Physical Climate Science since IPCC AR4

A brief update on new findings between 2007 and April 2010

Physical Climate Science since IPCC AR4

A brief update on new findings between
2007 and April 2010

Markku Rummukainen, Lund University, Sweden

Jouni Räisänen, University of Helsinki, Finland

Halldór Björnsson, Veðurstofu Íslands, Iceland

*Jens Hesselbjerg Christensen, Danish Meteorological Institute,
Denmark*

Physical Climate Science since IPCC AR4

A brief update on new findings between 2007 and April 2010

TemaNord 2010:549

© Nordic Council of Ministers, Copenhagen 2010

ISBN 978-92-893-2078-8

Print: Kailow Express

Cover photo: ImageSelect

Copies: 400

Printed on environmentally friendly paper

This publication can be ordered on www.norden.org/order. Other Nordic publications are available at www.norden.org/publications

Printed in Denmark

Nordic Council of Ministers

Ved Stranden 18

DK-1061 København K

Phone (+45) 3396 0200

Fax (+45) 3396 0202

Nordic Council

Ved Stranden 18

DK-1061 København K

Phone (+45) 3396 0400

Fax (+45) 3311 1870

www.norden.org

Nordic co-operation

Nordic co-operation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, and three autonomous areas: the Faroe Islands, Greenland, and Åland.

Nordic co-operation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic co-operation seeks to safeguard Nordic and regional interests and principles in the global community. Common Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Content

Preface	7
Summary	9
Introduction	11
1. Some physical climate system science reviews since IPCC AR4	13
1.1 Synthesis Report from the International Congress on Climate Change, Global Risks, Challenges & Decisions	13
1.2 The Copenhagen Diagnosis	13
1.3 News in Climate Science and Exploring Boundaries	13
1.4 AMAP 2009. Update on Selected Climate Issues of Concern and the Snow, Water, Ice and Permafrost in the Arctic-Project	14
1.5 New Climate Science 2006–2009	14
2. Observed climate changes	15
2.1 Global mean temperature change	15
2.2 Sea level	18
2.3 Cryosphere	19
3. Ocean acidification and the marine carbon cycle	23
4. Observed and Projected Extremes	25
4.1 Temperature extremes	25
4.2 Heavy precipitation and droughts	26
4.3 Tropical cyclones	27
4.4 Extratropical storms	27
4.5 Other categories of extreme events	28
5. Radiative forcing	29
5.1 Greenhouse gas concentrations	29
5.2 Particles	31
5.2.1 Trends	32
5.2.2 Soot	32
5.2.3 Secondary Organic Aerosol	33
5.2.4 Aerosol climate forcing	34
5.3 Land cover change	34
5.4 Solar effects	36
5.4.1 Solar irradiance variability and climate forcing	36
5.4.2 Galactic cosmic rays, clouds and climate	39
6. Attribution and internal variability	43
6.1 Attribution of observed climate changes	43
6.1.1 Changes in mean surface temperature	44
6.1.2 Changes in ocean temperature	45
6.1.3 Changes in the hydrological cycle	45
6.1.4 Changes in extremes	46
6.2 Internal variability	47
7. Climate change projections and scenarios	51
7.1 Climate and Earth system sensitivity	51
7.2 Feedback	54
7.2.1 Water vapour and cloud feedback	54
7.2.2 Climate-carbon feedback	56
7.2.3 Climate-Atmospheric chemistry feedback	57

8. Climate projections, new emission scenarios (RCPs) and climate prediction	59
8.1 Global climate modelling.....	59
8.2 Climate prediction.....	60
8.3 Regional climate modelling	62
9. Tipping points	65
10. Science of stabilisation.....	69
10.1 Climate stabilisation targets.....	69
10.2 Climate change commitment	70
Sammanfattning	73
References and notes.....	75

Preface

The Nordic Ministers of Environments established the Nordic COP 15 Group early in 2008. In January 2010 the group was renamed to the Nordic ad hoc Group on Global Climate Negotiations. The main tasks of the group are to prepare reports and studies, conduct relevant meetings and organize conferences supporting the Nordic negotiators in the UN climate negotiations. The overall aim of the group is to contribute to a global and comprehensive agreement on climate change with ambitious emission reduction commitments.

This report provides an update of the IPCC Fourth Assessment Report (AR4), focusing on the physical climate system that in the IPCC work is addressed by its Working Group I. The report considers progress in understanding of the human and natural drivers of climate change, climate observations and attribution and key climate feedback, ocean acidification. Developments and near future prospects of climate modeling are also discussed in brief.

The report is written by four leading Nordic climate scientists: Markku Rummukainen, Jouni Räisänen, Jens Hesselbjerg Christensen and Halldór Björnsson. The focus is on the physical climate system and climate change science. The overall volume of international climate research and new findings does not allow a fully comprehensive account of all new findings. The aim has been to provide an educated and representative account on new findings over the past four years of scientific research on the physical climate system of key relevance to contemporary climate change.

We would like to thank the authors as well as Professor Jean-Pascal van Ypersele and Professor Frank Raes who have conducted a review of the report. The authors are responsible for the content of this report. The views expressed and conclusions drawn do not necessarily reflect those of the Nordic Ad Hoc Group on Global Climate Negotiations.

Stockholm May 2010

Olle Björk

Chair of the Nordic Ad Hoc Group on Global Climate Negotiations

Summary

Since IPCC AR4 in 2007, climate science has made continual progress for more than three years. This is reflected both in the number of new scientific papers, but also in the development of the research agenda. By and large, the physical climate science as assessed by IPCC Working Group I in AR4 appears robust in the light of more recent research. The knowledge base is of course continuously developing. For example, there has been clear progress on research questions such as ocean acidification and Earth system feedback.

Some of the key findings that the recent literature brings forth include:

- Signs of continued climate change are evident. Warming in the last few years has not been as strong as in the years immediately before, but this falls within expected short-term variations due to e.g. internal climate system variability
- The global sea level also continues to rise. Recent estimates of the future sea level rise indicate values beyond the higher end of the AR4 range. Due to persisting limitations in modelling ice sheet dynamics, many of these more recent studies are based on semi-empirical modelling or inferences from past climates
- The 2007 summer Arctic sea ice minimum was not followed by yet lower amounts, but the long-term trend is unchanged, towards continued reductions in sea ice
- Parts of the Greenland ice sheet have shown rapid melt over recent years. It is not well-established whether this is a temporary phenomenon or signals a long-term trend. The Antarctic ice sheet is also losing mass
- The so-called other CO₂ problem, ocean acidification, is becoming more extensively studied. Whereas the acidity increase of ocean water is fairly easy to quantify for a given rise in atmospheric CO₂, the impacts on marine systems are not well understood
- There is no firm evidence of major changes in tropical cyclone behaviour resulting from global warming, although with continued global warming some gradual intensification of the strongest cyclones is possible
- After quite a few years of no significant changes since the early 1990s, the atmospheric methane concentration has exhibited renewed growth since 2007
- Solar cycle effects on global temperatures are small and even though it is possible that we are entering a prolonged period with low solar

activity, this will at best temporarily slow down future warming. The galactic cosmic ray/clouds/climate hypothesis remains unproven

- Warming has now also been detected over some of the Antarctic ice sheet. Observed Arctic warming has been difficult to attribute to anthropogenic global warming due to the large natural variability in the region. Such attribution has now progressed. Attribution studies have in general started to address scales smaller than the global or continental scales, as was the case in AR4, and a wider range of variables in addition to temperature
- Estimates of climate sensitivity remain essentially unchanged since AR4
- The CO₂ concentration may increase more for a given amount of global emissions than previously assessed, in light of new studies on the climate-carbon feedback and the possibility of climate change reducing the efficiency of natural carbon sinks
- A positive climate-carbon feedback reduces any “allowable emission space”, in the sense that when targeting some atmospheric stabilisation level, or some specific temperature target, the total emissions must be less than if the carbon cycle did not react to climate change

Introduction

The science of the physical climate system underlies our understanding of how our actions may affect the climate, as well as providing constraints on efforts to limit climate change. Available knowledge, at any time, consists of robust findings and various uncertainties. The latter represent limits to our knowledge and are as important to policy-makers as those aspects that are scientifically well-established. Research successively transfers uncertainties into more robust knowledge, but also leads to new questions. Sometimes, knowledge that previously has been seen as robust (well established) may undergo important revisions.

The scientific process is continuously ongoing. New pieces are constantly added, earlier ones are tested anew and some perhaps replaced. New scientific findings, especially the most recent, need to be examined and placed in context with earlier knowledge. This can be done through reviews that update scientific knowledge in some specific field. Such reviews make frontline research available to policy-makers more readily than findings published in articles in scientific journals. Any knowledge update is nevertheless conditional on new findings.

The current report provides an update on the science of the physical climate system. The review builds on peer-reviewed scientific literature published since the Working Group I report in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) of 2007¹. Some reviews of this kind have recently been published^{2,3,4,5,6}. We provide a brief commentary on these.

Our review covers recent observations on the climate system, natural and anthropogenic climate forcing, climate system sensitivity and Earth system feedback, specific issues such as sea levels and the cryosphere, as well as projections of climate change over the 21st century. Recent findings are discussed against the backdrop of the AR4 assessment and thus the pre-2007 literature.

Physical climate system science as such is thoroughly policy-relevant, but there is also a need to frame the discussion with directly relevant climate policy issues. Consequently, we discuss briefly how physical climate system science relates to climate stabilisation issues, via climate sensitivity, feedback within the climate system and climate system inertia issues.

1. Some physical climate system science reviews since IPCC AR4

1.1 Synthesis Report from the International Congress on Climate Change, Global Risks, Challenges & Decisions

A large scientific climate change symposium was held at the University of Copenhagen in March 2009. It covered many aspects of climate change research, the physical climate system aspects being just a part of the scientific programme².

1.2 The Copenhagen Diagnosis

The Copenhagen Diagnosis³ was written by 26 authors, and published in November 2009 by the University of New South Wales (UNSW) Climate Research Centre. Their stated aim was to “synthesize the most policy-relevant climate science published since the close-off of material for the last IPCC report”, on the eve of the Copenhagen climate talks in December 2009.

Compared to AR4, the Copenhagen Diagnosis has an added emphasis on larger-than-expected ongoing and future changes. The spotlight is not least on new science, according to which ice-sheets, glaciers and ice caps show accelerating melting, as does the summer-time Arctic sea ice cover. The authors also conclude that future dynamical changes in ice sheet melting might increase the global sea level rise by 2100 to around twice that stated in AR4. In AR4 this factor was excluded from the estimates due to rather limited understanding.

1.3 News in Climate Science and Exploring Boundaries

The Netherlands Environmental Assessment Agency was tasked by the Dutch Environment Minister to look into new scientific findings since AR4. Their report⁴ came out in November 2009. The authors build on around 1000 scientific articles. The report touches on the scientific domains of each of the three Working Groups of the IPCC, with the overall finding that AR4 remains a valid scientific basis for climate policy.

At the same time, the report noted indications of faster changes than previously projected, as well as of more severe impacts. In terms of physical climate science, these concerned more or less the same phenomena as noted

in the Copenhagen Diagnosis: greater ice sheet melt, higher sea level rise and faster Arctic sea ice reduction compared to the assessments in AR4. Another difference was the fairly explicit mention of the possibility that we might be facing a period of very low solar activity, which could give rise to a cooling effect of around 0.2°C over the next 2–3 decades. Should this happen, the anthropogenic warming trend would be somewhat less obvious over the same period, but still clearly discernible. The longer-term prospects of continued global warming would not be affected.

1.4 AMAP 2009. Update on Selected Climate Issues of Concern and the Snow, Water, Ice and Permafrost in the Arctic-Project

The Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) published a brief report⁵ in 2009 on recent observations and some science issues of particular relevance for the Arctic region (such as climate forcing of soot, tropospheric ozone and methane, and the Arctic carbon cycle). The report did not refer extensively to published literature. Attention was drawn not least to the continued warming signals in data collected in the Arctic region, along the lines outlined in AR4 and in the ACIA assessment of 2005.

Under this heading, we also make note of the *Snow, Water, Ice and Permafrost in the Arctic* (SWIPA) project⁷, set up by the Arctic Council in April 2008, whose aim is to assess new scientific information on changes in the Arctic cryosphere (ice, snow, and permafrost). The report is expected to be finalised in 2010.

In a first report, concerning the Greenland ice sheet⁸, the contribution to sea-level rise from melting of the Greenland ice sheet was considered, among other issues. One of the findings is that there is a contribution to sea level rise, assessed to be around 10–20% (i.e., 0.3–0.5 mm) of the 3 mm observed global sea level rise each year. The report also states that the rapidity of ice sheet changes and hence their future contribution to sea level rise is highly unknown and is directly related to our understanding of processes accelerating ice streams and fast-moving glaciers.

1.5 New Climate Science 2006–2009

The Swedish government's Commission on Sustainable Development commissioned a brief climate science update⁶ in 2009. The update considered about 120 articles more recent than AR4, in the area of physical climate science. The overall assessment was that more recent research confirms earlier research findings, and also adds some new knowledge. It was noted that many new findings were emerging, not least in respect of sea level rise, land ice sensitivity to global warming and Arctic sea ice.

2. Observed climate changes

The IPCC's AR4 (WG I SPM, page 5) noted that

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Since then, a few years' worth of observations have been added to the data, which is discussed below.

2.1 Global mean temperature change

In AR4 it was established that the global average surface air temperature increased by approximately 0.74°C during the period 1906 to 2005. A period of particularly rapid warming commenced in the mid-1970s. For the years 1979–2005, a warming trend of 0.17°C per decade was reported.

Since 2005, the warming has slowed down, which is very probably a temporary development. The global mean temperature has remained high. The years 2001–2009 are all among the 11 warmest in the instrumental record (Figure 1). It should be noted here that the magnitude of the global warming trend is expected to vary from year to year, despite being unambiguous over time. A decade is still a short period when it comes to the climate. Nevertheless, the most recent decade is discussed below, both to provide an update on global temperature data and to elucidate the apparent lack of a continued warming trend.

Figure 1. Average global temperature anomalies (with respect to the 1961–90 average) since 1850 according to the Climatic Research Unit (CRU) HadCRUT3 data set. (© Copyright 2010, CRU, University of East Anglia.)

Estimates of the global mean surface air temperature that are based on peer-reviewed methods are maintained by three research groups. These use slightly different data sets and averaging methods. This leads to modest differences in the specific annual values (Figure 2). For example, 2009 was the 6th warmest year on record according to the CRU⁹ and NCDC¹⁰ analyses, but the second warmest according to GISS^{11,12}. All three analyses show that the rate of warming has stalled since 2005. As already mentioned, for brief periods the warming rates may vary considerably from the long-term trend, although these variations tend to be short-lived.

In IPCC AR4, projections of 21st century temperature changes were based on simulations made by 21 global climate models^{13,14} forced with a range of non-climate-policy scenarios with the 20-year mean temperature for 1980–1999 as a baseline. For the four-year period 2006–2009, the observed global mean temperature rise (0.24–0.28°C) from this baseline has been slightly lower than the average simulated by these models (0.42°C, Figure 2). However, the observed change is still well within the variation between the model results. In fact, in three of the 21 models the warming from 1980–1999 to 2006–2009 was less than the observed warming. Part of the explanation for short-term differences between observed and modelled trends might lie in the incomplete coverage of the observations. A reanalysis¹⁵-based study covering global land areas suggests that, on average, recent warming has been more rapid at high northern latitudes where few observations are available than what is suggested in climatologies based on station observations (e.g. Figure 1)¹⁶.

Of course, the global mean temperature is not expected to rise steadily from one year to the next, due to natural climate variability. Part of the natural variability is caused by variations in solar activity and by volcanic eruptions. For example, a temporary cooling was observed after the Mt. Pinatubo eruption in 1991, whereas low solar activity may have affected the lack of warming in the last few years¹⁷. Recently, it has also been proposed that variations in the stratospheric water vapour concentration (a decrease since 2000 preceded by an increase in the previous two decades) might partly explain the apparent variations in the global warming trend over the last few decades¹⁸.

Figure 2. Recent changes in global mean temperature according to three analyses of observations (HadCRUT3, GISS and NCDC) and the 21 climate model simulations without climate policies used in IPCC AR4¹⁹. The mean of the model results is given by the solid black line. The shading indicates a 5–95% range of variability according to the same model simulations. The temperatures are given as deviations from the mean value over the period 1980–1999.

Significant natural variability is also generated by internal fluctuations within the climate system, particularly in the oceans. 1998, with its exceptionally strong El Niño warming in the tropical Pacific still stands out as the year with the highest global mean temperature in one of the three observational analyses, whereas the relative coolness of 2008 coincided with a La Niña event, which is the opposite of an El Niño.

Internal climate variability has limited predictability, and the path of internal variability that arises in climate model simulations varies across model runs. Consequently, the multi-model mean temperature evolution is much smoother than observed (Figure 2). On the other hand, the model spread compares rather well with the observed variability. Another important notion is that individual model simulations that show pronounced long-term warming²⁰ include decade-long periods with little simulated warming, akin to what has characterised the last decade.

The last decade is the warmest in the instrumental record. The global mean trend over the last decade has been quite small, but this fits well with our understanding of internal climate system variability, possibly with some amount of natural climate forcing (such as solar forcing – see Section 5.4). Periods of very small global temperature change are also evident in climate model simulations that overall show a clear warming trend as a response to anthropogenic forcing. It does not seem that climate models systematically overestimate the warming that can be expected in the future.

Still, detailed understanding of observed temperature records on decadal time scales remains a challenge. By measuring the net incoming and outgo-

ing radiative energy at the top of the Earth's atmosphere, it is in principle possible to determine how much energy remains in the Earth system. But where exactly does the energy go? The main energy reservoir is the ocean, which sequesters energy as heat. Because energy is exchanged between the atmosphere and the ocean, this heat can resurface at a later time to affect the global climate. A change in the overall energy balance will thus sooner or later have consequences for the climate. Based on existing observational evidence, it is still not possible to fully account for energy partitioning over time in the climate system²¹.

2.2 Sea level

AR4 (WGI, SPM, page 5) noted that

Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003. The rate was faster over 1993 to 2003: about 3.1 [2.4 to 3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer term trend is unclear.

And (WGI, Chapter 10, page 750–751)

Sea level is projected to rise between the present (1980–1999) and the end of this century (2090–2099) under the SRES B1 scenario by 0.18 to 0.38 m, B2 by 0.20 to 0.43 m, A1B by 0.21 to 0.48 m, A1T by 0.20 to 0.45 m, A2 by 0.23 to 0.51 m, and A1FI by 0.26 to 0.59 m. These are 5 to 95% ranges based on the spread of AOGCM results, not including uncertainty in carbon cycle feedbacks. ... further accelerations in ice flow of the kind recently observed... could substantially increase the contribution from the ice sheets... Understanding these effects is too limited to assess their likelihood or to give a best estimate.

