US National Research Council convened a committee to examine the state of the science of reconstructing the climate of the past millennium. The NRC report published in 2006 largely supported the original findings of Mann et al. (1998, 1999) and recommended a path toward continued progress in this area (NRC, 2006).

Mann et al. (2008) addressed the recommendations of the NRC report by reconstructing surface temperature at a hemispheric and global scale for much of the last 2,000 years using a greatly expanded data set for decadal-to-centennial climate changes, along with recently updated instrumental data and complementary methods that have been thoroughly tested and

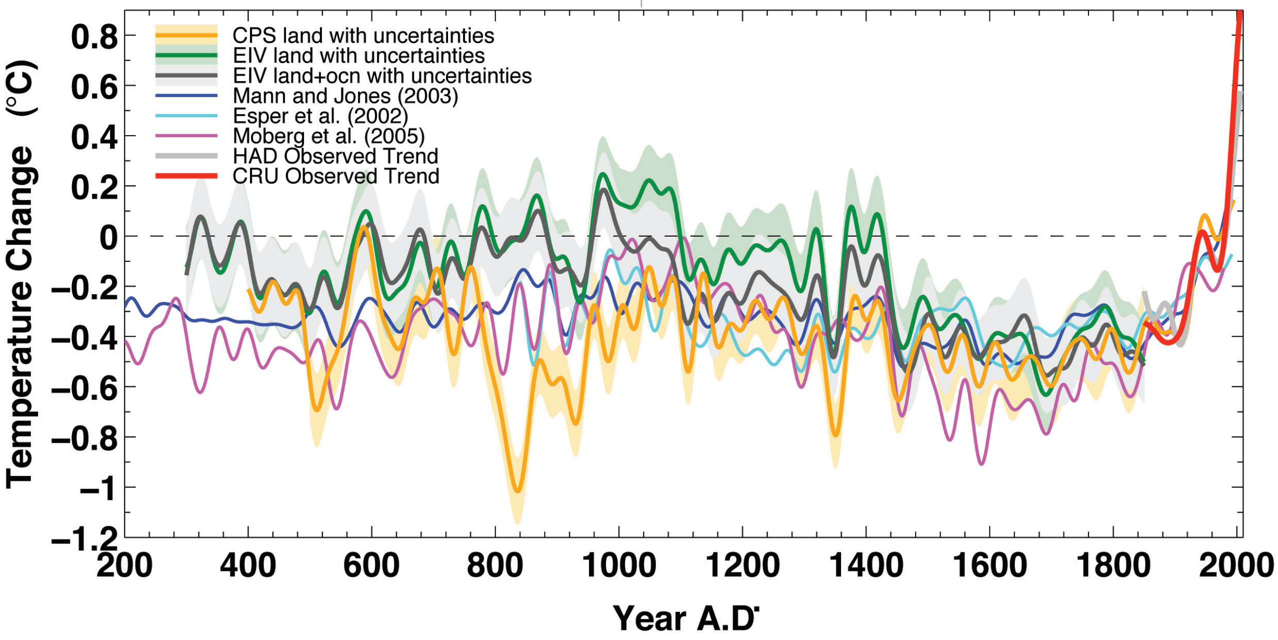


Figure 19. Comparison of various Northern Hemisphere temperature reconstructions, with estimated 95% confidence intervals shown (from Mann et al. 2008).

validated with climate model simulations. Their results extend previous studies and conclude that recent Northern Hemisphere surface temperature increases are likely anomalous in a long-term context (Figure 19).

Kaufman et al. (2009) independently concluded that recent Arctic warming is without precedent in at least 2000 years (Figure 20) reversing a long-term millennial-scale cooling trend caused by astronomical forcing (i.e. orbital cycles). Warmth during the peak of the "Medieval Climate Anomaly" of roughly AD 900-1100 may have rivalled modern warmth for certain regions such as the western tropical Pacific (Oppo et al. 2009), and some regions neighbouring the North Atlantic (Mann et al. in-press). However, such regional warming appears to reflect a redistribution of warmth by changes in atmospheric circulation, and is generally offset by cooling elsewhere (e.g. the eastern and central tropical Pacific) to yield hemispheric and global temperatures that are lower than those of recent decades.

Ice Core Records of Greenhouse Gases

Changes in past atmospheric Carbon Dioxide (CO_2) and Methane (CH_4) concentrations can be determined by measuring the composition of air trapped in ice cores and through the analyses of leaf stomata density and geochemical analyses of marine sediment cores.

The Dome Concordia (Dome C) ice core CO_2 and CH_4 records, drilled by the European Project for Ice Coring in Antarctica (EPICA), were published in 2004 and 2005 detailing events back to 440,000 years and 650,000 years respectively (EPICA community members 2004; Siegenthaler et al. 2005). In 2008 the record was extended to 800,000 years (Lüthi et al. 2008; Loulergue et al. 2008). The newly extended records reveal that current greenhouse gas levels (~385ppm) are at least 40% higher than at any time over the past 800,000 years. We must travel back at least two to three million years, and perhaps as far as fifteen million years, to the Pliocene and Miocene epochs of geological time to find equivalent greenhouse gas levels in the atmosphere (Haywood et al. 2007; Raymo et al. 1996; Kürschner et al. 1996; Tripati et al. 2009).

Strong correlations of CH_4 and CO_2 with temperature reconstructions are maintained throughout the new 800,000 year record (Lüthi et al. 2008; Loulergue et al. 2008). Temperature warming typically comes before increases in atmospheric CO_2 over the ice-core record. This finding is consistent with the view that natural CO_2 variations constitute a feedback in the glacial-interglacial cycle rather than a primary cause (Shackleton 2000); something that has recently been explained in detail with the help of climate model experiments (Ganopolski and Roche 2009). Changes in the Earth's orbit around the Sun are the pacemaker for glacial-interglacial cycles (Hays et al. 1976; Berger 1978), but these rather subtle orbital changes must be amplified by climate feedbacks in order to explain the large differences in global temperature and ice volume, and the relative abruptness of the transitions between glacial and interglacial periods (Berger et al. 1998; Clark et al. 1999).

Palaeo Constraints on Climate and Earth System Sensitivity

One of the key questions for climate research is to determine how sensitively the Earth's climate responds to a given change