In AR4 the sea level rise for the 20th century was estimated at 1.7 ± 0.5 mm per year²², with an increased rate towards the end of the century; the rate of sea level rise between 1993 and 2003 was estimated at 3.1 ± 0.7 mm. Over the few more recent years of 2004–2007/2008, the rate of sea level rise has decreased somewhat, by around 15%, which still well exceeds the 20th century rate^{23,24}. However, new results from the GRACE (Gravity Recovery and Climate Experiment) satellite gravity mission show that the rate of mass loss for the Greenland and Antarctic ice sheets is increasing²⁵ (see Section 2.3). In AR4, the sum of estimates of the contributions to sea level rise from thermal expansion and the melting of glaciers, ice caps and ice sheets fell short of the observed rise. Studies since then have greatly reduced this gap^{26,27,28}. The sum of the contributing effects now matches the observed total rise much better, signalling improved understanding of the mechanisms behind sea level rise.

Projections of future sea level rise depend on the emission scenario, although in the short run, this dependence is moderated by the long response

times of the oceans and ice sheets. In AR4, projections of sea level change from 1990 to 2095 spanned a range of 0.18–0.38 m for the lowest (B1) and 0.26–0.59 m for the highest (A1FI) scenario. A large proportion of the estimated sea level rise was due to thermal expansion of sea water. The results did not incorporate the possibility of a rapid increase in the discharge from ice sheets as has recently been observed in many outlet glaciers in Greenland. It was concluded that our understanding of the salient dynamical processes within ice sheets is too limited to address possible rapid changes in discharge. But it was noted that if such processes increase in line with warming, then a further 0.1–0.2 m sea level rise could ensue.

The realisation that ice sheets are playing a larger role in current sea level rise, and that their past role may have been underestimated, suggests that the contribution of ice melt to future sea level rise may be greater than projected in AR4. It has also been noted that the earlier projected global mean sea level rise was only 60% of the actual sea level rise from 1990–2006²⁹.

New methods of relating observed variations in global sea level and changes in global temperature support the idea that the projections in AR4 may have been too conservative. Empirical studies^{30,31,32} suggest that the AR4 climate change scenario range could imply projections for sea level rise of 0.8 to 1.8 m for the 21st century. Generally similar estimates have been reported in studies using other methodologies^{33,34,35}. A particular study³⁶ suggests that during the previous interglacial period 125,000 years ago, the global sea level might have risen by as much as 6.6–9.4 metres, which exceeds some previous estimates, as a response to a global mean warming of perhaps only as little as 1–2°C, pointing to relatively extensive melting of the ice sheets. It should be noted, however, that the sea level rise during the last interglacial period was a slow process, perhaps of the order of 6–9 metres per 1000 years. Past climate events are not necessarily good analogues for our own time. Nevertheless, along the lines of the studies discussed above, it was concluded in a recent review³⁷ that

global sea level rise could significantly exceed 1 m by 2100.

2.3 Cryosphere

In AR4, an extensive review was made of changes in the cryosphere, i.e. of frozen water in various forms, such as snow, river and lake ice, ground ice, sea ice, floating ice shelves, glaciers and ice caps and ice sheets. This included a discussion of ice sheet melt, decreasing Arctic sea ice cover, warming permafrost and reduced snow cover in the Northern hemisphere spring. It was also noted that no apparent changes were evident in sea ice in the Antarctic region³⁸.

Since then, in 2007, Arctic sea ice cover exhibited an unprecedented September minimum of 4.3 million km²^{39,40,41}. This remains the all-time low, even though the minima in 2008 and 2009 were also severe (see Figure 3).

One way to express this is by noting that whereas the trend in the reduction in late-summer Arctic sea ice cover was 0.6 ± 0.20 million km^2 per decade between 1979 and 2005, the trend increases to 0.79 ± 0.22 million km^2 per decade when the subsequent years are accounted for.

Figure 3. Changes in Arctic sea ice extent from 1979 to 2009. The upper panel shows results for February and the lower panel for September (when the ice extent is at its seasonal minimum). The circles indicate monthly means, while the blue curve shows decadal variations. The thin dashed line indicates the linear trend, which is $0.44 (\pm 0.10) 10^6 \text{ km}^2$ per decade for February and $0.79 (\pm 0.22) 10^6 \text{ km}^2$ per decade for September. These numbers correspond approximately to a decline of 2.9% and 11.9% per decade, respectively. (Expanded and updated from Fig. 4.9 in AR4, using sea ice data from NSIDC.)

Figure 3 shows time series of the sea ice extent for February and September. The decline documented in AR4 has continued. Furthermore, the fraction of multi-year ice has decreased and a larger proportion of the area covered by sea ice is now occupied by younger ice⁴².

In AR4, a continued decline in sea ice extent was projected. It was considered likely that towards the end of the 21st century very little sea ice would remain during summer. As the observed summer decline in recent years is greater than what had been projected by climate models⁴³, there has been some debate on whether or not the last few years' developments signal a faster sea ice melt than foreseen earlier^{44,45,46}. This remains to be seen.

Significant advances have been made since AR4 in estimating mass changes in the ice sheets in Antarctica and Greenland. In AR4 altimetry measurements were reviewed both from Greenland and Antarctica. The results indicate thinning due to increased melting on the margins of the ice sheets, but also of thickening in the interior due to increased accumulation. The net changes were found to be relatively small, especially in Antarctica. Results from the GRACE mission have since provided evidence that also some areas in the western parts of the Antarctic ice sheet are losing mass, as well as that the rate of mass loss has increased in recent years^{25,47}. GRACE

measurements also show extensive mass loss in Greenland⁴⁸. Between early 2002 and early 2009, the Greenland ice sheet is estimated to have lost 230 ± 30 Gt of ice per year, and Antarctica 143 ± 73 Gt ice per year (another estimate suggests 190 ± 77 Gt ice per year⁴⁷). These ice sheet melt tendencies correspond to 1.1 ± 0.2 mm/year of the global mean sea level rise. For comparison, AR4 (WGI, Table 5.3) gave an estimate of only 0.4 ± 0.4 mm/year, for the years 1993–2003.

Thinning on the margins of the ice sheets is especially apparent in the Amundsen Sea Embayment portion of the West Antarctic ice sheet⁴⁹ but extensive thinning also seems to be occurring elsewhere on the margins of Antarctica⁵⁰ (see Figure 4).

Figure 4. Rate of change of surface elevation [metres per year] for Antarctica and Greenland, over the period 2003–2007. A negative rate of change indicates thinning. (Reprinted by permission of Macmillan Publishers Ltd: *Nature*, Pritchard et al. 2009⁵⁰, copyright 2009.)

Major ice shelf break-ups have occurred in Antarctica in recent years, such as the Wilkins ice bridge in 2009. Following such a break-up, the glaciers behind the ice shelves can speed up, at least temporarily⁵¹, driving dynamic thinning which can spread far into the interior of the ice sheet.

For Greenland, such acceleration in the velocity of outlet glaciers was discussed in AR4. Later research has documented the extent of the phenomena^{52,53}, and a connection to warming sea waters has also been implicated⁵⁴. Some attention has been paid to a “lubrication effect”⁵⁵ whereby increased water pressure from surface meltwater increases the flow speed of the glacier. Larger contributions from this process are mentioned to likely be confined to certain areas of Greenland⁵⁶. It has also been pointed out⁵⁷ that the recent marked and accelerating dynamics of Greenland’s tidewater outlet

glaciers may prove to be temporary. Other factors, such as dynamic thinning, may be more important elsewhere.

The mass loss of glaciers and small ice caps in recent years is estimated to be of a similar magnitude as the total mass loss of the large ice sheets, i.e. equivalent to 1.1 mm/year in sea level rise⁵⁸. In AR4 (WGI, Table 5.3), a slightly smaller contribution of 0.8 ± 0.2 mm/year was estimated, for the years 1993–2003.

To summarise, new evidence since the publication of AR4 emphasises that ice is melting at a rate that is faster than previously estimated. This is true for Arctic sea ice, for the large ice sheets of Greenland and Antarctica, and for the smaller ice caps and glaciers.

3. Ocean acidification and the marine carbon cycle

The current rate of increase in the atmospheric carbon dioxide concentration corresponds to only about 45% of the overall anthropogenic emissions. About 30% of these emissions are taken up by the terrestrial biosphere, and the remaining 25% by the oceans⁵⁹. Ocean acidification results from the following process: when carbon dioxide is taken up by the ocean, CO₂ combines with water to produce carbonic acid. In this process, hydrogen ions (H⁺) are released, which lowers the pH of the water. Hydrogen ions combine with carbonate ions (CO₃²⁻), which leads to a decrease in carbonate in the water. In turn, this affects, for example, corals that need carbonates for building their skeletal bodies. Ocean acidification therefore has consequences for marine species and ecosystems.

In AR4 (SPM, page 14, see also WGI Chapters 5.4, 10.4 and Box 7.3), it was assessed that:

Increasing atmospheric carbon dioxide concentrations lead to increasing acidification of the ocean. Projections based on SRES scenarios give reductions in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century, adding to the present decrease of 0.1 units since pre-industrial times.

The changes in pH will vary from region to region, and the resulting effects on marine organisms also depend on the current saturation state of aragonite (a form of calcium carbonate) in the ocean water⁶⁰. As a consequence, coral reefs in some regions (e.g. the Great Barrier Reef, the Coral Sea and the Caribbean Sea) appear to be more at risk than those in others (e.g. Central Pacific)⁶¹. In addition to corals, increasing CO₂ affects many other groups of marine organisms. An emerging body of evidence suggests that the impact on marine biota will be more varied than previously thought, with both ecological winners and losers. These impacts could have far-reaching but as yet largely unknown consequences for the structure and function of marine ecosystems⁶⁰. In addition to the acidification effects, the impacts on marine species and ecosystems also depend on changes in (e.g.) temperature⁶².

Ocean acidification is a direct consequence of carbon dioxide emissions, rather than being mediated by changes in e.g. temperature⁶³. Sea-water warming can have some effect on ocean acidification, but this seems to be marginal^{64,65}. Consequently, ocean acidification can only be mitigated by reducing CO₂ emissions.

Ocean acidification by itself affects the capacity of the oceans to act as a carbon sink^{66,67}. When the concentration of inorganic dissolved carbon (the

sum of CO_2 , HCO_3^- and CO_3^{2-}) increases, atmospheric CO_2 starts to dissolve in the ocean water less efficiently. Consequently, increasing CO_2 will tend to make the ocean carbon sink less efficient. On the other hand, retreating ice-shelves reveals more of the ocean surface, which can lead to more phytoplankton activity and some additional CO_2 uptake⁶⁸.

Also the mere warming of the oceans would seem to reduce the ocean sink⁶⁹. Indeed, the role of the oceans as a carbon sink can change due to changes in temperature, but also due to changes in ocean circulation and winds. The latter two affect the exchange of CO_2 between the atmosphere and the surface ocean on the one hand, and between the surface, subsurface and the deep ocean on the other⁷⁰. A slow continued CO_2 uptake over longer timescales involves the deep ocean, whereas surface water becomes saturated quickly.

Ocean acidification remains a relatively unexplored topic, although more studies have begun to emerge over the past 5–6 years. The phenomenon is important not least due to its impact on ecosystems, but it is also intimately tied to the role of the oceans as a natural carbon sink. The latter has consequences for the emission pathways required for achieving a stabilisation of atmospheric CO_2 concentration at any given target level.

4. Observed and Projected Extremes

AR4 (WGI, SPM, page 7) noted regarding observed changes in extremes:

At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones [hurricanes and typhoons].

The assessed likelihood of occurred changes in extremes was greatest for warmer and more frequent hot days and nights and warmer and fewer cold days and nights, over most land areas during the late 20th century (likelihood > 90%). In the case of changes in warm spells/heat waves, heavy precipitation, extent of droughts, increased tropical cyclone activity and increased incidence of extreme high sea level, the likelihood of a recent trend was lower (66–90%). There was not enough evidence to assess whether changes might have occurred in phenomena such as tornadoes, hail, lightning and dust storms.

4.1 Temperature extremes

Studies on heat waves in the European region, not least prompted by the recent events of 2003 and 2006, have continued^{71,72,73}, largely confirming projections of increasing likelihood of such events. The mechanisms responsible for more frequent and more intensive European heat waves are more complicated than the effect of a general increase in temperature alone⁷². The occurrence of persistent blocking high pressure systems is relevant, as is the drying-out of soil⁷⁴.

Global warming is projected to lead to increasing heat waves across the northern hemisphere⁷⁵ and globally⁷⁶. Changes in warm and cold extremes may in many areas be characterised by disproportional rises in temperature compared to corresponding changes in average temperatures^{77,78}. The former characterises not least warm areas that warm up (warming leads to a depletion of soil moisture that in turn reduces evaporative cooling) and the latter cold regions that warm up (warming leads to a reduction in wintertime snow cover and so to changes in the surface energy balance). Model studies suggest that, globally, cold extremes will warm faster than warm extremes by about 30–40%⁷⁹. However, results vary somewhat between models and also for the exact type of an extreme condition considered. Some results

point to 100-year return levels for annual maximum temperature exceeding 40°C in e.g. Southern Europe and the US Midwest and as much as 50°C in parts of India and Australia⁷⁸. The quoted number for Europe might not seem so dramatic after the recent heatwaves of 2003 and 2006. As the 2003 heatwave event very possibly corresponded to a return period of several thousand years, it was a considerably more extreme event than one with a 100-year return period. A summer with a comparable length of return period at the end of this century would exhibit significantly higher temperatures than around 40°C, due to the overall warming over time.

4.2 Heavy precipitation and droughts

Studies suggest that global warming increases atmospheric (absolute) humidity in line with the Clausius-Clapeyron relationship, which implies a 7% increase for each degree of rise in temperature (7%/K). This means more water vapour in the atmosphere. Changes in relative humidity on the global scale are not anticipated, whereas regional variations to this may ensue. Global precipitation is projected to increase in line with increasing evaporation, which is less than the increasing amount of water vapour in the atmosphere⁸⁰. The projected increases in global precipitation lie around 2%/K. However, there are also inferences from short-term climate variability that the increase in global precipitation could be more comparable with that of atmospheric humidity⁸¹.

In contrast to average precipitation, climate model projections indicate that extreme precipitation changes will be comparable to increases in atmospheric humidity. For example, according to a multi-model projection (12 GCMs), the change in globally averaged 20-year return values of extreme daily precipitation could be 6%/K⁷⁹. According to other studies, changes in the even more extreme daily precipitation events (such as the 99th, 99.9th and 99.99th percentiles), may differ regionally. Some results suggest that extreme daily precipitation could increase more in the tropics^{82,83,84}, than in the extratropics. Such regional variation would be due to varying local temperature and moisture changes, as well as changes in upward velocity and the moist-adiabatic lapse rate. On time scales shorter than the daily, changes in extreme precipitation could be even larger⁸⁵.

In AR4, it was noted that available projections are consistent with increasing risk of drought in various continental areas at mid-latitudes: central Europe, the Mediterranean region, Central America, Australia and Eastern New Zealand. In some cases, it is the seasonal risk of drought rather than the year-round risk that changes. Later studies also address the Southwestern North America⁸⁶ and Central America⁸⁷.

4.3 Tropical cyclones

In AR4, observed increase in intensive tropical cyclone activity (including hurricanes and typhoons) during the late 20th century were mentioned as “likely”. A recent review of tropical cyclones and climate change⁸⁸, summarising almost 50 different studies of both observations and climate modelling, concludes that

- it remains uncertain whether the apparent changes in tropical cyclone activity in recent times exceed natural variability
- it is likely that climate change will not lead to increased global frequency of tropical cyclones, but that the frequency of the most intense storms is “more likely than not” to increase
- some increase in maximum wind speeds and rainfall rates is likely
- possible changes in characteristic storm formation regions and tropical storm tracks cannot be estimated with much robustness. Neither is there firm evidence of the possibility of tropical storms more often transiting to high latitudes

The implication is that unless tropical cyclones respond to climate change more strongly than suggested by current research, it should at this stage be difficult to detect possible trends due to climate change.

Tropical cyclones (storms, hurricanes and typhoons) form over warm sea surface regions somewhat polewards of the equator in both hemispheres. In addition, atmospheric conditions have to be suitable and, in particular, wind shear should be small (i.e. wind speed should not change much with altitude). The latter is connected to atmospheric circulation features and is in turn related to the relative warmth of different ocean basins^{89,90}. Thus, the connection between sea surface temperature changes and tropical cyclones is not necessarily straightforward, although this connection is suggested in some research⁹¹. Recent literature emphasises that recent tropical cyclone statistics do not lend themselves well to extrapolations into the future^{90,92,93}.

The possible impacts of global warming on tropical cyclones remain elusive. Findings such as those referred to above point to some intensification in maximum wind speeds and rainfall rates and, with less confidence, increasing frequency of more intensive tropical storms. Regional shifts in storminess might also ensue.

4.4 Extratropical storms

In AR4, mid-latitude westerly winds were noted to have increased, there also being some evidence of more northern hemisphere extratropical storm activity over recent decades. As in the case of tropical storms, findings are

still rather preliminary. Extratropical storms are mainly related to large-scale atmospheric thermal gradients, and how these evolve.

Some recent work appears to contest notions of significant intensification in extratropical storm activity^{94,95}, although this is based on particular climate models, rather than employing several models. Poleward shifts in storm tracks is a more general finding^{96,97}. Any such change leads to changes in regions affected by storm-related strong winds and heavy precipitation, as well as high waves and storm surges^{98,99}.

4.5 Other categories of extreme events

Findings regarding extreme wind events in the projections over the 21st century in many of the GCMs considered in AR4 suggest that the frequency of extreme wind events will generally decrease in and around the tropics (between 40°S and 40°N), but increase at high latitudes⁹⁷. These shifts are found to be fairly robust across the models. There are also some regional studies, such as for Europe, suggesting increases and decreases in extreme winds within the region^{100,101}.

There is a range of additional weather and climate-related extremes. Some are very small-scale, such as tornadoes and lightning and very challenging to study using climate model simulations. These types of extremes are not discussed in this review.

Fire is another example of a climate-related extreme¹⁰². The relevant precursor conditions are dryness and available combustible material. Consequently, regions with ample precipitation are not necessarily exempt from fire occurrence. The man-made suppression of natural burning further adds to the potential for extreme burning when fire is ignited due to natural or human causes. Enhanced burning accompanies heat waves⁷², but also regionally anomalous conditions such as in connection with ENSO. Fire regimes are sensitive to climate fluctuations and, by extension, to climate change¹⁰².

5. Radiative forcing

The balance between incoming solar radiation and outgoing thermal radiation is fundamental for the Earth's climate. Atmospheric composition has a key role in this, as the presence of various gases and particles affects radiation transfer. Indeed, as is well known, the natural greenhouse effect leads to a higher surface temperature on Earth than would otherwise be the case. Changes in the composition of the atmosphere due to anthropogenic emissions exert an imbalance between incoming and outgoing radiation, i.e. a radiative forcing, in response to which the climate changes.

Radiative forcing also occurs in conjunction with changing solar activity, land cover change and some additional processes. Radiative forcing is defined as the change in net downward minus upward irradiance (expressed in Wm^{-2}) at the tropopause, due to a change in an external driver of climate change. The full definition is longer and contains a few additional specifications on how radiative forcing is calculated.