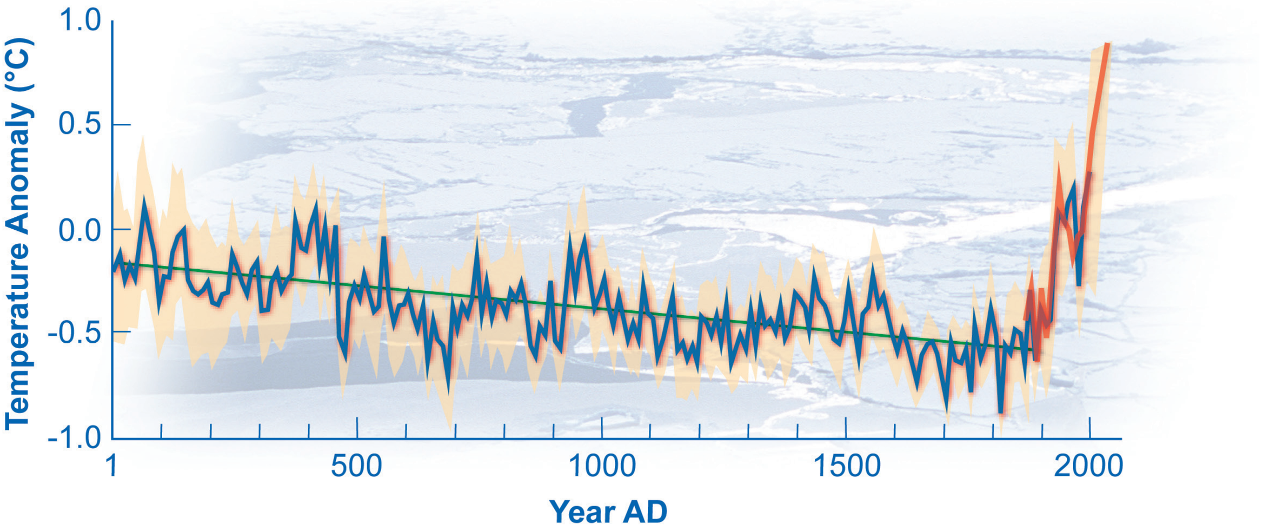


Figure 20. Blue line: estimates of Arctic air temperatures over the last 2,000 years based on proxy records from lake sediments, ice cores and tree rings. The green line shows the best fit long-term cooling trend for the period ending 1900. The red line shows the recent warming based on actual observations. (Courtesy Science, modified by the University Corporation for Atmospheric Research).

in our planet's radiation budget. This is often described by the "Climate Sensitivity", defined as the equilibrium global temperature response to a doubling of atmospheric CO_2 concentration.

IPCC AR4 summarizes the research aimed at characterizing the uncertainty in climate sensitivity (e.g. Andronova and Schlesinger 2001; Frame et al. 2005; Annan and Hargreaves 2006) by stating that "climate sensitivity is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C". More recent studies have agreed with this assessment (e.g. Knutti and Hegerl 2008). These estimates of climate sensitivity have also been used to determine the likely impacts, both environmental and social/economic, of various CO_2 stabilization scenarios, or the level of greenhouse gas emissions consistent with stabilization of the global mean temperature below a certain value (e.g. Meinshausen et al. 2009; this document section "Mitigating global warming").

Isn't climate always changing, even without human interference?

Of course. But past climate changes are no cause for complacency; indeed, they tell us that the Earth's climate is very sensitive to changes in forcing. Two main conclusions can be drawn from climate history:

Climate has always responded strongly if the radiation balance of the Earth was disturbed. That suggests the same will happen again, now that humans are altering the radiation balance by increasing greenhouse gas concentrations. In fact, data from climate changes in the Earth's history have been used to quantify how strongly a given change in the radiation balance alters the global temperature (i.e., to determine the *climate sensitivity*). The data confirm that our climate system is as sensitive as our climate models suggest, perhaps even more so.

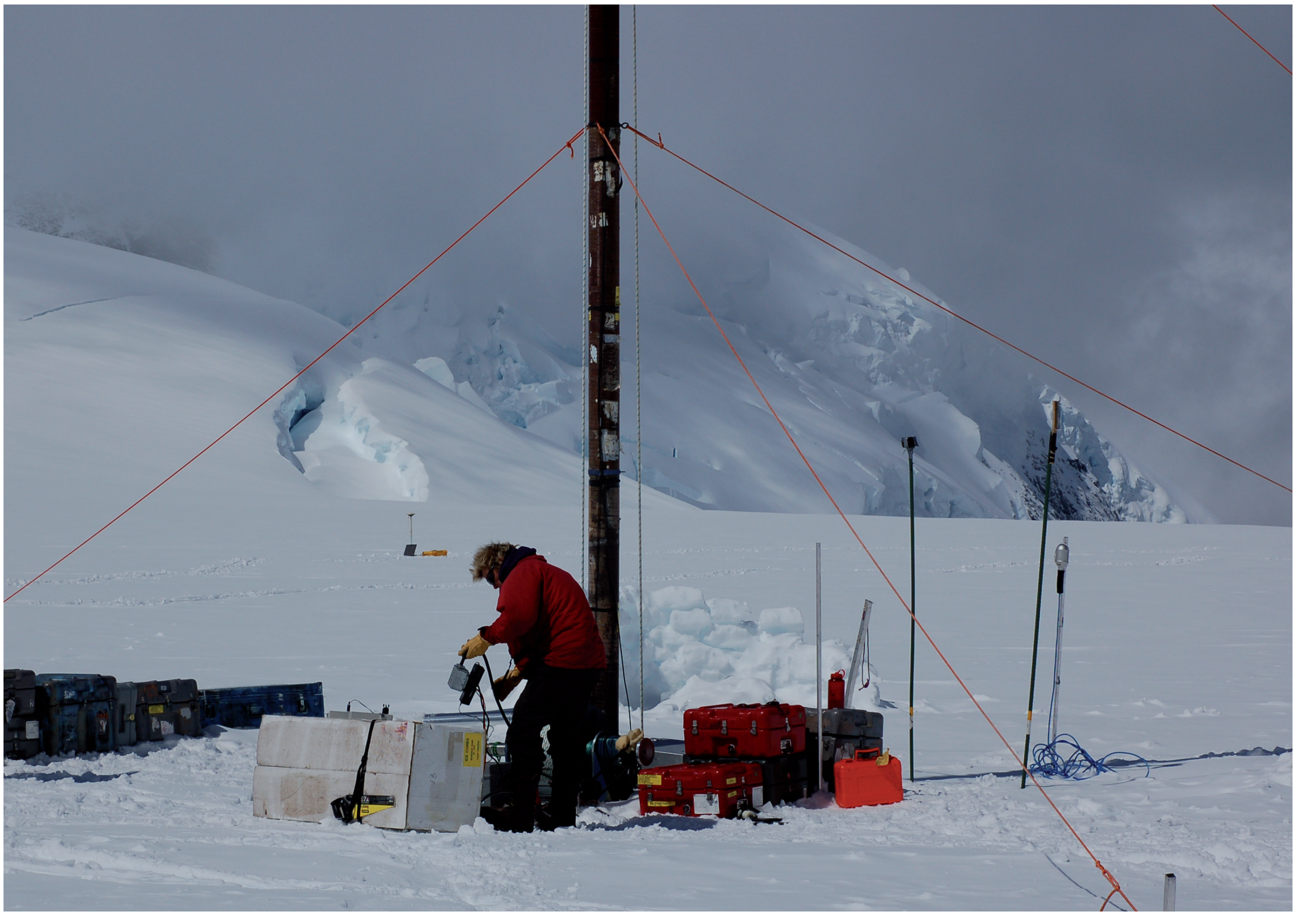
Impacts of past climate changes have been severe. The last great Ice Age, when it was globally 4-7 °C colder than now, completely transformed the Earth's surface and its ecosystems, and sea level was 120 meters lower. When the Earth last was 2-3 °C warmer than now, during the Pliocene 3 million years ago, sea level was 25-35 meters higher due to the smaller ice sheets present in the warmer climate.

Despite the large natural climate changes, the recent global warming does stick out already. Climate reconstructions suggest that over the past two millennia, global temperature has never changed by more than 0.5 °C in a century (e.g. Mann et al. 2008; and references therein).

Are we just in a natural warming phase, recovering from the "little ice age"?

No. A "recovery" of climate is not a scientific concept, since the climate does not respond like a pendulum that swings back after it was pushed in one direction. Rather, the climate responds like a pot of water on the stove: it can only get warmer if you add heat, according to the most fundamental law of physics, conservation of energy. The Earth's heat budget (its *radiation balance*) is well understood. By far the biggest change in the radiation balance over the past 50 years, during which three quarters of global warming has occurred, is due to the human-caused increase in greenhouse gas concentrations (see above). Natural factors have had a slightly cooling effect during this period.

Global temperatures are now not only warmer than in the 16th-19th centuries, sometimes dubbed the "the little ice age" (although this term is somewhat misleading in that this largely regional phenomenon has little in common with real ice ages). Temperatures are in fact now globally warmer than any time in the past 2000 years – even warmer than in the "medieval optimum" a thousand years ago (see Figure 19). This is a point that all global climate reconstructions by different groups of researchers, based on different data and methods, agree upon.