5.1 Greenhouse gas concentrations

Changes in the main greenhouse gas concentration since pre-industrial times were discussed in AR4. Until 2005, the concentration of carbon dioxide (CO_2) had risen to 379 ppm (parts per million), from a pre-industrial value of 280 ppm. During the latter years, the concentration of CO_2 also grew at a faster rate. The growth rate for the 10-year period from 1995 to 2005 was 1.9 ppm per year, whereas in the longer period from 1960 to 2004 the average growth rate was 1.4 ppm per year.

The methane (CH_4) concentration in 2005 was about 1774 ppb (parts per billion). This is more than double the pre-industrial concentration. In the early 1970s and early 1980s the maximum growth rates for CH_4 exceeded 1% per year. From the early 1990s, the growth rates decreased almost to zero, with a few specific years forming an exception.

The nitrous oxide (N_2O) concentration was 319 ppb in 2005, which is about 18% higher than the preindustrial value.

Since AR4, the atmospheric CO_2 concentration has continued to increase. At the end of 2009 the concentration at Mauna Loa was measured at 388 ppm. The current trend of the de-seasonalised concentration (black line in Figure 5) points to around 390 ppm in 2010.

Figure 5. CO₂ concentrations at Mauna Loa, Hawaii from 1957 to early 2000. The red curve shows monthly values, and the black curve annual averages. (Data courtesy of the Global Monitoring Division of NOAA's Earth Systems Research Laboratory; www.esrl.noaa.gov.)

During the first years of the 21st century, anthropogenic carbon dioxide emissions increased faster than in the preceding decade¹⁰³. The actual recent emission trends are well among the highest SRES scenarios (for example, the 2008 emissions were above 34 of the 40 SRES scenarios; Corinne Le Quéré, personal communication (see Figure 6)¹⁰⁴. Estimated 2009 emissions are characterised by a downturn. This coincides with the strong economic downturn at the end of the decade and is as such likely to prove to be a temporary develop.

Figure 6. Fossil fuel emissions of CO_2 from 1990 to 2008 (thick black line). The shading indicates the uncertainty in the emission estimate. The coloured thin lines show some of the SRES emission scenarios (note, the full lines are for the average SRES scenarios instead of the SRES marker scenarios). The red dot represents an estimate of emissions in 2009. (Adapted from¹⁰³, courtesy of Corinne Le Quéré.)

The period of a slowdown in the growth of methane concentrations mentioned earlier seems to have ended in 2007¹⁰⁵. Since then, measurements show a renewed global increase. In 2007, the global increase was 8.3 ± 0.6 ppb. In 2008, the globally averaged increase was 4.4 ± 0.6 ppb, i.e. again a fair bit higher than for the majority of the period since the early 1990s. Although there is considerable interannual variability in natural methane emissions, it is noteworthy that in 2007 the growth in CH_4 concentrations was regionally high in the Arctic region, whereas in 2008 the same was true for the tropics. This was concurrent with higher than average temperatures in the Arctic in 2007, and larger than average precipitation in the tropics in 2008. The reasons for the renewed growth in methane concentrations are still unclear, it has been suggested that in the Arctic a possible feedback from permafrost and CH_4 hydrates was involved, but given the geographical pattern mentioned above, the cause may well be more complex¹⁰⁶.

5.2 Particles

Particulate matter in the atmosphere (often called particles or aerosols) affects the climate either by interaction with radiation or indirectly via impacts on cloud properties and the hydrological cycle. While there are natural sources of particles, there have to be changes in the amounts, distribution or

properties of aerosols, for there to be climate *forcing*. Anthropogenic fossil fuel and biomass combustion activities lead to such changes. Changes in natural emissions, for example due to climate effects, would also exert climate forcing¹⁰⁷.

In AR4 (WGI SPM, page 4. See also Chapters 2.4, 2.9 and 7.5), it was assessed that:

Anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of -0.5 [-0.9 to -0.1] W m^{-2} and an indirect cloud albedo forcing of -0.7 [-1.8 to -0.3] W m^{-2} . These forcings are now better understood than at the time of the TAR due to improved in situ, satellite and ground-based measurements and more comprehensive modelling, but remain the dominant uncertainty in radiative forcing. Aerosols also influence cloud lifetime and precipitation.

The central estimate of net anthropogenic aerosol forcing is significant, but still falls short of the positive anthropogenic greenhouse gas forcing. Aerosols either cause negative or positive radiative forcing, depending on whether they reflect or absorb solar radiation (i.e. change in balance of incoming and outgoing radiative energy at the tropopause). However, in the case of aerosols, their direct effect on the surface temperature is one of cooling, as solar radiation is either reflected or absorbed into the air. The latter effect is sometimes called (global) dimming. At the same time, absorption of solar radiation by soot warms up the surrounding air and may lead to changes in circulation features. It may also lead to reduced cloudiness and thus indirectly a surface warming effect¹⁰⁸.

A recent observational estimate of the net aerosol forcing supports the AR4 assessment of the magnitude of direct and indirect aerosol effects¹⁰⁹. The study also suggests that estimates of the indirect aerosol effect at the upper end of the AR4 uncertainty range are overestimates. Nevertheless, the role of aerosols in the climate system continues to be a scientific challenge.

5.2.1 Trends

Recent studies provide a somewhat mixed picture of how atmospheric aerosol loading evolves. In some regions, decreases have been observed (Europe¹¹⁰, Canadian High Arctic¹¹¹), while in others there seem to be increases^{112,113}. Land-based observations (from 1973 to 2007) indicate regional decreases and increases¹¹⁴, but increases over the global land area as a whole¹¹⁵. Satellite measurements available over the oceans suggest declining global particle amounts for the somewhat shorter period since the 1980s¹¹⁶.

5.2.2 Soot

Soot (black carbon) may have significant regional impacts such as in South-east Asia^{117,118}. Some recent estimates of its global radiative forcing, up to

0.9 Wm^{-2} in one study¹¹⁸, are much higher than estimated in AR4 (i.e. best estimates of 0.2 Wm^{-2} for direct forcing and 0.1 Wm^{-2} for darkening of snow surfaces). The suggestion that radiative forcing due to soot has been underestimated is also supported by comparisons between observations and global climate models incorporating aerosol chemistry and physics¹¹⁹. In turn, one recent study suggests that the Global Warming Potential (GWP) of black carbon¹²⁰ is considerably higher than in earlier studies^{121,122}. GWPs for such short-lived forcers as black carbon are of course inherently regionally-specific. Also, they need to be compared to greenhouse gases' GWPs with due care as the respective characteristic timescales are so different.

Soot is potentially a significant contributing agent to warming in the Arctic, possibly regionally dwarfing the effect of greenhouse gas increases¹²³. The same research team suggests that between 1976 and 2007 about one degree of the regional warming ($1.09 \pm 0.81^\circ\text{C}$)¹²⁴ that has occurred might be due to changes in aerosol amounts in the Arctic. This has come about due to the combined effect of decreased sulphur emissions in North America and Europe and increased Asian soot emissions.

The aerosol effects in the Arctic are mixed, including both reflection of incoming solar radiation and darkening of snow/ice-covered surface due to deposited particulate matter. A specific study suggests that this could have a significant influence on the reduction in springtime snow cover especially in Eurasia¹²⁵.

The sources of soot are outside the Arctic, so both soot emissions and their atmospheric transportation patterns affect the presence of soot in the region¹¹¹.

5.2.3 Secondary Organic Aerosol

Aerosols that are formed in the atmosphere from some precursor gases are called secondary aerosols. Sulphate, which was the first aerosol type to be studied extensively in the global warming context, is a secondary aerosol, formed from emitted sulphur dioxide (SO_2). Soot, on the other hand, is emitted as particles and thus a primary aerosol.

The spectrum of different aerosol types is considerable and in many cases the uncertainties are large when it comes to emissions, atmospheric burdens and the impacts on climate. So-called Secondary Organic Aerosol (SOA) is a type of a secondary aerosol that is relatively ubiquitous¹²⁶ and thus has potentially significant climate effects¹²⁷. SOA is formed from emitted volatile organic compounds (VOC), e.g. from terrestrial ecosystems (BVOCs), leading to biogenic SOA (BSOA). Depending on future changes in land use, as well as possible climate impacts on the emission of various BVOCs, the consequence could be cooling or warming effects^{128,129}, adding to the climate forcing due to greenhouse gas and anthropogenic aerosol changes, etc.

5.2.4 Aerosol climate forcing

There are many aspects to the role of aerosols in climate change. Recent findings on the direct effects of aerosols were discussed above, including the reflection and absorption of solar radiation and surface darkening due to deposited particles.

Aerosols also impact cloud properties (the so-called indirect effect), potentially making them more reflective, giving rise to another surface cooling effect. In addition, there are various ideas about the aerosol-induced impacts on cloud properties, also affecting the life-time of clouds and, depending on the cloud regime, increasing or decreasing precipitation¹³⁰. These are seen as feedbacks, rather than forcing contributions of aerosols.

A recent review¹³¹ suggests that due to compensating effects the cloud life-time effects of aerosols are smaller on a global scale than what specific studies have suggested to be the case. Regional effects may, however, be significant, such as in some maritime, tropical and Arctic cloud regimes.

Reduced emissions of aerosol precursors and primary aerosols can have quite complicated climate impacts. In general, overall reductions in aerosol and aerosol precursor emissions may accelerate global warming over the next decades^{132,133}. Also, studies have already been referred to that suggest that less sulphate, compounded by more soot, enhances regional warming in the Arctic. Other specific regional warming and cooling trends may also ensue, which may affect circulation and consequently regional precipitation and drought^{134,135}.

In conclusion, it is well established that aerosols have direct and indirect climate forcing effects. Estimates vary of the magnitude of the respective effect including the role of deposited soot in the Arctic. Changes in the relative amount of sulphate and soot aerosol due to changes in emissions furthermore lead to regional changes in the net aerosol effects. There is also an emerging insight that ecosystems contribute to aerosols in the atmosphere. This could be important in further constraining the role of anthropogenic aerosol.

In terms of ecosystem changes due to climate change or land use, aerosols of biogenic origin could add to the overall climate forcing. This has hardly been studied in coupled climate models so far, and remains to be addressed. Aerosol effects on cloud lifetime and precipitation are estimated to be small in global terms, but possibly significant in some regions and climate regimes.

5.3 Land cover change

Changes in land cover due to structural responses in vegetation to e.g. climate change, and due to anthropogenic land use transitions and management affect the climate in several ways: by perturbing the global carbon cycle (a biogeochemical effect), by changing the surface albedo, and by modifying

the water and energy budgets (a biogeophysical effect). The land surface also affects the partitioning of rainfall into evapotranspiration (which cools the surface and moistens the atmosphere) and runoff. This partitioning can affect local convection and therefore rainfall, as well as surface temperature. However, land cover change is not straightforward to describe in climate models, and was omitted in most of the climate model projections reported in IPCC AR4.

The present effect of land use on the carbon cycle is dominated by tropical deforestation. Current estimates indicate that the net land use contribution to CO₂ emissions was 1500±700 GtC per year in 1990–2005¹⁰³. There are also human land use contributions to other greenhouse gas emissions. A recent regional study for Europe suggests that regional methane and nitrous oxide emissions from feedstock and arable agriculture, respectively, are comparable to the regional terrestrial carbon sinks over 2000–2005¹³⁶. This would mean that the regional terrestrial greenhouse gas balance is neutral, rather than exhibiting net uptake.

Absolute emissions due to global land use appear to have changed relatively little over the past few decades. However, due to the increase in CO₂ emissions from fossil fuels and cement manufacture, the relative share of land use change of total anthropogenic CO₂ emissions has gradually decreased, being now of the order of 15%. The degradation of peatlands can be a growing source of anthropogenic greenhouse gas emissions¹³⁷.

Historically, over the past millennium, it has been estimated that the biogeochemical effect has dominated over the biogeophysical effect, both in terms of the global mean, and also in most regions^{138,139}. Regionally, where the land cover has come to be increasingly characterised by agriculture, such as in Europe, parts of Eurasia and Southeast Asia, and in North America, the local negative forcing due to the replacement of forests by cropland and pasture could nevertheless have been the dominant land use change effect.

The effect of land use on surface albedo depends on the nature of the land cover. In general, where vegetation cover is reduced, land use change leads to a higher surface albedo and negative climate forcing. In AR4, the contribution of land use change to globally averaged radiative forcing was estimated at $-0.2 \pm 0.2 \text{ W m}^{-2}$. Ref¹³⁹ estimates that the overall global biogeophysical land use effect over the 20th century is one of marginal cooling (-0.03°C), and the biogeochemical effect one of warming, of around $0.16\text{--}0.18^\circ\text{C}$. As mentioned above, the effects vary by region and to some degree between different periods¹⁴⁰.

Indeed, in regions with the most intense land cover change, biogeophysical effects might already be substantially impacting the local climate^{141,142}. For example, four out of seven models included in a recent intercomparison¹⁴³ implied that anthropogenic land cover change has cooled summer temperatures locally by up to 2°C in the eastern-central United States. However, one of the seven models indicated a significant warming in the same area. Land cover change is also potentially important for projecting future

climate changes, at least in some regions^{144,145}. Changes in land cover can also perturb the climate far away from the area in which land cover changes¹⁴⁶. For land cover changes thus far, such teleconnections are probably quite small at best^{141,147}.

Climate change-related changes in unmanaged land cover, such as in vegetation due to changes in temperature, precipitation, etc., represent a feedback rather than forcing. For example, changes in the composition or range of forests in the Arctic, due to changing climate, change the albedo and evapotranspiration, and thus feed back to the climate¹⁴⁸. The climate-carbon feedback, as concerns terrestrial systems, is discussed further in Section 7.2.

5.4 Solar effects

Solar variability is a ubiquitous factor in natural climate variability and change. In AR4 (WGI, Chapter 9, page 671), it was concluded that although there has been some net warming effect from solar variability over the past 100 years, it is an order of magnitude smaller than the concurrent anthropogenic influences:

...the direct radiative forcing due to increases in solar irradiance is estimated to be $+0.12$ (90% range from 0.06 to 0.3) W m^{-2} concludes that it is exceptionally unlikely that the combined natural (solar and volcanic) radiative forcing has had a warming influence comparable to that of the combined anthropogenic forcing over the period 1950 to 2005.

Knowledge of the effects of solar variability on the climate system is nevertheless important, e.g. in attribution research. There has also been some debate on the solar modulation of the atmospheric penetration of galactic cosmic rays, the possible effects on cloudiness and consequently on temperature. More recently, it has also been noted that the present solar cycle (the 11-year cycle) exhibits a rather pronounced minimum. Should it persist, or if there are other solar cycle variations over the next decades that are significantly different from those over the last few centuries, it would either add to or reduce anthropogenic climate trends.

5.4.1 Solar irradiance variability and climate forcing

The observed variability in total solar irradiance (TSI) is small (the amplitude over the Sun's 11-year cycle being less than 0.1 W m^{-2}). Nevertheless, studies suggest an observable correlation with the global temperature variability^{149,150}, the latter spanning $0.1\text{--}0.2^\circ\text{C}$ between a solar cycle minimum and maximum. The variation in solar cycle irradiance is, however, so small that its effect needs to be enhanced by some climate system feedback in the same way as water vapour amplifies the direct effect of anthropogenic forc-

ing of CO₂. The deduced climate response to solar cycle variability exhibits various regional and seasonal flavours¹⁵¹, which also suggests that climate system feedback must be in play, modulating the effect of imposed irradiation variations.

The 11-year cycle varies over prolonged timescales due to solar processes, and exhibits periods of lowered and heightened activity. For example, there was a well known pronounced minimum (the Maunder minimum) in the 17th century. Over much of the 20th century, solar activity was high on a historical perspective (“a grand maximum”). The most recent solar cycle has indeed exhibited the lowest activity levels over the past 80–90 years. There are studies that suggest that the level of solar activity may again decline over the first couple of decades of the 21st century^{152,153}. This could lead to a new “grand minimum”, perhaps akin to the Maunder minimum, that could last for several decades. Still, the estimated effect on the global mean temperature is around 0.1–0.2°C¹⁵⁴. In some regions, there could at the same time be additional warming, due to the regional effects of solar variability as mentioned above¹⁵⁵. This is in line with findings based on measurements as well as model studies indicating that the global mean temperature response to this magnitude of solar irradiance variations is small.

Overall, even though TSI variations exert natural climate forcing, as is indicated by some of the past climate variability, their impact is minor compared to anthropogenic forcing^{151,156,157,158,159}. Contradictory findings¹⁶⁰ have also been reported, where solar influence is claimed to be much larger, even dominating 20th century warming. The robustness of the latter findings has been questioned¹⁶¹.

Solar variability can still modify the anthropogenic warming trend over shorter periods¹⁶². For example, some of the apparent plateau in the global temperature record over the last decade may correspond to the recent solar cycle minimum. Likewise, unless a transition to lower solar activity is indeed imminent, the approaching solar cycle maximum over the next half-decade would tend to boost the warming trend. Likewise, the trend should again slow down over the second half of the 2010s as the next solar cycle minimum approaches (Figure 7). There are, of course, also other modifying influences, including intermittent major volcanic eruptions and internal climate system variability that will also be in play.

Figure 7. (a) Observed monthly mean global temperatures (black) and an empirical model (orange) that combines the effects of ENSO, volcanic aerosols, solar irradiance and anthropogenic forcing. (b) Individual warming contributions of ENSO, volcanic aerosols, solar irradiance and anthropogenic effects. (Figure 1 in Lean, J.L. and Rind, D.H., 2009. How will Earth's surface temperature change in future decades? *Geophys. Res. Lett.*, 36, L15708, doi:10.1029/2009GL038932162. Published in 2009 by the American Geophysical Union.)

In addition to the total solar irradiance, the climate system quite possibly also responds to solar variability in other, more complicated ways. Solar variability is much greater on the ultraviolet part of the radiation spectrum than on the visible wavelengths. The latter contribute most to the TSI. Variations in ultraviolet radiation mainly affect the upper atmosphere, but changes there could be transferred to the lower atmosphere via atmospheric circulation. Such postulated additional mechanisms are difficult to translate into quantitative physical understanding, which would be needed to investigate their significance in relation to anthropogenic forcing. The same is true for proposed galactic cosmic rays/clouds/climate relationships.

5.4.2 Galactic cosmic rays, clouds and climate

Various empirical associations have been suggested between low-level cloud cover and cosmic ray fluxes. This research was also discussed in AR4, the assessment (WGI AR4 TS, page 31. See also Chapter 2, page 132) being that:

Empirical associations have been reported between solar-modulated cosmic ray ionization of the atmosphere and global average low-level cloud cover, but evidence for a systematic indirect solar effect remains ambiguous.

and:

Together with the lack of a proven physical mechanism and the plausibility of other causal factors affecting changes in cloud cover, this makes the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial.