In climate history, didn't CO_2 change in response to temperature, rather than the other way round?

It works both ways: CO_2 changes affect temperature due to the greenhouse effect, while temperature changes affect CO_2 concentrations due to the carbon cycle response. This is what scientists call a feedback loop.

If global temperatures are changed, the carbon cycle will respond (typically with a delay of centuries). This can be seen during the ice age cycles of the past 3 million years, which were caused by variations in the Earth's orbit (the so-called Milankovich cycles). The CO_2 feedback amplified and globalized these orbital climate changes: without the lowered CO_2 concentrations and reduced greenhouse effect, the full extent of ice ages cannot be explained, nor can the fact that the ice ages occurred simultaneously in both hemispheres. The details of the lag-relationship of temperature and CO_2 in Antarctic records have recently been reproduced in climate model experiments (Ganopolski and Roche 2009) and they are entirely consistent with the major role of CO_2 in climate change. During the warming at the end of ice ages, CO_2 was released from the oceans – just the opposite of what we observe today, where CO_2 is increasing in both the ocean and the atmosphere.

If the CO_2 concentration in the atmosphere is changed, then the temperature follows because of the greenhouse effect. This is what is happening now that humans release CO_2 from fossil sources. But this has also happened many times in Earth's history. CO_2 concentrations have changed over millions of years due to natural carbon cycle changes associated with plate tectonics (continental drift), and climate has tracked those CO_2 changes (e.g. the gradual cooling into ice-age climates over the past 50 million years).

A rapid carbon release, not unlike what humans are causing today, has also occurred at least once in climate history, as sediment data from 55 million years ago show. This "Paleocene-Eocene thermal maximum" brought a major global warming of ~ 5 °C, a detrimental ocean acidification and a mass extinction event. It serves as a stark warning to us today.

THE FUTURE

- ❏ *Global mean air-temperature is projected to warm 2°C – 7°C above pre-industrial by 2100. The wide range is mainly due to uncertainty in future emissions.*
- ❏ *There is a very high probability of the warming exceeding 2°C unless global emissions peak and start to decline rapidly by 2020.*
- ❏ *Warming rates will accelerate if positive carbon feedbacks significantly diminish the efficiency of the land and ocean to absorb our CO_2 emissions.*
- ❏ *Many indicators are currently tracking near or above the worst case projections from the IPCC AR4 set of model simulations.*

Climate Projections

There has been no new coordinated set of future climate model projections undertaken since the IPCC AR4. Instead, much of the new research over the past few years has focused on preparation for the next round of IPCC simulations for AR5, and continued evaluation of the AR4 model runs. This includes new analyses of the observed rate of climate change in comparison to the IPCC AR4 projections (e.g., Rahmstorf 2007; Stroeve et al. 2007), and new calculations that take existing simulations and incorporate coupled carbon feedbacks and other processes (e.g. Zickfeld et al. 2009; Allen et al. 2009). While models exhibit good skill at capturing the mean present-day climate, some recent observed changes, notably sea-level rise and Arctic sea-ice melt, are occurring at a faster rate than anticipated by IPCC AR4. This is a cause for concern as it suggests that some amplifying feedbacks and processes, such as land-ice melt, are occurring faster than first predicted.

The latest estimates of global mean air temperature projected out to 2100 are shown in Figure 21. The wide range in the projection envelope is primarily due to uncertainty in future emissions. At the high end of emissions, with business as usual for several decades to come, global mean warming is estimated to reach 4-7°C by 2100, locking in climate change at a scale that would profoundly and adversely affect all of human civilization and all of the world's major ecosystems. At the lower end of emissions, something that would require urgent, deep and long-lasting cuts in fossil fuel use, and active preservation of the world's forests, global mean warming is projected to reach 2-3°C by century's end. While clearly a better outcome than the high emissions route, global mean warming of even just 1.5-2.0°C still carries a significant risk of adverse impacts on ecosystems and human society. For example, 2°C global temperature rise could lead to sufficient warming over Greenland to eventually melt much of its ice sheet (Oppenheimer and Alley 2005), raising sea level by over six meters and displacing hundreds of millions of people worldwide.

Despite the certainty of a long-term warming trend in response to rising greenhouse gases, there is no expectation that the warming will be monotonic and follow the emissions pathway on a year-to-year basis. This is because natural variability and the 11-year solar cycle, as well as sporadic volcanic eruptions, generate short-term variations superimposed on the long term trend (Lean and Rind 2009). Even under a robust century-long warming trend of around 4°C, we still expect to see the temperature record punctuated by isolated but regular ten-year periods of no trend, or even modest cooling (Easterling and Wehner 2009). Such decades therefore do not spell the end of global warming – emissions must peak and decline well before that is to occur. In fact, the peak in global temperature might not be reached until several centuries after emissions peak (e.g., Allen et al. 2009). Even after emissions stop completely, atmospheric temperatures are not expected to decline much for many centuries to millennia (Matthews and Caldeira 2008; Solomon et al. 2009; Eby et al. 2009) because of the long lifetime of CO_2 in the atmosphere. Furthermore, dry season rainfall reductions in several regions are expected to become irreversible (Solomon et al. 2009).

< Meltwater lake on the Greenland Ice Sheet

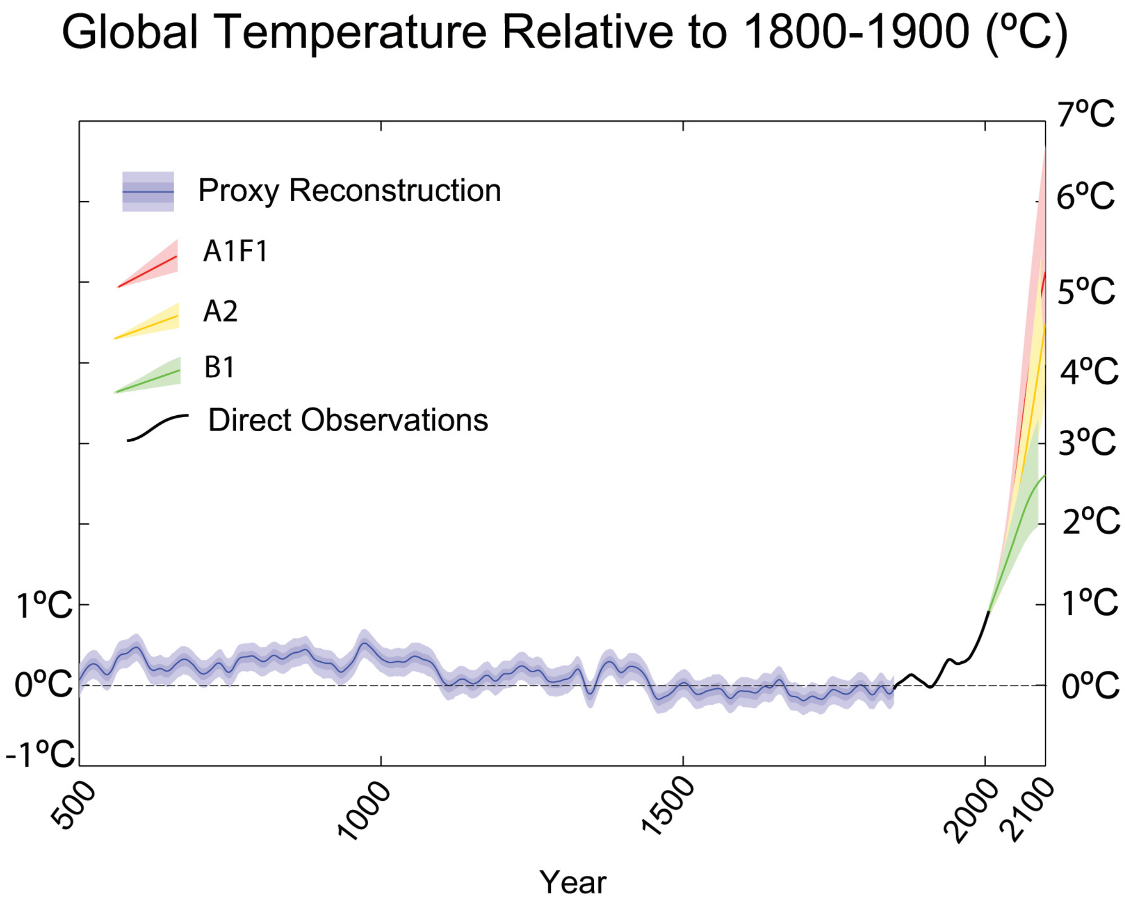


Figure 21. Reconstructed global-average temperature relative to 1800-1900 (blue) and projected global-average temperature out to 2100 (the latter from IPCC AR4). The envelopes B1, A2, A1F1 refer to the IPCC AR4 projections using those scenarios. The reconstruction record is taken from Mann et al. (2008).

Mitigating global warming

While global warming can be stopped, it cannot easily be reversed due to the long lifetime of carbon dioxide in the atmosphere (Solomon et al. 2009; Eby et al. 2009). Even a thousand years after reaching a zero-emission society, temperatures will remain elevated, likely cooling down by only a few tenths of a degree below their peak values. Therefore, decisions taken now have profound and practically irreversible consequences for many generations to come, unless affordable ways to extract CO_2 from the atmosphere in massive amounts can be found in the future. The chances of this do not appear to be promising.