The hypothesis of a climate mechanism caused by galactic cosmic ray variation is that changing ionization of the atmosphere due to solar-modulated cosmic ray fluxes has an impact on clouds. As in the overall literature until 2006 (cf. AR4), this remains controversial due to uncertainties about whether there is a signal, the phasing or anti-phasing with solar activity, and the effect on low, middle and high clouds. In particular, the cosmic ray time series does not correspond to global total cloud cover after 1991 or to global low-level cloud cover after 1994, which would be a condition for there to be a significant global temperature effect. In contrast, the apparent relationship between solar variability and cloud cover has been interpreted to result not only from solar-induced changes, but also from sea surface temperatures altered directly by TSI variations and by natural internal variability due to El Niño-Southern Oscillation (ENSO). Of course, different direct and indirect physical processes may operate simultaneously.

Recently, it was claimed in a study¹⁶³ that cloud water content, cloud cover and aerosol concentrations as measured by different satellites show significant reduction during 26 so-called Forbush decreases^{*}. However, a reanalysis of the liquid water cloud fraction data measured by MODIS and the corresponding Forbush events suggests that liquid water cloud fraction variations are unrelated to these events¹⁶⁴. A similar conclusion was drawn in a study using a stringent test of any hypothesis based on a cosmic ray cloud connection¹⁶⁵ as no sign was evident of any response by global cloud cover to Forbush decreases at any altitude or latitude.

Even if it could be shown that galactic cosmic rays are important for the climate, the hypothesis of this being a significant part of the explanation for the current global warming would still be challenged by data that does not indicate any long-term trend in incoming galactic cosmic rays, which would be required for climate *forcing* to ensue. Figure 8 shows an updated time

^{*} A Forbush decrease is a rapid decrease in the observed galactic cosmic ray intensity following a coronal mass ejection by the Sun.

series of cosmic rays as measured at Oulu in Finland, where these measurements were started in 1964. (The Oulu station is a part of the World Network of Neutron Monitors.)

Figure 8. Monthly mean variations in cosmic ray flux as monitored at Oulu, Finland¹⁶⁶.

This lack of trend has been demonstrated^{151,167}. A fit to the variation in the global mean temperature over the past half century indicates that anthropogenic factors contribute 75% of the rise since 1987, while the contribution from galactic cosmic rays shows up as a small downward trend between -0.7 and -1.9%¹⁶⁷ (see Figure 9). Nor do various studies based on different methodologies, including aerosol microphysics modelling, provide support for any significant connection between cosmic rays and clouds^{168,169,170}.

Figure 9. Scaled and filtered variations giving the best temperature fit. (a) contribution of deep ocean–surface heat exchange, (b) contribution of volcanoes, (c) galactic cosmic ray contribution, and (d) the best-fit linear drift. (From Lockwood, M. 2008. Recent changes in solar outputs and the global mean surface temperature. III. Analysis of contributions to global mean air surface temperature rise, *Proc. Roy. Soc. A*, 464, 1387–1404. Doi:10.1098/rspa.2007.0348¹⁶⁷. Courtesy of the Royal Society.)

6. Attribution and internal variability

Anthropogenic climate forcing (particularly greenhouse gas emissions) evolve relatively smoothly over time. The climate, on the other hand, exhibits some variability from year to year and also from decade to decade. This is very much due to variability generated internally within the climate system, as well as variations in climate forcing such as solar variability and volcanic eruptions.

The concepts of *detection* and *attribution* both relate to identifying the effects of external forcing in observed climate changes. A climate change is said to be detectable if it is too large to be plausibly explained by internal climate variability (e.g. “random” variations in atmospheric winds and ocean currents) alone. Attribution, in turn, attempts to estimate the contributions of various anthropogenic (e.g. changes in greenhouse and aerosol concentrations) and natural (solar activity and volcanic eruptions) external factors to those aspects of climate change that cannot be explained by internal variability.

In AR4 (WGI, SPM, page 10), an assessment of attribution research concluded that:

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the TAR’s conclusion that “most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations”. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns.

6.1 Attribution of observed climate changes

Attribution is usually based on a comparison between observed climate changes and the model-simulated response to a given external forcing. Thus attribution does not rely on global mean changes alone, but can also take into account the geographical and temporal patterns of the observed change. Different climate forcing factors lead to spatially and temporally different responses, known as “fingerprints”.

Detection and attribution are strongly dependent on the signal-to-noise ratio between the changes induced by external forcing and natural internal variability, as well as on the confidence that can be put in the ability of global climate models to capture the response to the relevant forcing factors.

As a result, much stronger attribution statements are possible for large-scale changes in temperature (and some other, strongly temperature-related climate variables) than for changes in (e.g.) atmospheric circulation and precipitation, and climate changes on local and regional scales in general¹⁷¹.

This section focuses on the detection and attribution of changes in four aspects of climate: the mean surface temperature, ocean temperatures, the hydrological cycle, and some types of extreme events. In the subsequent section, natural internal variability (variability that is generated within the climate system, which occurs in the absence of external forcing), is discussed as it represents the “noise” compared to which any forced changes need to be elucidated.

6.1.1 Changes in mean surface temperature

AR4 concluded that the effects of anthropogenic forcing are now evident in many aspects of observed climate change. The most prominent examples include warming of global and continental mean surface temperatures, tropospheric warming and stratospheric cooling, and warming of ocean water. In particular, regarding changes in long-term mean surface temperature it was noted (WGI, TS6.3) that

Greenhouse gas forcing has very likely caused most of the observed global warming over the last 50 years. Greenhouse gas forcing alone during the past half century would likely have resulted in greater than the observed warming if there had not been an offsetting cooling effect from aerosol and other forcing.

as well as (WGI, TS4.2) that

It is likely that there has been a substantial anthropogenic contribution of surface temperature increases over every continent except Antarctica since the middle of the 20th century.

Since AR4, observed changes in Antarctic and Arctic temperatures have also been shown to include a detectable anthropogenic signature¹⁷². A new analysis of observations indicates widespread warming over the Antarctic continent during the past 50 years, at an average rate comparable to the southern hemisphere as a whole¹⁷³. This overall warming is very likely attributable to increasing greenhouse gas concentrations, although changes in atmospheric circulation (which in AR4 were attributed to stratospheric ozone depletion and increasing greenhouse gas forcing) have modified the regional patterns of temperature change.

Nevertheless, natural variability has very likely affected some of the observed Arctic climate change features. In particular, the record-low sea ice extent in summer 2007 (see also Section 2.3) was partly due to anomalous winds that drove ice out of the Arctic basin¹⁷⁴. A recent study also attributes 1/3 of the decrease in the Arctic September sea ice extent in the past three decades to changes in wind conditions¹⁷⁵, the contemporary global warming

influence on Arctic sea ice decline also being clearly detectable¹⁷⁶. Furthermore, increasing greenhouse gas concentrations have not been the only anthropogenic cause of Arctic temperature changes. According to model simulations, the Arctic warming over the past three decades was substantially accelerated by decreasing concentrations of sulphate aerosols (the increase of which had suppressed the warming earlier) and increasing concentrations of black carbon¹⁷⁷ (see also Section 5.2).

In AR4, the attribution of temperature changes was considered on large (continental to global) spatial scales. On these scales, natural variability is much smaller, and the confidence in model simulations much higher than on the regional or, to an even greater extent, local scales. Nevertheless, one new study¹⁷⁸ that considered temperature trends in small individual regions (~500 km scale) found the warming since 1950 to be significant in most areas. Furthermore, even if it is difficult to strictly demonstrate an anthropogenic influence on observed warming for a single small region in isolation, the presence of detectable greenhouse gas-induced warming on the global scale implies that this forcing has also affected regional climates in most areas of the world¹⁷⁹. In some regions, however, such local forcing factors as land use change and irrigation are also very important¹⁸⁰, complicating rigorous attribution.

6.1.2 Changes in ocean temperature

In AR4, it was concluded that the observed warming of the upper ocean in the latter half of the 20th century was likely to have been due to anthropogenic forcing. However, at that time it seemed that observed interdecadal variations in global ocean heat content had been much larger than those simulated in models. A large part of this discrepancy now appears to be about instrumental errors¹⁸¹. The agreement across observations and model results is much better when these bias corrections are included²⁷. Interannual to interdecadal variability in upper ocean temperatures is partly attributable to volcanic eruptions. The longer-term warming is anthropogenic¹⁸².

6.1.3 Changes in the hydrological cycle

AR4 included only a few relatively weak attribution statements on changes in the hydrological cycle. Although uncertainties remain, recent research has improved this situation. An expected consequence of greenhouse gas induced warming is an increase in atmospheric water vapour content (by 7% for each 1°C of warming if relative humidity remains unchanged). Such moistening has now been detected in a new surface humidity dataset¹⁸³.

Despite the large increase in atmospheric moisture content, the globally averaged precipitation in model simulations of greenhouse gas-induced climate change only increases relatively slowly with temperature, by about 2% for each 1°C of global warming. A study, using a 20-year long satellite-

based precipitation data set, has suggested that global precipitation has increased much faster¹⁸⁴. However, a 20-year period is probably too short to determine if there is a genuine disagreement between model simulations and observations¹⁸⁵. Extrapolation of recent observations to the future is also problematic because the ratio of global precipitation change to global temperature change depends on the type of climate forcing, and the relative importance of different forcing factors is likely to change over time (with greenhouse gas forcing becoming increasingly dominant towards the late 21st century)¹⁸⁶.

Model simulations of greenhouse gas induced climate change also indicate robust latitudinal changes in precipitation, with more precipitation at high latitudes, less precipitation in the subtropics and increases in tropical region – an overall strengthening of the hydrological cycle. Such a pattern is detectable in 20th century observations and does not appear to be explainable by natural variability alone. However, the magnitude of the observed change exceeds what is simulated by models^{187,188}. The detection and attribution of precipitation changes on smaller scales remains generally difficult because precipitation varies considerably on these scales, implying a low signal-to-noise ratio. There is also a shortfall of reliable observations from many locations¹⁷¹.

Apart from changes in precipitation and evaporation, global warming also affects the hydrological cycle by changing snow conditions. In regional studies for the western United States, observed trends toward earlier snow-melt-driven streamflows have been found to be unexplainable by natural climate variability alone¹⁸⁹. One study attributes up to 60% of the trends in river flow, winter air temperature and snow pack in this region over the 1950–1999 period, to human influence¹⁹⁰. There has also been a reduction in the fraction of precipitation falling as snow in this area which cannot be explained by natural factors and is attributed to anthropogenic forcing¹⁹¹. Because many of these trends are directly related to warming that is a robust aspect of both observed and simulated climate change, a similar development may well be underway in other similar parts of the world that so far remain less extensively studied.

6.1.4 Changes in extremes

Extremes are a given aspect of natural climate variability. In Section 4, we discuss research on whether extremes might change together with the rest of the climate. Here, the focus is on whether extremes *are* observed to be changing in ways that can be associated with overall climate change.

Changes in extremes, due to extremes' sporadic nature and overall rarity, are more difficult to detect and attribute to specific causes than changes in mean climate. AR4 concluded that surface temperature extremes are likely to have been affected by anthropogenic warming, with a general decrease in cold and a general increase in warm extremes. Evidence was also presented

that anthropogenic forcing may already have multiplied the risk of extremely warm summers such as that observed in Europe in 2003, and this also seems to be the case in many other areas¹⁹². An analysis of model simulations suggests that the same also holds for recent record-mild winter months in northern Europe¹⁹³. Observed increases in heavy precipitation over the 20th century were also found in AR4 to be consistent with the anticipated response to anthropogenic forcing, but a formal attribution of this is still lacking.

Observed changes in tropical cyclones (hurricanes and typhoons) and their causes remain a controversial issue. Taking into account the improvement in observation systems over time, it is uncertain whether past changes in any aspect of tropical cyclone activity are discernible from natural variability¹⁹⁴. Observed increases in sea surface temperature in the main hurricane formation regions of the Atlantic and Pacific have been shown to be of mainly anthropogenic origin^{195,196}, but the effect of sea surface temperature change on tropical cyclone activity is still poorly understood. Apparently, the geographical patterns of the change are at least as important as the absolute warming of the sea surface¹⁹⁷.

6.2 Internal variability

Internal variability in the climate system results from non-linear dynamics in the atmosphere and the oceans, and their interaction with each other and with the land surface. Internal variability is particularly strong on relatively short time scales ranging from weeks to a few years. Some components of it have longer time scales and thus complicate the attribution of observed climate changes to external forcing.

AR4 presented strong evidence that global and hemispheric-scale temperature changes on multi-decadal time scales cannot be explained by internal variability. Observed temperature changes are much larger than the variations generated by internal variability in climate model simulations. Furthermore, the pattern of observed temperature changes, with some warming nearly everywhere but the greatest warming at high northern latitudes, does not correspond to any known mode of internal variability.

For shorter-term variations in climate, internal variability is more important, and it becomes progressively more important towards smaller spatial scales. Internal variability shows up more on regional scales than the effect it has on the global mean.

Internal variability tends to be dominated by a limited number of preferred spatial patterns, also known as “modes”. The El Niño – Southern Oscillation has widespread impacts in and around tropical regions, but it also affects the global mean temperature. The North Atlantic Oscillation and the Atlantic Multidecadal Oscillation strongly affect the climate in the North Atlantic – European area.

The *El Niño – Southern Oscillation* (ENSO) refers to an irregular variation of oceanic and atmospheric conditions in the tropical Pacific Ocean (Figure 10a). This leads to large variations in temperature and rainfall in many tropical regions. By inducing changes in atmospheric circulation, ENSO affects some higher latitude regions, particularly North and South America. There is also some evidence of smaller effects on the European climate^{198,199}.

ENSO can affect the global mean temperature, inducing interannual temperature variations of up to about 0.2°C ²⁰⁰. Years with a strong El Niño, such as 1998, tend to be unusually warm. La Niña years such as 1999–2000 and 2008 tend to be cooler than average. A moderate El Niño developed during the second half of 2009, persisting into 2010 (at the time of writing this report). This probably contributes to 2010 starting out as a quite warm year²⁰¹.

North Atlantic Oscillation (NAO)²⁰² is the mode of internal climate variability with the largest impact on Europe. The impact of NAO variability on the European climate is greatest in winter. Winters dominated by the positive phase of NAO are generally milder, wetter and stormier than average in northern Europe, but colder than average in Greenland and eastern Canada. Anomalies of the opposite sign occur during the negative phase of NAO²⁰³.

There was an increasing positive trend in the winter NAO index from the 1960s to the late 1980s and early 1990s (Figure 10b), which explained approximately half of the rapid warming of Eurasian winters over the same period²⁰⁴. However, this trend has not been sustained. Since then there have been both winters with a positive and with a negative NAO index. Notably, the rather cold winter of 2009–2010 in northern Europe was characterised by an extremely negative NAO index.

The reasons for multidecadal NAO variability are only partly understood. Studies cited in AR4 as well as later research²⁰⁵ suggest that sea surface temperatures in the tropical oceans may play a role. Increasing greenhouse gas concentrations also favour the positive phase of the NAO index in climate model simulations, but this change as simulated by models is too small to explain the trend observed in the second half of the 20th century²⁰⁶.

Atlantic multidecadal Oscillation (AMO) refers to an apparent long-term periodicity in sea surface temperatures in the North Atlantic Ocean, thought to be associated with slow variations in ocean thermohaline circulation^{207,208}. This oscillation was in a cold phase between around 1965 and 1995, but has returned to a warm phase in the early 21st century (Figure 10c). Observations and model simulations suggest that a warming of North Atlantic sea surface temperatures also tends to warm the climate in north-western Europe, particularly in summer and autumn^{209,210}. This, again, implies that part of the most recent warming in north-western Europe may have had to do with internal climate variability modes. However, the separation of natural sea surface temperature variability from the effects of anthropogenic climate forcing is not straightforward, so it is not clear whether the

recent AMO phases are solely natural or also carry some signal of forced climate change²¹⁰.

Figure 10. (a) Time series of the Niño3.4 sea surface temperature anomaly from 1950 to 2010. Strong positive (negative) values correspond to an El Niño (a La Niña) state. (b) The winter (December–January–February mean) North Atlantic Oscillation index from 1951 to 2010. Positive (negative) values correspond to stronger (weaker) than usual westerly winds over the northern North Atlantic Ocean. (c) Atlantic Multidecadal Oscillation index from 1856 to 2009. Positive (negative) values correspond to a relatively warm (cool) North Atlantic. For definitions and data sources, see note²¹¹.

7. Climate change projections and scenarios

Climate models are the most important research tool for projecting continued climate change through the 21st century and beyond. In studies of past climate changes and variability, climate system processes and feedback, as well as attribution, climate models complement theory and analyses of data collected in measurements either via regular programmes (monitoring) or in campaigns and field studies. The development and evaluation of climate models is a continuous field of research leading to a continuous update of new climate projections and scenarios. In AR4, the combined projection of the global mean warming over the 21st century, based on about 20 global climate models, provided a wealth of results regarding possible future global mean, but also regional, climate aspects^{13,212}. The “likely” range of the combined projected global mean temperature change between 1990 and 2095, based on the models and SRES emission scenarios, was 1.1–6.4°C. The simulated natural variability was found to be of secondary magnitude beyond the first few decades.

Scientific uncertainties regarding climate sensitivity and climate system feedbacks underline the so-called structural model uncertainty (i.e., differences between the models). Most climate models until now have featured atmospheric, land surface and ocean components, but have not incorporated such climate system components as interactive vegetation, dynamic land use (cf. biogeophysical effects), biogeochemistry or atmospheric chemistry. Some results of such more comprehensive climate models were included in AR4, but it is only now that models are beginning to include more of these components²¹³.

Below, we discuss recent research into climate sensitivity and feedbacks, and then turn to new findings as well as future prospects for climate modelling for the coming years.

A discussion on projected changes in extremes is found in Section 4.

7.1 Climate and Earth system sensitivity

Climate sensitivity (or Equilibrium climate sensitivity) is a cornerstone concept in climate change research and thus also for climate politics. Climate sensitivity is not the same as some climate change scenario result, as the atmospheric carbon dioxide concentration may come to change less or more than a doubling. However, it is useful as a measure of the long-term climate system response to sustained radiative forcing. It is defined as *the equilib-*

rium change in the global mean temperature resulting from a doubling of the atmospheric carbon dioxide concentration. One way of estimating climate sensitivity is by comparing the equilibrium states of two climate model simulations: a control experiment with fixed atmospheric carbon dioxide concentration and a second one in which it is gradually doubled (Figure 11).

Because of the energy required for heating up the oceans, this new equilibrium is first reached centuries if not millennia²¹⁴ after a stabilisation of the carbon dioxide concentration. Although the definition of climate sensitivity refers to changes in the carbon dioxide concentration, high (low) climate sensitivity also implies a strong (weak) temperature response to other sources of radiative forcing. Other ways to estimate climate sensitivity is with information on historical climate data on temperature and radiative forcing. Such results are in general in line with climate model studies (e.g. AR4 WGI Box 10.2, page 798).

Figure 11. A simplified view of the determination of equilibrium climate sensitivity in a climate model. The rate at which CO_2 is doubled is also not important for the final equilibrium, although it affects the warming realised at the time when CO_2 doubles. Zero on the vertical axis in the lower panel is the same model's equilibrium temperature when run with the original CO_2 concentration.