The temperature at which global warming will finally stop depends primarily on the total amount of CO_2 released to the atmosphere since industrialization (Meinshausen et al. 2009, Allen et al. 2009, Zickfeld et al. 2009). This is again due to the long life-time of atmospheric CO_2. Therefore if global warming is to be stopped, global CO_2 emissions must eventually decline to zero. The sooner emissions stop, the lower the final warming will be. From a scientific point of view, a cumulative CO_2 budget for the world would thus be a natural element of a climate policy agreement. Such an agreed global budget could then be distributed amongst countries, for example on the basis of equity principles (e.g., WBGU 2009).

The most widely supported policy goal is to limit global warming to at most 2 °C above the preindustrial temperature level (often taken for example as the average 19th Century temperature, although the exact definition does not matter much due to the small variations in preindustrial temperatures). Many nations have publically recognized the importance of this 2°C limit. Furthermore, the group of Least Developed Countries as well as the 43 small island states (AOSIS) are calling for limiting global warming to only 1.5°C. The Synthesis Report of the Copenhagen climate congress (Richardson et al. 2009), the largest climate science conference of 2009, concluded that "Temperature rises above 2 °C will be difficult for contemporary societies to cope with, and are likely to cause major societal and environmental disruptions through the rest of the century and beyond."

A number of recent scientific studies have investigated in detail what global emissions trajectories would be compatible with limiting global warming to 2 °C. The answer has to be given in terms of probabilities, to reflect the remaining uncertainty in the climate response to elevated CO_2, and the uncertainty in the stability of carbon stored in the land and ocean systems. Meinshausen et al. (2009) found that if a total of 1000 Gigatons of CO_2 is emitted for the period 2000-2050, the likelihood of exceeding the 2-degree warming limit is around 25%. In 2000-2009, about 350 Gigatons have already been emitted, leaving only 650 Gigatons for 2010-2050. At current emission rates this budget would be used up within 20 years.

An important consequence of the rapidly growing emissions rate, and the need for a limited emissions budget, is that any delay in reaching the peak in emissions drastically increases the required rapidity and depth of future emissions cuts (see Figure 22 and also England et al. 2009). In Figure 22, emissions in the green exemplary path are 4 Gt CO_2 in the year 2050, which, with a projected world population of around 9 billion, would leave only less than half a ton per person per year. While the exact number will depend strongly on the path taken, the required decline in emissions combined with a growing population will mean that by 2050, annual per capita CO_2 emissions very likely will need to be below 1 ton.

Although CO_2 is the most important anthropogenic climate forcing, other greenhouse gases as well as aerosols also play a non-negligible role. Successful limitation of the non- CO_2 climate forcing would therefore create more leeway in the allowable CO_2 emissions budget. Studies have shown that attractive options for particularly rapid and cost-effective climate mitigation are the reduction of black carbon (soot) pollution and tropospheric low-level ozone (Wallack and Ramanathan 2009). In contrast to CO_2, these are very short-lived gases in the atmosphere, and therefore respond rapidly to policy measures.

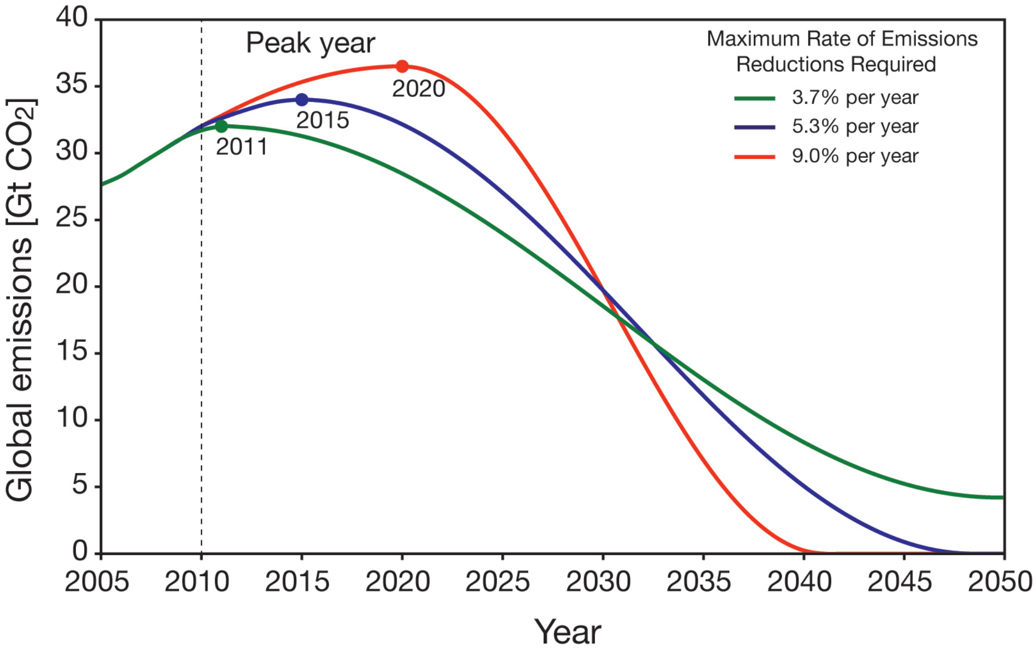


Figure 22. Examples of global emission pathways where cumulative CO_2 emissions equal 750 Gt during the time period 2010-2050 (1 Gt CO_2 = 3.67 Gt C). At this level, there is a 67% probability of limiting global warming to a maximum of 2°C. The graph shows that the later the peak in emissions is reached, the steeper their subsequent reduction has to be. The figure shows variants of a global emissions scenario with different peak years: 2011 (green), 2015 (blue) and 2020 (red). In order to achieve compliance with these curves, maximum annual reduction rates of 3.7 % (green), 5.3 % (blue) or 9.0 % (red) would be required (relative to 2008). (Source: German Advisory Council on Global Change; WBGU 2009).

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