Climate sensitivity is intimately linked to climate feedbacks (e.g. changes in water vapour, snow and ice cover, and clouds as a result of an initial temperature change) in the climate system²¹⁵. Without such feedbacks, climate sensitivity to a doubling of CO_2 would be just slightly over 1°C ²¹⁶. Because most of the known feedback processes tend to amplify climate changes, actual climate sensitivity is very likely to be higher. In AR4 (WGI TS4.5 and Box 10.2) it was assessed that:

Analysis of models together with constraints from observations suggest that the equilibrium climate sensitivity is likely to be in the range 2°C to 4.5°C , with a best estimate value of about 3°C . It is very unlikely to be less than 1.5°C . Values substantially higher than 4.5°C cannot be excluded, but agreement with observations is not as good for those values.

AR4 also concluded that cloud feedback (particularly changes in low clouds) was the single largest source of uncertainty in estimating climate sensitivity from model simulations.

The AR4 assessment of climate sensitivity was not based on model simulations alone, but also included information from instrumental observations (most importantly, climate change during the industrial era) and proxy estimates of pre-instrumental (e.g. glacial-interglacial) climate variations.

Since then, a number of new studies have addressed climate sensitivity using various methods and observational constraints. A few of them have suggested climate sensitivity near²¹⁷ or below²¹⁸ the lower end of the AR4 uncertainty range. However, as discussed in a recent review²¹⁹, these studies have weaknesses in their methodology, such as overly simplified assumptions, deficient uncertainty assessment, or errors in the analysis or data set. More comprehensive recent studies yield results consistent with AR4²²⁰. The conclusion that climate sensitivity is very unlikely to be below 1.5°C remains valid, as does the conclusion that an upper limit to the uncertainty range of climate sensitivity is very difficult to determine^{219,221}.

The traditional definition of climate sensitivity only takes into account feedback processes associated with the relatively fast responding parts of the climate system (e.g. atmospheric water vapour and clouds, and seasonal snow and ice cover). On longer timescales of centuries to millennia and beyond, slow feedbacks due to changes in, for example, ice sheets and vegetation may also become important. Recent research suggests that these slow feedbacks make the actual *Earth system sensitivity* (equilibrium temperature response to a doubling of carbon dioxide, taking into account all feedbacks in the climate system) greater than the traditionally defined climate sensitivity. One study²²², using greenhouse gas concentrations and temperature change estimates derived from Antarctic ice cores, concluded that the variation between ice ages and interglacial periods over the last several thousand years has been characterised by an Earth system sensitivity of about 6°C, in contrast to a traditional climate sensitivity of around 3°C. A similar conclusion was made for the 50 million years preceding the Pleistocene ice ages, when the global climate was warmer than today. This latter estimate is more uncertain because of the lower quality of climate and greenhouse gas data for that period. Another study²²³ combined model simulations with proxy data for the mid-Pliocene warm period (about three million years ago). It suggested that Earth system sensitivity to elevated atmospheric carbon dioxide concentrations is 30–50% greater than the response based on the fast-adjusting components that are accounted for in the more common estimates of climate sensitivity.

To conclude, (i) the AR4 assessment of climate sensitivity remains consistent with existing data, but (ii) there is initial evidence from palaeoclimatic studies that the long-term Earth system sensitivity to elevated greenhouse gas concentrations is greater. The patchy nature of proxy climate data far back in time, and the deficient understanding and capability to model

processes involved in long-term climate dynamics imply that the results concerning Earth system sensitivity must be regarded as tentative.

Both climate sensitivity and Earth system sensitivity refer to equilibrium climate change, which is distinct from the climate change to be expected over the 21st century. Model simulations indicate that the response time of the climate system increases with its sensitivity. This means that, at any given point in time, a larger fraction of the final equilibrium warming will have been realised if the sensitivity of the climate system is low than if it is high²²⁴. The rate of climate change over the next hundred years would in such a case not be as uncertain as would be inferred from the large uncertainties in climate sensitivity and Earth system sensitivity. On the other hand, the same relationship between response time and sensitivity also makes it more difficult to estimate equilibrium climate sensitivity from the warming observed hitherto.

7.2 Feedback

As mentioned above, the role of feedbacks is crucial for both the climate and Earth system sensitivity. As is evident from the discussion above on more or less unchanged estimates of climate sensitivity, later research on feedbacks has not led to any major changes in knowledge. However, there is some emerging progress not least on climate-carbon feedback (see further down).

A feedback is a process that is triggered by some initial change and either enhances it (a positive feedback), or counteracts the initial change (a negative feedback).

In AR4 (WGI, Chapter 8, page 591), climate feedback findings were summarised as follows:

Cloud feedbacks have been confirmed as a primary source of these differences, with low clouds making the largest contribution. New observational and modelling evidence strongly supports a combined water vapour-lapse rate feedback of a strength comparable to that found in General Circulation Models (approximately $1 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$, corresponding to around a 50% amplification of global mean warming). The magnitude of cryospheric feedbacks remains uncertain, contributing to the range of model climate responses at mid- to high latitudes.

and

To explore the potential importance of carbon cycle feedbacks in the climate system, explicit treatment of the carbon cycle has been introduced in a few climate AOGCMs and some Earth System Models of Intermediate Complexity (EMICs).

7.2.1 Water vapour and cloud feedback

The most important “fast” feedbacks concern atmospheric water vapour (positive feedback – an initial warming increases the water retaining capac-

ity of the atmosphere. Water vapour, being a greenhouse gas, drives the temperature to rise even more), changes in surface snow and ice cover (positive) and clouds (positive or negative feedback). Figure 12 summarises previous studies in that the sign and size of the water vapour feedback is quite robust.

Figure 12. Comparison of GCM climate feedback parameters for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour plus lapse rate (WV + LR) in units of $W m^{-2} °C^{-1}$. 'ALL' represents the sum of all feedbacks. The various symbols and colours depict different methodologies. The vertical bars depict estimated uncertainty. (Figure 8.14 in AR4, WGI, Chapter 8.)

This is further emphasised by recent studies looking into observations^{184,225,226,227,228,229,230}. One exception is a study that indicates a decrease in water vapour in the tropical upper troposphere²³¹. The authors present the data with a caveat. The NCEP reanalysis utilised relies on radiosoundings, and does not take into account satellite-derived humidity in the tropics.

Compared to water vapour feedback, there is more uncertainty regarding cloud feedback, not least in respect of low clouds. Understanding cloud feedbacks is probably the most important aspect in narrowing uncertainty in climate projections. In particular, how the amount or properties of low-level clouds might change due to greenhouse gas forcing is a crucial aspect. The climate models used in AR4 indicated a predominant decrease in low- and mid-level clouds during the 21st century, particularly in mid-latitudes, and an increase in the altitude of the highest clouds (AR4, WGI, Fig. 10.10). The cloud feedback in practically all current models was found to be positive when evaluated by rigorous methods, but with a very large inter-model variation in the magnitude of the feedback (Figure 12).

Studies on clouds and cloud feedback have continued since AR4 (e.g.^{232,233}) with additional insights into the relevant processes and the difficult-to-quantify ability of climate models to represent these aspects. Still, studies based on various observational data can arrive at quite different conclusions ranging from positive low-level cloud / climate feedback²³⁴ to negative feedbacks²³⁵. The latter study has been shown to contain serious errors²³⁶. Generalisation of any particular finding based on some specific observation to long-term global warming prospects requires much caution.

All in all, the level of scientific understanding of cloud feedback has not changed very much since AR4. Despite the considerable spread in cloud feedback in climate models, the overall result in climate projections is still a clear and significant warming due to anthropogenic forcing.

For the Earth system, “slow” feedbacks such as changes in the large ice sheets can also play a role²²² (See Section 7.1).

Research into feedbacks is extensive and intensive. Some of the relevant mechanisms involving biogeophysical and biogeochemical effects have already been discussed in conjunction with land use and ocean acidification. A complementary discussion follows below, focusing on climate-carbon and cloud feedback.

7.2.2 Climate-carbon feedback

Some carbon cycle feedbacks – changes in carbon sinks and sources in the ocean due to climate change have already been discussed in conjunction with ocean acidification (see Section 3). Another likely feedback between climate and carbon concerns terrestrial systems, in which carbon is taken up, stored and released by vegetation and soil. The soil carbon pool, globally, is larger than the atmospheric and vegetation pools. Vegetation and soil exchange carbon with the atmosphere through photosynthesis, respiration and volatilisation in fires. Episodic events such as droughts²³⁷, storms and fires cause vegetation mortality and may affect soil biogeochemical processes, typically resulting in a strong temporary increase in respiration.

In AR4 (WGI, Chapter 7, page 501), findings from climate models with a coupled carbon cycle (ocean and terrestrial carbon) were summarised thus:

The first-generation coupled climate-carbon cycle models indicate that global warming will increase the fraction of anthropogenic CO₂ that remains in the atmosphere. This positive climate-carbon cycle feedback leads to an additional increase in atmospheric CO₂ concentration of 20 to 224 ppm by 2100, in models run under the IPCC (2000) Special Report on Emission Scenarios (SRES) A2 emissions scenario.

As is evident, there is a considerable spread in the results of such coupled models, as there is in the pure physical climate system models. Still, the sign, if not the size (e.g.^{67,238,239}), of the climate-carbon feedback is robust across the models as well as inferences from historical records.

Similar findings indicating weaker net carbon uptake when feedbacks are taken into account are contained in the more recent literature^{240,241,242}. Climate change simulations by five Dynamic Global Vegetation Models (DGVM) show increased carbon uptake due to CO₂ fertilisation. The response of the carbon cycle to climate change itself (changes in temperature, etc.) varies more²⁴³. The net response, however, is the same: a positive climate-carbon feedback (release of stored land carbon). Under the A1FI emission scenario, three of the five DGVMs simulated a switch from a net sink to a net source of atmospheric carbon from land ecosystems by the end of the 21st century.

In present climate/carbon models, nitrogen is not explicitly accounted for, whereas nitrogen-carbon interactions in ecosystems are increasingly being built into ‘offline’ dynamic vegetation models. The availability of nitrogen limits plant production in many terrestrial ecosystems and when this constraint is taken into account, the direct implication would be reduced carbon uptake under global warming because CO₂ fertilisation is suppressed^{244,245}. However, depending on the particular ecosystem and for small to moderate warming, increased decomposition in warmer soils can also increase the availability of nitrogen, and thus increase land carbon uptake. The global effect of nitrogen limitation may nevertheless be reduced carbon sinks. Compared to climate-carbon modelling results without nitrogen interactions, the effect could be 50 ppm of additional atmospheric CO₂ by the year 2100²⁴⁵.

Quite a lot of the carbon in terrestrial systems is found in regions subject to permafrost conditions. In these areas, the carbon balance may be particularly vulnerable to warming as the permafrost melts and the fossil carbon it contains begins to respire. A recent article suggests that the amount of carbon stored in the permafrost may be twice as large as suggested by earlier estimates²⁴⁶. Potentially, the carbon loss due to climate warming could be around 0.5–1.0 GtC/year over the 21st century, leading to accumulated emissions of around 50–100 GtC by 2100.

In addition to possible climate change-induced carbon release, permafrost areas could also start releasing nitrous oxide (N₂O) as a result of continued warming²⁴⁷. This would add to the positive climate-carbon feedback from permafrost regions.

7.2.3 Climate-Atmospheric chemistry feedback

The presence of chemically reactive species in the atmosphere can in principle also lead to feedbacks, with consequences for the climate sensitivity. Examples are: increasing temperature leading to increasing emissions of biogenic volatile organic carbon (BVOC, see above), leading to more secondary organic aerosol and consequently some cooling influence (negative feedback). Increasing temperature, on the other hand, may shift the equilibrium between the liquid phase (aerosol) and the gas phase towards the latter,

leading in turn to less aerosol, and hence a warming influence (positive feedback). Research to quantify the importance of feedbacks related to atmospheric chemistry is entering a new phase of development²⁴⁸.

8. Climate projections, new emission scenarios (RCPs) and climate prediction

8.1 Global climate modelling

Many of the global climate modelling findings that were available for AR4 were achieved within the Coupled Model Intercomparison Project 3¹⁴ (CMIP3), and were derived using the models of the various research teams all around the world. CMIP3 provided coordination and thus facilitated more comprehensive and consistent research into climate projections than if the groups had had their own experimental protocols. The CMIP3 runs continue to support new studies. By April 2010, the CMIP3 website listed about 550 papers²⁴⁹, quite a few of which date from 2007 or later.

A new phase of CMIP is underway (CMIP5)²⁵⁰. As before, it provides suggestions for coordinated simulations, and invites all groups to contribute. The simulations are expected to be completed before the next IPCC Assessment, so that new findings will be available for it, including climate model evaluations, projections and new insights into climate processes as well as key feedbacks.

CMIP5 focuses on two time horizons. One of them is comparable to CMIP3, and covers the entire 21st century. Some runs will be extended until 2300. The other time horizon is near-term predictions (some 10–30 years). The CMIP5 setup recognises that different research groups have different computing and human resources, and also that whereas some climate models still consider only physical climate system components (atmosphere, ocean, land surface, sea ice), there are now also a number of models that incorporate interactive biospheric components and atmospheric chemistry. Thus, in addition to “core” experiments, there are additional “tiers” that address specific key issues.

The same core-tier set-up characterises the choice of emission scenarios. The latter consider the new set of Representative Concentration Pathway scenarios²⁵¹ (RCP) that extend from 2006 to 2300. In contrast to the earlier SRES emission scenarios underlying the CMIP3 and thus AR4 global climate projections, the RCPs are prepared in terms of radiative forcing changes taking place by 2100. The 2100 radiative forcing provides the labelling of the RCPs: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. These span much of the earlier SRES scenario range, but also extend it to lower climate forcing levels. In terms of present climate policy approaches RCP2.6 is probably the most interesting from the mitigation point of view. The higher RCPs are

interesting for studying impacts and vulnerabilities that could be avoided by climate mitigation. One should note that RCP2.6 is one of the tiered simulations, rather than being at the core (Figure 13), which suggest that not all the models necessarily run RCP2.6 experiments.

	#	Experiment	Notes	# of years
CORE	4.1	RCP4.5 (2006-2100)	Radiative forcing stabilizes at $\sim 4.5 \text{ W m}^{-2}$ after 2100. (if ESM, save CO_2 fluxes from the surface to calculate allowable emissions)	95
	4.2	RCP8.5 (2006-2100)	Radiative forcing reaches $\sim 8.5 \text{ W m}^{-2}$ near ~ 2100 . (if ESM, save CO_2 fluxes from the surface to calculate allowable emissions)	95
TIER 1	4.3	RCP2.6 (2006-2100)	Radiative forcing peaks at $\sim 2.6 \text{ W m}^{-2}$ near 2100.	95
	4.4	RCP6 (2006-2100)	Radiative forcing stabilizes at $\sim 6 \text{ W m}^{-2}$ after ~ 2100 .	95
	4.1-L	RCP4.5 extended through year 2300	Extension of expt. 4.1 through the end of the 23 rd century.	200
TIER 2	4.2-L & 4.3-L	Extend RCP8.5 & RCP2.6 through year 2300	Extension of expts. 4.2 and 4.3 through the end of the 23 rd century.	2x200

Figure 13. CMIP5 future climate projection set-up (Table 4 in²⁵⁰).

As noted earlier, there have been quite a few additional analyses based on CMIP3 since 2006–2007, and these have led to various specific new results. There have also been new climate model projections, and not least simulations with added Earth system components (vegetation, chemistry, etc.). This will be further explored among the CMIP5 tiered studies.

8.2 Climate prediction

The near-term projection focus in CMIP5 is something that is becoming known as *climate prediction* (as opposed to *climate projection* and *climate scenarios*)²⁵². It follows earlier lines of research on decadal prediction, but with an explicit consideration of anthropogenic forcing whilst attempting to capture the actual course of natural variability. The underlying idea is to utilise possible “memory” in ocean conditions (sub-surface heat content) that exhibit longer time constants than the atmosphere does (i.e. respond more slowly to forcing and changes in other climate system components). For example, the strength of the North Atlantic thermohaline circulation is characterised by long time scales and is potentially predictable for longer periods. To the extent that phenomena that significantly affect the atmosphere can be predicted, there are at least prospects of improving short-term climate projections for the next one or two decades^{253,254}. This could mean,

for example, foretelling possible temporary pauses in the warming trend such as the one experienced over the last few years, or the opposite of this, an enhanced warming period, due to aligning natural variations and anthropogenic forcing.

Predictability in the climate system is affected by both initial conditions and external forcing. Weather prediction for time scales ranging from hours to a couple of weeks is largely based on knowledge of the initial conditions –observed weather conditions in the atmosphere and the surface ocean. By contrast, climate projection for multi-decadal and longer time scales is based on scenarios of external forcing. In the anthropogenic context, this means emissions and subsequent changes in atmospheric greenhouse gas concentrations and particles.

The reasons for including only external condition information in climate projection are threefold. First, the climate system “memory” of atmospheric initial conditions is lost rapidly, due to the chaotic nature of atmospheric dynamics. Second, climate projections/scenarios target the *climate* (statistical properties of the climate system state including averages, variability and extremes). A sufficiently long model simulation will include both (e.g.) relatively warm and relatively cold periods, which means that the essentials of natural variability are also captured, even though their course may be different than in reality. Third, although some longer-lasting initial condition information may be available, especially in the ocean, a lack of sufficient observations and biases in climate models complicate the use of this information. Ocean currents, sub-surface water temperature and salinity are observed much less regularly than the atmospheric weather.

Nevertheless, by including initial ocean conditions some success has been seen in *seasonal* prediction. The most important example of this is the El Niño – Southern Oscillation (ENSO) phenomenon in the tropical Pacific area. Current models provide useful predictions of ENSO for a lead time of 6–12 months²⁵⁵. In some specific cases, the phenomenon may be predictable two years in advance²⁵⁶. Because the tropical atmosphere is strongly controlled by sea surface temperatures, a good forecast of ENSO-related tropical Pacific sea surface temperature variations also allows useful prediction of seasonal temperature and precipitation anomalies in large parts of the tropics, and to a lesser extent, in some extratropical areas such as North America^{257,258}.

Research on decadal climate prediction is still in its infancy. Two recent studies^{259,260} suggest that decadal predictions including initial-condition information may have more skill than projections based on external forcing alone, but the origin of the skill and its statistical significance have not yet been well evaluated. The first of these studies concluded that at least half of the years between 2009 and 2014 should be warmer in terms of the global mean temperature than the warmest years hitherto (1998 or 2005). In contrast, the second study suggests that cooling associated with natural variability may offset anthropogenic global warming during the next decade, yield-

ing little net change. In particular, this study predicts a temporary weakening of the Atlantic Ocean overturning circulation, and a resulting slight cooling of European and North American surface temperatures during the next decade despite increasing greenhouse gas concentrations.

The prospects for decadal prediction are best for those aspects of the climate that are most directly affected by sea surface temperatures. This concerns first and foremost air temperature over the oceans themselves, notably the northern North Atlantic, but model simulations indicate that some more modest temperature predictability also extends to nearby and downstream land areas such as Scandinavia²⁶¹. Further inland, the predictability associated with oceanic initial conditions is largely drowned by the “noise” generated by purely atmospheric processes. Models also indicate that precipitation is considerably less predictable on decadal time scales than temperature is, with nearly negligible predictability over land areas as a rule.

Whether the predictability associated with initial conditions can be sufficiently skilfully captured in climate models remains unclear for the time being. Climate prediction for the next 10–30 years will be assessed more systematically in the next IPCC assessment to be completed in 2013, using model simulations conducted as a part of CMIP5²⁵⁰.

8.3 Regional climate modelling

In AR4, much of the information on regional climate projections was derived from global climate modelling. As global climate models have a relatively coarse resolution, the results they can provide address fairly large scales. More specific regional-scale climate projections come from regional climate modelling as well as statistical downscaling techniques. In AR4, several such studies were assessed, but due to the heterogeneity of methodologies and study set-ups, the resulting overall assessment remained patchy.

Regional climate modelling has also advanced since AR4²⁶². A number of coordinated initiatives involving multiple models have been put forward. So far, however, few new conclusions about the future climate at the regional scale have emerged. Some of the major technological achievements taking full advantage of ensembles techniques and new research utilising these are very recent, and have thus not yet been published in the scientific literature.

Four major initiatives since AR4 should be highlighted:

- One of the research themes of the very recent European ENSEMBLES project²⁶³ was to explore probabilistic climate scenarios for Europe. Although major advances in the methodological approach were achieved within ENSEMBLES, the main limitation in producing climate scenarios for Europe is unchanged. The first and foremost reason for this is that the global models that provide boundary

conditions for regional climate modelling were essentially the same as already used in the regional climate modelling underlying the results assessed in AR4. The largest source of uncertainty in the regional projections for Europe is related to possible changes in atmospheric circulation as also pointed out in AR4. However, improved understanding of systematic behaviour of also systematic biases in regional climate model²⁶⁴ is important in narrowing model spread (i.e., to reduce such climate projection uncertainty as arises due to different models).

- The North American project NARCCAP²⁶⁵, which was reported upon briefly in AR4, but has since progressed considerably, is now performing new analyses on regional climate change projections for North America²⁶⁶.
- The East Asian project RMIP²⁶⁷ follows the same approach as the above-mentioned initiatives for Europe and North America, but for temperate East Asia.
- Finally, CORDEX: a new and very extensive COordinated Regional climate Downscaling EXperiment has recently been designed²⁶⁸. It aims to provide coordinated regional climate change information by means of both dynamical and statistical methods, not least for impact and adaptation studies. CORDEX is an international effort and plans to address many world regions. The first concentrated study region is the African continent.

Thus, over the next few years, a considerable amount of new advanced knowledge on the utility and projections of regional climate models is expected to emerge and be available, e.g., for AR5, the upcoming IPCC fifth Assessment Report due in 2013–2014.

9. Tipping points

So-called tipping points in the climate system can be thought of as "points of no return", when a relatively small additional forcing induces a larger or much faster change than due to earlier forcing. Already before this point, the occurred forcing that has taken place may have led to some gradual change. A tipping point marks a significant change in the response of the system in question, brought about by crossing a threshold in the system's resilience or its capacity to withstand forcing.

A tipping element is some part of the Earth system that has a tipping point (see Figure 14)²⁶⁹. The system change after passing a tipping point can be either "rapid" or "slow", and the change that ensues can be either permanent or potentially reversible²⁷⁰. These tipping points might in turn be related to key vulnerabilities in ecosystems and societies²⁷¹.

Figure 14. Possible major climate system tipping elements according to²⁶⁹ The background colour shows population density. (© Copyright 2008 National Academy of Sciences, U.S.A.)

Some potential climate system tipping points are:

- *Arctic summertime sea-ice.* As is discussed in Section 2.3, the extent of Arctic sea ice cover in summer 2007 was an all-time low for the period with satellite sea ice data (about the last 30 years). While the following summers did not show even larger reductions, a tipping might ensue when the gradual increase in the loss of summertime sea ice leaves less and less multi-year ice and thus preconditions the Arctic to even larger summertime ice losses²⁷². There is considerable debate within the literature regarding the existence of a tipping point in sea ice²⁷³
- *Greenland ice sheet (GIS).* Climate warming affects the mass balance (net accumulation and melt) of the GIS. At a certain amount of net melt, the GIS may pass a tipping point and continue to shrink, quite possibly irreversibly. This transition would take several centuries^{270,274}
- *West Antarctic ice sheet (WAIS)* is probably more sensitive to warming influences than other major parts of the Antarctic ice sheet. The WAIS is considered to be more resilient than the GIS, but there is paleoclimate evidence of destabilisation of the WAIS in warm epochs in the distant past
- *Atlantic meridional overturning circulation (MOC)* It has been known for some time that the large-scale North Atlantic overturning circulation can have circulation regimes where deep water forms in the northern part of the basin, and other regimes where such deep water formation is shut off or shifted elsewhere. Alterations between such circulation states may have been responsible for some of the millennial-scale climate variability that has been inferred from the Greenland ice cores. In past decades, this circulation has been considered to be driven by temperature (“thermo”) and salinity (“haline”) differences, and is referred to as thermohaline circulation. More recent research has shown that due to low vertical mixing in the ocean, wind forcing in the Atlantic probably plays a bigger part in driving this circulation (sometimes referred to as the conveyor belt) than previously thought. Nevertheless, if the surface waters in the deep-water formation regions around Greenland warm up and/or freshen sufficiently, deep water formation may be reduced²⁷⁴. A dramatic change is considered rather unlikely, but many climate models (AR4) do project some slowdown as global warming progresses
- *Indian summer monsoon (ISM).* During the last glacial period, the ISM exhibited rapid variability. During recent years, it may have been affected by the so-called atmospheric brown cloud (massive regional air pollution) over the Indian sub-continent and the Indian Ocean²⁷⁵. The soot particles in this cloud originate from human activities. Its presence reduces the seasonal land-ocean temperature difference

which is a crucial driver of the ISM. In some model simulations the brown cloud can lead to more frequent droughts. As a tipping point this one is reversible, since its origins can be traced to particulate pollution

- *Sahara/Sahel and the West African monsoon (WAM)*. Following the termination of the last glacial period, the Sahara/Sahel region was far greener than today. This is thought to have been the result of slight differences in the seasonal cycle of insolation (roughly speaking, solar heating) which varies over longer time scales due to changes in orbital factors and the inclination of the Earth's axis. However, the collapse of regional vegetation around 5000 years ago occurred faster than the orbital forcing changed. The reason could be vegetation feedback²⁷⁶. Nevertheless, this system is highly dependent on WAM circulation. In some climate model simulations for the 21st century, changes are brought about that lead to a wetting of parts of the Sahel^{277, 278}. The ensuing greening would be a rare example of a “beneficial” tipping element
- *Amazon rainforest*. The precipitation climate of the Amazon basin is sensitive to deforestation, and the ecosystems to precipitation. Increased frequency of droughts and overall warming in the course of climate change could lead to an almost irreversible reduction in forest cover. There is considerable uncertainty as to the likelihood of this²⁷⁹, as there is a complex interplay between land use, local precipitation and large scale climate change

There are yet other tipping elements, such as methane hydrates in various parts of the global ocean floor. Oceanic warming could destabilise these, thus leading to a release of methane²⁸⁰. The timescale associated with this is long²⁸¹, perhaps thousands of years. However, as methane is a potent greenhouse gas, such an event would continue climate forcing, even well after the anthropogenic emissions of greenhouse gases are cut. Similarly, possible methane release from thawing permafrost²⁸² is a candidate for a tipping element (see Section 7.2.2).

The likelihood of when (i.e. at which amount of climate forcing) these various tipping points may be encountered is largely unknown. Probability estimates based on subjective expert assessments of some of these tipping elements have been reported²⁸³ as ranging from less than 10% when warming is contained below 2°C, up to more than 50% if the warming exceeds 4°C. However, the spread of expert assessments is quite large, emphasizing the large uncertainties in these estimates.

10. Science of stabilisation

Climate science underlies the societal response to climate change, including mitigation and adaptation. Whereas many of the related aspects concern social and technical sciences, important fundamental physical climate science aspects are of course relevant as well. Projections of climate change can clarify adaptation needs and challenges, as well as what mitigation actions would need to be pursued politically in order to achieve goals for reducing anthropogenic climate forcing and stabilising the climate. The central physical climate science issues herein relate to climate system sensitivity (how will the climate change as a response to forcing, see Section 7), inertia in the climate system (how fast does the climate system react to emission changes, including reductions), Earth system feedback (changing carbon cycle as a response to climate change, see Section 7) that might reduce the “allowable emission space”, etc.

While climate science cannot prescribe decision, it may provide relevant information to support policy. Often, however, there is a gap between the nature of the science output and stakeholders’ needs. Science can be made more accessible, for example by assessing available results in terms of policy-related issues, such as proposed climate stabilisation targets.

Recent research on these issues is discussed below. In some cases, the highlighted literature overlaps mitigation issues that fall outside the core physical climate sciences aspects.

10.1 Climate stabilisation targets

By climate stabilisation we refer to developments that keep the atmospheric concentration of greenhouse gases from increasing above some specific level and/or limit global mean warming due to anthropogenic forcing to some set amount. These two metrics are related, but there are uncertainties in terms of how they map to each other (cf. climate sensitivity). Furthermore, the same is true for the relationship between emissions and atmospheric concentrations (cf. carbon cycle feedback). Another, albeit shorter-term, issue is the increasing need to reduce emissions of greenhouse gases and soot when emissions of the precursor gases of atmospheric particles with a negative radiative forcing effect are reduced²⁸⁴. As the latter exert some cooling influence, their removal leads to net warming, unless there are compensating reductions in the greenhouse gas and soot emissions^{132,133}.

An important constraint is how fast the climate system reacts to forcing, and how long the effect persists in the climate system (cf. “overshooting” or “peaking” emission pathways²⁸⁵). On the one hand, if emissions were re-

duced immediately to zero, atmospheric concentrations of greenhouse gases would start to decline slowly, so allowing us to avoid a long-term warming corresponding to peak concentration levels²⁸⁶. On the other hand, a significant fraction of past and future carbon dioxide emissions are nevertheless expected to stay in the atmosphere for several hundred years. Therefore, when considering the long-term climate change commitment, the cumulative amount of emissions is more important than their precise distribution over time^{287,288}. This, however, does not mean that other formulations of emission targets, such as sectorial targets or targets for different time periods, are not useful to guide climate change mitigation²⁸⁹.

A positive climate-carbon feedback affects the “allowable emission space”, in the sense that when targeting some atmospheric stabilisation level, or a temperature target, the compounded emissions must be smaller than otherwise.

In broad terms, recent research that attempts to capture the effects of climate-carbon feedback associates the so-called 2-degree climate target to around 1000 GtC total cumulative CO₂ emissions or less^{290,291,288}. As the cumulative anthropogenic emissions hitherto, including those from land use change, are around 500 GtC, the implication is that the remaining CO₂ emission space is largely comparable to the cumulative historical emissions. A closer quantification depends, among other things, on the desired likelihood of staying below the 2-degree target. Furthermore, while the future warming is likely dominated by CO₂ emissions, aerosol cooling effects and the warming effect of other greenhouse gases also need to be considered^{288,291}. Finally, other climate stabilisation targets of course imply other cumulative and remaining emission amounts.

In addition to implied constraints to the cumulative emissions, another implication is that the timing of the global emission peak and the speed of the subsequent emission reduction rates are related. A delay in the peak emissions implies a need of faster emission reduction rates later on.

10.2 Climate change commitment

According to AR4, had the atmospheric concentration of greenhouse gases stabilised at the level attained in 2000, there would still have been a continued global mean warming of around 0.3–0.9°C by the end of this century. This results from climate system inertia, i.e., it takes time for the climate system to respond fully to forcing²⁹². The measure of this lingering effect is called the climate change commitment. This of course implies that even after the atmospheric concentration of greenhouse gases is stabilised, there will still be some further climate change to come thereafter.

The uncertainty surrounding the climate effects of aerosols (see Section 5.2) is an important complication in assessing the climate change commitment. Should the negative aerosol radiative forcing be larger than in many

earlier estimates^{293,294}, it would imply that those studies of climate sensitivity that are based on the instrumental data period assume a too small an aerosol cooling effect and, consequently, underestimate the greenhouse gas warming effect and thus climate sensitivity. This, in turn, would imply that current climate change projections would tend to underestimate the future warming due to historical, as well as continued, greenhouse gas emissions.

The climate impact commitment, like the climate change commitment, is probably quite incompletely measured in terms of the global mean temperature. Impacts, such as on ecosystems, also host inertia in their responses, which means that climate impacts continue beyond climate stabilisation²⁹⁵.

In terms of policy-relevance, aspects like ocean acidification and tipping points might well fall under the range of aspects that could be evaluated when defining Dangerous Anthropogenic Interference (DAI) with the climate system, as referred to in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC)^{271,296}.

As such, the likelihood that we approach tipping points at least qualitatively increases with climate change, i.e. with distance to the present-day climate. Increased risks in this area in turn represent a particular climate change commitment aspect that has not been thoroughly explored in policy.

As yet, science can give us at best broad quantitative estimates of the long-term consequences of anthropogenic greenhouse gas emissions. The relatively slow progress on some key fronts such as climate sensitivity (Section 7) suggests that this scientific uncertainty may not come to be reduced in the near future. On the other hand, the qualitative understanding of time lags in the climate system already is already quite robust. This tells us that if the goal is to stabilise the climate at some given level, emissions need to be reduced well before their full effects on the climate and the Earth system are with us.

Sammanfattning

Sedan IPCC AR4 2007 har klimatvetenskapen gjort fortsatta framsteg i över tre års tid. Detta visar sig i antalet nya vetenskapliga uppsatser, men också i utvecklingen för forskningsagendan. På det hela taget verkar den klimatforskningen, enligt den bedömning som gjordes av IPCC:s arbetsgrupp I i AR4, stå stadigt även i ljuset av nyare forskning. Kunskapsbasen utvecklas naturligtvis fortlöpande. Det har exempelvis skett framsteg inom forskningsfrågor som havsförurning och jordsystemåterkopplingar, till exempel mellan klimatet och geobiosfären.

Några av de viktigaste slutsatserna som dras i den senaste litteraturen är bland annat följande:

- Tecknen på pågående klimatförändringar är uppenbara. Uppvärmningen under de senaste åren har inte varit så kraftig som under de omedelbart föregående åren, men detta faller inom ramen för förväntade kortsiktiga variationer på grund av till exempel interna variationer i klimatsystemet
- Den globala havsnivån fortsätter att stiga. Nyligen gjorda uppskattningar av den framtida höjningen av havsnivån visar på värden i den övre delen och till och med bortom av AR4-spannet. På grund av att det alltså finns begränsningar med modelleringen av dynamiken i istäcket är många av dessa nyare studier baserade på semiempirisk modellering eller slutsatser från klimatvariationer långt tillbaka i tiden
- Havsisminimum i Ishavet sommaren 2007 åtföljdes inte av ännu lägre siffror, men den långsiktiga trendens natur är oförändrad och går i riktning mot en fortsatt minskning av havsisens utbredning
- Delar av istäcket på Grönland har visat på en snabb avsmältning de senaste åren. Man har inte kunnat bevisa huruvida det är fråga om tillfälliga företeelser eller ett tecken på en accelererande trend. Istäcket i Antarktis håller också på att minska i massa enligt mätningar
- Det så kallade andra koldioxidproblemet, havsförurning, är ett ämne som det forskas om i allt högre grad. Medan ökningen av surhetsgraden i havsvattnet är ganska enkel att kvantifiera vid en given ökning av koldioxidnivåerna i atmosfären är påverkan på de marina systemen oklar
- Det finns inga starka belägg på större förändringar i de tropiska cyklonernas beteende som en följd av den globala uppvärmningen, även om en viss gradvis intensifiering av de starkaste cyklonerna är möjlig vid en fortsatt global uppvärmning

- Efter ganska många år av avsaknad av betydande förändringar i koncentrationen av metan i atmosfären sedan tidigt 1990-tal, har man sett en förnyad ökning sedan 2007
- Solens 11-årscykelns påverkan på de globala temperaturerna är liten och även om det är möjligt att vi går in i en längre period av låg solaktivitet så kommer detta som bäst att tillfälligt bromsa in den framtida uppvärmningen. Hypotesen om galaktisk kosmisk strålning/moln/klimat förblir obevisad
- Det har varit svårt att tillskriva den uppvärmning i Arktis som observerats till antropogenisk klimatpåverkan på grund av den betydande naturliga variabiliteten i regionen. Sådan tillskrivning (attribution) görs nu i allt högre grad. Attributionsstudier har allmänt börjat få en mer småskalig fokus jämfört med tidigare globala eller kontinentala omfattning, såsom var fallet i AR4, och innehålla ett bredare spektrum av variabler utöver temperaturen. Man har nu även upptäckt uppvärmning över en del av det antarktiska istäcket
- Uppskattningarna av klimatkänsligheten är i stort sett oförändrade sedan AR4
- Koldioxidkoncentrationen kan öka mer vid en given mängd globala utsläpp än enligt tidigare bedömningar, i ljuset av nya studier av återkopplingar mellan klimatet och kolcykeln, och möjligheten att klimatförändringen minskar effektiviteten hos naturliga kolsänkor
- En positiv återkoppling mellan klimatet och kolcykeln minskar ett eventuellt ”tillåtet utsläppsutrymme”, i den mening att när man sätter upp ett mål för stabilisering av halterna i atmosfären, eller ett särskilt temperaturmål, måste de totala utsläppen vara lägre än om kolcykeln inte reagerade på klimatförändringar

References and notes

-
- ¹ IPCC 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change. Solomon, S., et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
- ² University of Copenhagen 2009. Synthesis Report from the International Congress Climate Change, Global Risks, Challenges & Decisions, 10–12 March 2009, Copenhagen. Richardson K. et al. (eds.) 39 pp.
- ³ The Copenhagen Diagnosis, 2009. Updating the world on the Latest Climate Science. I. Allison, et al. The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60pp.
- ⁴ Netherlands Environmental Assessment Agency, 2009. News in Climate Science and Exploring Boundaries. A Policy Brief on developments since the IPCC AR4 report in 2007. PBL publication number 500114013. 32 pp.
- ⁵ AMAP 2009. AMAP 2009 Update on Selected Climate Issues of Concern. Arctic Monitoring and Assessment Programme, Oslo. V+15 pp. ISBN 978-82-7971-049.3.
- ⁶ Rummukainen, M. and Källén, E. 2009. New Climate Science 2006–2009, Commission on Sustainable Development, Swedish Government Offices, 64 pp.
- ⁷ <http://www.amap.no/swipa/> (last read on 29 April, 2010)
- ⁸ AMAP 2009. The Greenland Ice Sheet in a Changing Climate: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2009. By: D. Dahl-Jensen, J., et al. Arctic Monitoring and Assessment Programme (AMAP), Oslo. 115 pp.
- ⁹ Brohan, P., et al. 2006. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophys. Res.* 111, D12106. Doi:10.1029/2005JD006548
- ¹⁰ Smith, T.M. and Reynolds, R.W. 2005. A Global Merged Land–Air–Sea Surface Temperature Reconstruction Based on Historical Observations (1880–1997). *J. Climate*, 18, 2021–2036.
- ¹¹ Hansen, J., et al. 2001. A closer look at United States and global surface temperature change. *J. Geophys. Res.*, 106, 23947–23963. Doi:10.1029/2001JD000354
- ¹² There are different versions of the GISS temperature series. The one used here (LOTI) is what is recommended on the GISS web pages, and is consistent with IPCC (2007). The “Copenhagen diagnosis” report (see Ref #3 above) shows another version with larger global warming during the past 10 years.
- ¹³ Meehl, G. A., et al., 2007. Global climate projections. In: *Climate Change 2007: the Physical Science Basis* (eds. S. Solomon, et al.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 747–845
- ¹⁴ Meehl, G.A, et al. 2007. The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. *Bull. Amer. Meteor. Soc.* 88, 1383–1394.
- ¹⁵ A reanalysis is a best estimate of the three-dimensional state of the atmosphere at a given point of time, given all available observations and the physics of climate as built in the equations of a weather prediction model.
- ¹⁶ Simmons, A.J., Willett, K.M. Jones, P.D., Thorne, P.W. and Dee, D. 2010. Low-frequency variations in surface atmospheric humidity, temperature and precipitation: Inferences from reanalyses and monthly gridded observational datasets. *J. Geophys. Res.*, 115, D01110. Doi:10.1029/2009JD012442
- ¹⁷ Lockwood, M. 2010. Solar change and climate: and update in the light of the current exceptional solar minimum. *Proc. R. Soc. A*, 466, 303–329. Doi: 10.1098/rspa.2009.0519.

-
- ¹⁸ Solomon, S., et al. 2010. Contributions of stratospheric water vapour to decadal changes in the rate of global warming. *Science*, 327, 1219–1223.
- ¹⁹ The simulations follow the SRES A1B emission scenario. This choice is unimportant here, as all SRES scenarios stay close to each other in the first decades of the 21st century.
- ²⁰ Easterling, D.R. and Wehner, M.F. 2009. Is the climate warming or cooling? *Geophys. Res. Lett.*, 36, L08706. Doi:10.1029/2009GL037810
- ²¹ Trenberth, K.E and Fasullo, J.T. 2010. Climate Change: Tracking Earth's Energy. *Science*, 328, 316–317. Doi:10.1126/science.1187272
- ²² Bindoff, N.L., et al. 2007. Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: the Physical Science Basis* (eds. Solomon, S. et al.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 385–432.
- ²³ Cazenave, A., et al. 2008. Present-day sea level rise: A synthesis. *Comptes Rendus Geoscience*, 340, 761–770.
- ²⁴ Leuliette, E.W. and Miller, L. 2009. Closing the sea level budget with altimetry, Argo and GRACE. *Geophys. Res. Lett.*, 36:L04608. Doi:10.1029/2008GL036010
- ²⁵ Velicogna, I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophys. Res. Lett.*, 36, L19503. Doi:10.1029/2009GL040222
- ²⁶ Chao, B.F., et al. 2008. Impact of artificial reservoir water impoundment on global sea level. *Science*, 320, 212–214.
- ²⁷ Domingues, C.M., et al. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature*, 453, 1090–1094. Doi:10.1038/nature07080
- ²⁸ Milne, G.A., et al. 2009. Identifying the causes of sea-level change. *Nature Geoscience*, 2, 471–478. Doi:10.1038/ngeo544
- ²⁹ Rahmstorf, S., et al. 2007. Recent climate observations compared to projections. *Science*, 316, 709.
- ³⁰ Vermeer, M. and Rahmstorf, S. 2009. Global sea level linked to global temperature. *Proc. Natl. Acad. Sci.*, 106, 21527–21532. Doi:10.1073/pnas.0907765106
- ³¹ Rahmstorf, S. 2007. A semiempirical approach to projecting future sea-level rise. *Science* 315, 368–370.
- ³² Rahmstorf, S. 2010. A new view on sea level rise. *Nature Reports Climate Change*. Published online: 6 April 2010. Doi:10.1038/climate.2010.29
- ³³ Grinsted, A., et al. 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100. *Clim. Dyn.*, 34, 461–472. Doi:10.1007/s00382-008-0507-2
- ³⁴ Pfeffer, W.T., et al. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, 321, 1340–1343. Doi:10.1126/science.1159099
- ³⁵ Jevrejeva, S., et al. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophys. Res. Lett.*, 37, L07703. Doi:10.1029/2010GL042947
- ³⁶ Kopp, R.E., et al. 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature*, 462, 863–867. Doi:10.1038/nature08686
- ³⁷ Overpeck, J.T and Weiss, J.L. 2009. Projections of future sea level becoming more dire. *Proc. Natl. Acad. Sci.*, 106, 21461–21462. Doi:10.1073/pnas.0912878107
- ³⁸ Lemke, P., et al. 2007. Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007: the Physical Science Basis* (eds. Solomon, S., et al.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp 338–383.
- ³⁹ Comiso, J.C., et al. 2008. Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.*, 35, L01703. Doi:10.1029/2007GL031972
- ⁴⁰ Stroeve, J., et al. 2008. Arctic sea ice extent plummets in 2007. *Eos, Trans. Amer. Geophys. Union*, 89, 13.
- ⁴¹ Perovich, D.K., et al. 2008. Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007. *Geophys. Res. Lett.*, 35, L11501. Doi:10.1029/2008GL034007
- ⁴² Drobot, S., et al. 2008. Evolution of the 2007–2008 Arctic sea ice cover and prospects for a new record in 2008. *Geophys. Res. Lett.*, 35, L19501. Doi:10.1029/2008GL035316

-
- ⁴³ Stroeve, J., et al. 2007. Arctic sea ice decline: Faster than forecast. *Geophys. Res. Lett.*, 34, L09591. Doi:10.1029/2007GL029703
- ⁴⁴ Eisenman, I. and Wettlaufer, J.S. 2009. Nonlinear threshold behavior during the loss of Arctic sea ice. *Proc. Natl. Acad. Sci.*, 106, 28–32. Doi:10.1073/pnas.0806887106
- ⁴⁵ Serreze, M.C., et al. 2007. Perspectives on the Arctic's shrinking sea-ice cover. *Science*, 315, 1533–1536.
- ⁴⁶ Boé, J., et al. 2009. September sea-ice cover in the Arctic Ocean projected to vanish by 2100. *Nature Geoscience*, 2, 341–343. Doi:10.1038/ngeo467
- ⁴⁷ Chen, J.L., et al. 2009. Accelerated Antarctic ice loss from satellite gravity measurements. *Nature Geoscience*, 2, 859–862. Doi:10.1038/ngeo694
- ⁴⁸ Wouters, B., et al. 2008. GRACE observes small-scale mass loss in Greenland. *Geophys. Res. Lett.*, 35, L20501. Doi:10.1029/2008GL034816
- ⁴⁹ Vaughan, D. 2008. West Antarctic Ice Sheet collapse – the fall and rise of a paradigm. *Clim. Change* 91:1–2, 65–79. Doi:10.1007/s10584-008-9448-3
- ⁵⁰ Pritchard, H.D. et al. 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, 461, 971–975. Doi:10.1038/nature08471
- ⁵¹ Pritchard, H.D. and Vaughan, D.G. 2007. Widespread acceleration of tide water glaciers on the Antarctic Peninsula. *J. Geophys. Res.*, 112, F03S29. Doi:10.1029/2006JF000597
- ⁵² Stearns, L.A. and Hamilton, G.S. 2007. Rapid volume loss from two East Greenland outlet glaciers quantified using repeat stereo satellite imagery, *Geophys. Res. Lett.*, 34, L05503. Doi:10.1029/2006GL028982
- ⁵³ Dietrich, R., et al. 2007. Jakobshavn Isbræ, West Greenland: Flow velocities and tidal interaction of the front area from 2004 field observations. *J. Geophys. Res.*, 112, F03S21. Doi:10.1029/2006JF000601
- ⁵⁴ Holland D.M., et al. 2008. Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geoscience*, 1, 659–664. Doi:10.1038/ngeo316
- ⁵⁵ Zwally, H.J., et al. 2002. Surface melt-induced acceleration of Greenland Ice-Sheet flow. *Science*, 297, 218–222. Doi:10.1126/science.1072708
- ⁵⁶ Joughin, I., et al. 2008. Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science*, 320, 781–783.
- ⁵⁷ Nick, F.M., et al. 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience*, 2, 110–114. Doi:10.1038/ngeo394
- ⁵⁸ Meier, F.M., et al. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, 317, 1064–1067.
- ⁵⁹ Raupach, M.R., et al. 2008. Anthropogenic and biophysical contributions to increasing atmospheric CO₂ growth rate and airborne fraction. *Biogeosciences*, 5, 1601–1613.
- ⁶⁰ Doney, C., et al. 2009. Ocean acidification: the other CO₂ problem. *Annu. Rev. Mar. Sci.*, 1, 169–192. Doi:10.1146/annurev.marine.010908.163834
- ⁶¹ Hoegh-Guldberg, O., et al. 2007. Coral reefs under rapid climate change and ocean acidification. *Science*, 318, 1737–1742.
- ⁶² Silverman, J., et al. 2009. Coral reefs may start dissolving when atmospheric CO₂ doubles. *Geophys. Res. Lett.*, 36, L05606. Doi:10.1029/2008GL036282
- ⁶³ Cao, L. and Kaldeira, K. 2008. Atmospheric CO₂ stabilization and ocean acidification. *Geophys. Res. Lett.*, 35, L19609. Doi:10.1029/2008GL035072
- ⁶⁴ Mcneil, B.I. and Matear, R.J. 2007. Climate change feedbacks on future oceanic acidification. *Tellus*, 59B, 191–198. Doi:10.1111/j.1600-0889.2006.00241.x
- ⁶⁵ Cao, L., et al. 2007. Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophys. Res. Lett.*, 34, L05607. Doi:10.1029/2006GL028605
- ⁶⁶ Goodwin, P., et al. 2009. Climate sensitivity to the carbon cycle modulated by past and future changes in ocean chemistry. *Nature Geoscience*, 2, 145–150. Doi:10.1038/ngeo416
- ⁶⁷ Tjiputra, J.F., et al. 2010. Bergen Earth system model (BCM-C): model description and regional climate-carbon cycle feedbacks assessment. *Geosci. Model Dev.*, 3, 123–141.
- ⁶⁸ Peck, L.S., et al. 2009. Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. *Global Change Biology*. Doi:10.1111/j.1365-2486.200902071.x

-
- ⁶⁹ Goodwin, P. and Lenton, T.M. 2009. Quantifying the feedback between ocean heating and CO₂ solubility as an equivalent carbon emission. *Geophys. Res. Lett.*, 36, L15609. Doi:10.1029/2009GL039247
- ⁷⁰ Schuster, U. and Watson, A.J. 2007. A variable and decreasing sink for atmospheric CO₂ in the North Atlantic. *J. Geophys. Res.*, 112, C11006. Doi:10.1029/2006JC003941
- ⁷¹ Jones, G.S., et al. 2008. Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers. *J. Geophys. Res.*, 113, D02109. Doi:10.1029/2007JD008914
- ⁷² García-Herrera, R., et al. 2010. A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40, 267–306.
- ⁷³ Kysely, J. 2009. Recent severe heat waves in Central Europe: how to view them in a long-term prospect? *Int. J. Climatol.*, 30, 89–109. Doi:10.1002/joc.1874
- ⁷⁴ Seneviratne, S.I., et al. 2006. Land-atmosphere coupling and climate change in Europe. *Nature*, 443, 205–209. Doi:10.1038/nature05095
- ⁷⁵ Jones, G.S., et al. 2008. Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers. *J. Geophys. Res.*, 113, D02109. Doi:10.1029/2007JD008914
- ⁷⁶ Weisheimer, A. and Palmer, T.N. 2005. Changing frequency of occurrence of extreme seasonal temperatures under global warming. *Geophys. Res. Lett.*, 32, L20721. Doi:10.1029/2005GL023365
- ⁷⁷ Kjellström, E., et al. 2007. Modelling temperature extremes: recent climate and future changes over Europe. *Clim. Change*, 81:Supplement 1, 249–265. Doi:10.1007/s10584-006-9220-5
- ⁷⁸ Sterl, A., et al. 2008. When can we expect extremely high surface temperatures? *Geophys. Res. Lett.*, 35, L14703. Doi:10.1029/2008GL034071
- ⁷⁹ Kharin, V.V., et al. 2007. Changes in temperature and precipitation extremes in the IPCC ensembles of global coupled model simulations. *J. Climate*, 20, 1419–1444. Doi:10.1175/JCLI4066.1
- ⁸⁰ Held, I.M. and Soden, B.J. 2006. Robust responses of the hydrological cycle to global warming. *J. Climate*, 19, 5686–5699.
- ⁸¹ Wentz, F.J., et al. 2007. How much more rain will global warming bring? *Science*, 317, 233–235.
- ⁸² Gorman, P.A. and Schneider, T. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proc. Natl. Acad. Sci.*, 106:35, 14773–14777. Doi:10.1073/pnas.0907610106
- ⁸³ Sugiyama, M., et al. 2010. Precipitation extreme changes exceeding moisture content increases in MIROC and IPCC climate models. *Proc. Natl. Acad. Sci.*, 107:2, 571–575. Doi 10.1073/pnas.0903186107
- ⁸⁴ Pall, P., et al. 2007. Testing the Clausius-Clapeyron constraint on changes in extreme precipitation under CO₂ warming. *Clim. Dyn.*, 28, 351–363. Doi:10.1007/s00382-006-0180-2
- ⁸⁵ Lenderink, G. and van Meijgaard, E. 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, 1, 511–514. Doi:10.1038/ngeo262
- ⁸⁶ Seager, R., et al. 2007. Model projections of an imminent transition to a more arid climate in Southwestern North America. *Science*, 316, 1181–1184.
- ⁸⁷ Rauscher, S.A., et al. 2008. Extension and intensification of the Meso-American mid-summer drought in the twenty-first century. *Clim. Dyn.*, 31, 551–571. Doi:10.1007/s00382-007-0359-1
- ⁸⁸ Knutson, T.R., et al. 2010. Tropical cyclones and climate change. *Nature Geoscience*, 3, 157–163. Doi:10.1038/ngeo779
- ⁸⁹ Chen, G. and Tam, C.-Y. 2010. Different impacts of two kinds of Pacific Ocean warming on tropical cyclone frequency over the western North Pacific. *Geophys. Res. Lett.*, 37, L01803. Doi:10.1029/2009GL041708
- ⁹⁰ Vecchi, G.A., et al. 2008. Whither hurricane activity. *Science*, 322, 687–689.

-
- ⁹¹ Saunders, M.A. and Lea, A.S. 2008. Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature*, 451, 557–560. Doi:10.1038/nature06422
- ⁹² Enfield, D.B. and Cid-Serrano, L. 2010. Secular and multidecadal warmings in the North Atlantic and their relationships with major hurricane activity. *International Journal of Climatology*, 30, 174–184. Doi:10.1002/joc.1881
- ⁹³ Mann, M.E., et al. 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature*, 460, 880–883. Doi:10.1038/nature08219
- ⁹⁴ Löptien, U., et al. 2008. Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. *Clim Dyn.*, 31, 507–532. Doi:10.1007/s00382-007-0355-5
- ⁹⁵ Bengtsson, L., et al. 2009. Will extratropical storms intensify in a warmer climate? *J. Climate*, 22, 2276–2301. Doi:10.1175/2008JCLI2678.1
- ⁹⁶ Yin, J.H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st Century Climate. *Geophys. Res. Lett.*, 32, L18701. Doi:10.1029/2005GL023684
- ⁹⁷ Gastienau, G. and Soden, B.J. 2009. Model projected changes of extreme wind events in response to global warming. *Geophys. Res. Lett.*, 36, L10810. Doi:10.1029/2009GL037500
- ⁹⁸ Salathé Jr, E.P. 2006. Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming. *Geophys. Res. Lett.*, 33, L19820. Doi:10.1029/2006GL026882
- ⁹⁹ Jiang, J. and Perrie, W. 2008. Climate change effects on North Atlantic cyclones. *J. Geophys. Res.*, 113, D09102. Doi:10.1029/2007JD008749
- ¹⁰⁰ Woth, K., et al. 2006. Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. *Ocean Dyn.*, 56, 3–15. Doi:10.1007/s10236-005-0024-3
- ¹⁰¹ Pryor, S.C., et al. 2006. Winds of change?: Projections of near-surface winds under climate change scenarios. *Geophys. Res. Lett.*, 33, L11702. Doi:10.1029/2006GL026000
- ¹⁰² Bowman, D.M.J.S., et al. 2009. Fire in the Earth System. *Science*, 324, 481–484.
- ¹⁰³ Le Quéré, C., et al. 2009. Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2, 831–836. Doi:10.1038/ngeo689
- ¹⁰⁴ Nakicenovic, N., et al. 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp.
- ¹⁰⁵ Rigby, M., et al. 2008. Renewed growth of atmospheric methane, *Geophys. Res. Lett.*, 35, L22805. Doi:10.1029/2008GL036037
- ¹⁰⁶ Dlugokencky, E.J., et al. 2009. Observational constraints on recent increases in the atmospheric CH₄ burden, *Geophys. Res. Lett.*, 36, L18803. Doi:10.1029/2009GL039780
- ¹⁰⁷ Carslaw, K.S., et al. 2010. A review of natural aerosol interactions and feedbacks within the Earth system. *Atmos. Chem. Phys.*, 10, 1701–1737. Doi:10.5194/acp-10-1701-2010
- ¹⁰⁸ Allen, R.J. and Sherwood, S.C. 2010. Aerosol-cloud semi-direct effect and land-sea temperature contrast in a GCM. *Geophys. Res. Lett.*, 37, L07702. Doi:10.1029/2010GL042759
- ¹⁰⁹ Murphy, D.M., et al. 2009. An observationally based energy balance for the Earth since 1950. *J. Geophys. Res.*, 114, D17107. Doi:10.1029/2009JD012105
- ¹¹⁰ Vautard, R., et al. 2009. Decline of fog, mist and haze in Europe over the past 30 years. *Nature Geoscience*, 2, 115–119. Doi:10.1038/ngeo414
- ¹¹¹ Gong, S.L., et al. 2010. Identification of trends and interannual variability of sulphate and black carbon in the Canadian High Arctic: 1981–2007. *J. Geophys. Res.*, 115, D07305. Doi:10.1029/2009JD012943
- ¹¹² Ramanathan, V., et al. 2007. Warming trends in Asia amplified by brown cloud solar absorption. *Nature*, 448, 575–578. Doi:10.1038/nature06019
- ¹¹³ Kumari, B.P. and Goswami, B.M. 2010. Seminal role of clouds on solar dimming over the Indian monsoon region. *Geophys. Res. Lett.*, 37, L06703. Doi:10.1029/2009GL042133

-
- ¹¹⁴ Streets, D.G., et al. 2006. Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. *Geophys. Res. Lett.*, 33:L15806. Doi:10.1029/2006GL026471
- ¹¹⁵ Wang, K., et al. 2009. Clear sky visibility has decreased over land globally from 1973 to 2007. *Science*, 323, 1468–1470.
- ¹¹⁶ Mischchenko, M.I., et al. 2007. Long-term satellite record reveals likely recent aerosol trend. *Science*, 315, 1543.
- ¹¹⁷ Gustafsson, Ö., et al. 2009. Brown Clouds over South Asia: Biomass or Fossil Fuel Combustion? *Science*, 323, 495–498.
- ¹¹⁸ Ramanathan, V. and Carmichael, G. 2008. Global and regional climate changes due to black carbon. *Nature Geoscience*, 1, 221–227. Doi:10.1038/ngeo156
- ¹¹⁹ Koch, D., et al. 2009. Evaluation of black carbon estimations in global aerosol models. *Atmos. Chem. Phys.*, 9, 9001–9026.
- ¹²⁰ Rypdal, K., et al. 2009. Costs and implications of black carbon abatement strategies. *Tellus*, 61B, 625–641. Doi:10.1111/j.1600-0889.2009.00430.x
- ¹²¹ Reddy, M.S. and Boucher, O. 2007. Climate impact of black carbon emitted from energy consumption in the world's regions. *Geophys. Res. Lett.*, 34, L11802. Doi:10.1029/2006GL028904
- ¹²² Bond, T.C. and Sun, H. 2005. Can reducing black carbon emissions counteract global warming? *Environ. Sci. Technol.*, 39:16, 5921–5926.
- ¹²³ Shindell, D. 2007. Local and remote contributions to Arctic warming. *Geophys. Res. Lett.*, 34, L14704. Doi:10.1029/2007GL030221
- ¹²⁴ Shindell, D. and Faluvegi, G. 2009. Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience*, 2, 294–300. Doi:10.1038/ngeo473
- ¹²⁵ Flanner, M.G., et al. 2009. Springtime warming and reduced snow cover from carbonaceous particles. *Atm. Chem. Phys.*, 9, 2481–2497.
- ¹²⁶ Jimenez, J.L., et al. 2009. Evolution of organic aerosols in the atmosphere. *Science*, 326, 1525–1529.
- ¹²⁷ Hallquist, M., et al. 2009. The formation, properties and impact of secondary organic aerosol: current and emerging issues. *Atmos. Chem. Phys.*, 9, 5155–5236.
- ¹²⁸ Kiendler-Scharr, A., et al. 2009. New particle formation in forests inhibited by isoprene emissions. *Nature*, 461, 381–384. Doi:10.1038/nature08292
- ¹²⁹ Arneth, A., et al. 2007. CO₂ inhibition of global terrestrial isoprene emissions: Potential implications for atmospheric chemistry. *Geophys. Res. Lett.*, 34, L18813. Doi:10.1029/2007GL030615
- ¹³⁰ Rosenfield, D., et al. 2008. Flood or drought: How do aerosols affect precipitation? *Science*, 321, 1309–1313.
- ¹³¹ Stevens, B. and Feingold, G. 2009. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature*, 461, 607–613. Doi:10.1038/nature08281
- ¹³² Ramanathan, V. and Feng, Y. 2008. On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proc. Natl. Aca. Sci.*, 105, 14245–14250. Doi:10.1073/pnas.0803838105
- ¹³³ Raes, F. and Seinfeld, J.H. 2009. New directions: Climate change and air pollution abatement: A bumpy road. *Atmos. Env.*, 43, 5123–5133.
- ¹³⁴ Cox, P.M., et al. 2008. Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature*, 453, 212–215. Doi:10.1038/nature06960
- ¹³⁵ Kirkevåg, A., et al. 2008. On the additivity of climate response to anthropogenic aerosols and CO₂, and the enhancement of future global warming by carbonaceous aerosols. *Tellus*, 60A, 513–527. Doi:10.1111/j.1600-0870.2008.00308.x
- ¹³⁶ Schulze, E.D., et al. 2009. Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. *Nature Geoscience*, 2, 842–850. Doi: 10.1038/ngeo686
- ¹³⁷ Parish, F., et al. (eds.) 2008. *Assessment on Peatlands, Biodiversity and Climate Change: Main report*. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen. 179 pp + front matter. ISBN 978-983-43751-0-2
- ¹³⁸ Strassman, K.M., et al. 2008. Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric CO₂ increases and future commitments due to losses

-
- of terrestrial sink capacity. *Tellus*, 60B, 583–603. Doi:10.1111/j.1600-0889.2008.00340.x
- ¹³⁹ Pongratz, J., et al. 2010. Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change. *Geophys. Res. Lett.*, 37, L08702. Doi:10.1029/2010GL043010
- ¹⁴⁰ Betts, R.A., et al. 2007. Biophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change. *Agricultural and Forest Meteorology*, 142, 216–233. Doi:10.1016/j.agrformet.2006.08.021
- ¹⁴¹ Findell, K.L., et al. 2007. Modeled impact of anthropogenic land cover change on climate. *J. Climate*, 20, 3621–3634. Doi:10.1175/JCLI4185.1
- ¹⁴² Pielke, R.A. Sr, et al. 2007. An overview of regional land-use and land-cover impacts on rainfall. *Tellus* 59B, 587–601. Doi:10.1111/j.1600-0889.2007.00251.x
- ¹⁴³ Pitman, A.J., et al. 2009. Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys. Res. Lett.*, 36, L14814. Doi:10.1029/2009GL039076
- ¹⁴⁴ Paeth, H., et al. 2009. Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. *J. Climate*, 22, 114–132. Doi:10.1175/2009JCLI3123.1
- ¹⁴⁵ Pitman, A.J., et al. 2009. Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys. Res. Lett.*, 36, L14814. Doi:10.1029/2009GL039076
- ¹⁴⁶ Feddema, J.J., et al. 2005. The Importance of Land-Cover Change in Simulating Future Climates. *Science*, 310, 1674–1678.
- ¹⁴⁷ Pitman, A.J., et al. 2009. Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys. Res. Lett.*, 36, L14814. Doi:10.1029/2009GL039076
- ¹⁴⁸ Swann, A.L., et al. 2010. Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proc. Natl. Acad. Sci.*, 107, 1295–1300. Doi:10.1073/pnas.0913846107
- ¹⁴⁹ Erlykin, A.D., et al. 2009. Solar activity and the mean global temperature. *Environ. Res. Lett.*, 4, 014006. Doi:10.1088/1748-9326/4/014006
- ¹⁵⁰ Camp, C.D. and Tung, K.K. 2007. Surface warming by the solar cycle as revealed by the composite mean difference projection. *Geophys. Res. Lett.*, 34, L14703. Doi:10.1029/2007GL030207
- ¹⁵¹ Lean, J.L., 2010. Cycles and trends in solar irradiance and climate. *WIRE Climate Change*, 1, 111–122. Doi:10.1002/wcc.018
- ¹⁵² Abreu, J.A., et al. 2008. For how long will the current grand maximum of solar activity persist? *Geophys. Res. Lett.*, 35, L20109. Doi:10.1029/2008GL035442
- ¹⁵³ de Jager, C. and Duhau, S. 2009. Forecasting the parameters of sunspot cycle 24 and beyond. *J. Atmos. Sol. Terr. Phys.* 71:2, 239–245. Doi:10.1016/j.jastp.2008.11.006
- ¹⁵⁴ Feulner, G. and Rahmstorf, S. 2010. On the effect of a new grand minimum of solar activity on the future climate on Earth. *Geophys. Res. Lett.*, 37, L05707. Doi:10.1029/2010GL042710
- ¹⁵⁵ Song, X., et al. 2010. Increased greenhouse gases enhance regional climate response to a Maunder Minimum. *Geophys. Res. Lett.*, 37, L01703. Doi:10.1029/2009GL041290
- ¹⁵⁶ Zhang, P., et al. 2008. A test of climate, sun and culture relationships from an 1810-year Chinese cave record. *Science*, 322, 940–942.
- ¹⁵⁷ Foukal, P., et al. 2006. Variations in solar luminosity and their effect on the Earth's climate. *Nature*, 443, 161–166. Doi:10.1038/nature05072
- ¹⁵⁸ Lockwood, M. and Frölich, C. 2007. Recently oppositely directed trends in solar climate forcing and the global mean surface air temperature. *Proc. R. Soc. A*, 1367–1385. Doi:10.1098/rspa.2007.1880
- ¹⁵⁹ Ammann, C.M., et al. 2007. Solar influence on climate during the past millennium: Results from transient simulations with the NCAR Climate System Model. *Proc. Nat. Aca. Sci.*, 104, 3713–3718. Doi:10.1073/pnas.0605064103

-
- ¹⁶⁰ Scafetta, N. and West, B.J. 2007. Phenomenological reconstructions of the solar signature in the Northern Hemisphere surface temperature records since 1600. *J. Geophys. Res.*, 112, D24S03. Doi:10.1029/2007JD008437
- ¹⁶¹ Benestad, R.E. and Schmidt, G.A. 2009. Solar trends and global warming. *J. Geophys. Res.*, 114, D14101. Doi:10.1029/2008JD011639
- ¹⁶² Lean, J.L., and Rind, D.H. 2009. How will Earth's surface temperature change in future decades? *Geophys. Res. Lett.*, 36, L15708. Doi:10.1029/2009GL038932
- ¹⁶³ Svensmark, H., et al. 2009. Cosmic ray decreases affect atmospheric aerosols and clouds. *Geophys. Res. Lett.*, 36, L15101. Doi:10.1029/2009GL038429
- ¹⁶⁴ Laken, B., et al. 2009. Cosmic ray decreases and changes in liquid water cloud fraction over oceans. *Geophys. Res. Lett.*, 36, L23803. Doi: 10.1029/2009GL040961
- ¹⁶⁵ Calogovic, J., et al. 2010. Sudden cosmic ray decreases: No change of global cloud cover. *Geophys. Res. Lett.*, 37, L03802. Doi:10.1029/2009/GL041327
- ¹⁶⁶ <http://cosmicrays oulu.fi/> (last read 7 May, 2010)
- ¹⁶⁷ Lockwood, M. 2008. Recent changes in solar outputs and the global mean surface temperature. III. Analysis of contributions to global mean air surface temperature rise, *Proc. Roy. Soc. A*, 464, 1387–1404. Doi:10.1098/rspa.2007.0348
- ¹⁶⁸ Pierce, J.R. and Adams, P.J. 2009. Can cosmic rays affect cloud condensation nuclei by altering new particle formation rates? *Geophys. Res. Lett.*, 36, L09820. Doi:10.1029/2009GL037946
- ¹⁶⁹ Kulmala, M., et al. 2010. Atmospheric data over a solar cycle: no connection between galactic cosmic rays and new particle formation. *Atmos. Chem. Phys.*, 10, 1885–1898.
- ¹⁷⁰ Sloan, T. and Wolfendale, A.D. 2008. Testing the proposed causal link between cosmic rays and cloud cover. *Environ. Res. Lett.* 3 (2008) 024001. Doi:10.1088/1748-9326/3/2/024001
- ¹⁷¹ Stott, P.A., et al. 2010. Detection and attribution of climate change: a regional perspective. *WIREs climate change*, 1, 192–211. Doi:10.1002/wcc.34
- ¹⁷² Gillett, N.P., et al. 2008. Attribution of polar warming to human influence. *Nature Geoscience*, 1, 750–754.
- ¹⁷³ Steig, E.J., et al. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature*, 457, 459–462. Doi:10.1038/nature07669
- ¹⁷⁴ Ogi, M., et al. 2008. Summer retreat of Arctic sea ice: role of summer winds. *Geophys. Res. Lett.*, 35, L24701. Doi:10.1029/2008GL035672
- ¹⁷⁵ Ogi, M., et al. 2010. Influence of winter and summer surface wind anomalies on summer Arctic sea ice extent. *Geophys. Res. Lett.*, 37, L07701. Doi:10.1029/2009GL042356
- ¹⁷⁶ Min, S.-K., et al. 2008. Human influence on Arctic sea ice detectable from early 1990s onwards. *Geophys. Res. Lett.*, 35, L21701. Doi:10.1029/2008GL035725
- ¹⁷⁷ Shindell, D. and Faluvegi, G. 2009. Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience*, 2, 294–300. Doi:10.1038/ngeo473
- ¹⁷⁸ Wu, Q. and Karoly, D.J. 2007. Implications of changes in the atmospheric circulation on the detection of regional surface air temperature trends. *Geophys. Res. Lett.*, 34, L08703. Doi:10.1029/2006GL028502
- ¹⁷⁹ Christidis, N., et al. 2009. Probabilistic estimates of recent changes in temperature: a multi-scale attribution analysis. *Clim. Dyn.*, Published online: 28 June 2009. Doi:10.1007/s00382-009-0615-7
- ¹⁸⁰ Lobell, D.B. and Bonfils, C. 2008. The effect of irrigation on regional temperatures: a spatial and temporal analysis of trends in California, 1934–2002. *J. Climate*, 21, 2063–2071. Doi:10.1175/2007JCLI1755.1
- ¹⁸¹ Wijffels, S.E., et al. 2008. Changing Expendable Bathythermograph Fall Rates and Their Impact on Estimates of Thermosteric Sea Level Rise. *J. Climate*, 21, 5657–5672. Doi:10.1175/2008JCLI2290.1
- ¹⁸² Palmer, M.D., et al. 2009. A new perspective on warming of the global oceans. *Geophys. Res. Lett.*, 36, L20709. Doi:10.1029/2009GL039491
- ¹⁸³ Willett, K.M., et al. 2007. Attribution of observed surface humidity changes to human influence. *Nature*, 449, 710–713. Doi:10.1038/nature06207

-
- ¹⁸⁴ Wentz, F.J., et al. 2007. How much more rain will global warming bring? *Science*, 317, 233–235.
- ¹⁸⁵ Liepert, B.G. and Previdi, M. 2009. Do models and observations disagree on the rain-fall response to global warming? *J. Climate*, 22, 3156–3166.
Doi:10.1175/2008JCLI2472.1
- ¹⁸⁶ Lambert, F.H. and Allen, M.R. 2009. Are changes in global precipitation constrained by the tropospheric energy budget? *J. Climate*, 23, 499–517.
Doi:10.1175/2008JCLI2135.1
- ¹⁸⁷ Zhang, X., et al. 2007. Detection of human influence on twentieth century precipitation trends. *Nature*, 448, 461–465. Doi:10.1038/nature06025
- ¹⁸⁸ Min, S.-K., et al. 2008. Human-induced Arctic moistening. *Science*, 320, 518–520.
- ¹⁸⁹ Hidalgo, H.G., et al. 2009. Detection and attribution of streamflow timing changes to climate change in western United States. *J. Climate*, 22, 3838–3855.
Doi:10.1175/2009JHM1095.1
- ¹⁹⁰ Barnett, T.P., et al. 2008. Human-induced changes in the hydrology of the western United States. *Science*, 319, 1080–1083.
- ¹⁹¹ Pierce, D.W., et al. 2008. Attribution of declining western US snowpacks to human effects. *J. Climate*, 22, 2124–2145. Doi:10.1175/2008JCLI2405.1
- ¹⁹² Jones, G.S., et al. 2008. Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers, *J. Geophys. Res.*, 113, D02109.
Doi:10.1029/2007JD008914
- ¹⁹³ Räisänen, J. and Ruokolainen, L. 2008. Ongoing global warming and local warm extremes: a case study of winter 2006–2007 in Helsinki, Finland. *Geophysica*, 44, 45–65.
- ¹⁹⁴ Knutson, T.R., et al. 2010. Tropical cyclones and climate change. *Nature Geoscience*, 3, 157–163.
- ¹⁹⁵ Santer, B.D., et al. 2006. Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proc. Natl. Acad. Sci.* 103, 905–913.
Doi:10.1073/pnas.0602861103
- ¹⁹⁶ Gillett, N.P., et al. 2008. Attribution of cyclogenesis region sea surface temperature change to anthropogenic influence. *Geophys. Res. Lett.*, 35, L09707.
Doi:10.1029/GLO33670
- ¹⁹⁷ Vecchi, G.A. and Soden, B.J. 2007. Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature*, 450, 1066–1070.
Doi:10.1038/nature06423
- ¹⁹⁸ Brönnimann, S., 2007. Impact of El Nino-Southern Oscillation on European Climate. *Rev. Geophysics*, 45, RG3003. Doi:10.1029/2006RG000199
- ¹⁹⁹ Bell, C.J., et al. 2009. Stratospheric communication of El Niño teleconnections to European winter. *J. Climate*, 22, 4083–4096. Doi:10.1175/2009JCLI2717.1
- ²⁰⁰ Thompson, D.W.J., et al. 2009. Identifying signatures of natural climate variability in time series of global-mean surface temperature: methodology and insights. *J. Climate*, 22, 6120–6141.
- ²⁰¹ NOAA’s preliminary analyses place the January–March 2010 global combined land and ocean surface temperature 0.66°C above the 20th century average, which is the fourth warmest January–March period in their global temperature analysis. (See NOAA State of the Climate, Global Analysis, March 2010, at <http://www.ncdc.noaa.gov/sotc/> Last read in 16 May. 2010.)
- ²⁰² A close relative of NAO is the Arctic Oscillation (AO, a.k.a. the Northern Annual Mode). In the Atlantic sector, the two modes have a similar structure. However, the AO extends to the northern North Pacific. There is scientific debate on whether AO or NAO represents a more fundamental characteristic of atmospheric dynamics (Ambaum, M.H.P., et al. 2001. Arctic Oscillation or North Atlantic Oscillation? *J. Climate*, 14, 3495–3507). As the time series of NAO and AO are closely correlated, their difference is not critical for the current discussion.
- ²⁰³ The NAO index may change sign several times during a single winter. A winter mean NAO index represents the average conditions during the whole winter.

-
- ²⁰⁴ Thompson, D.W.J., et al. 2000. Annular modes in the extratropical circulation. Part II: Trends. *J. Climate*, 13, 1018–1036.
- ²⁰⁵ Deser, C. and Phillips, A.S. 2009. Atmospheric Circulation Trends, 1950–2000: The Relative Roles of Sea Surface Temperature Forcing and Direct Atmospheric Radiative Forcing. *J. Climate*, 22, 396–413.
- ²⁰⁶ Gillett, N.P., et al. 2005. Detection of external influence on sea level pressure with a multi-model ensemble. *Geophys. Res. Lett.*, 32, L19714. Doi:10.1029/2005GL023640
- ²⁰⁷ Dima, M. and Lohmann, G. 2007. A hemispheric mechanism for the Atlantic multidecadal oscillation. *J. Climate*, 20, 2706–2719. Doi:10.1175/JCLI4174.1
- ²⁰⁸ Knight, J.R. 2009. The Atlantic multidecadal oscillation inferred from the forced climate response in coupled general circulation models. *J. Climate*, 22, 1610–1625. Doi:10.1175/2008JCLI2628.1
- ²⁰⁹ Sutton, R.T. and Hodson, L.R. 2005. Atlantic Ocean forcing of North American and European summer climate. *Science*, 309, 115–118.
- ²¹⁰ Knight, J.R., et al. 2006. Climate impacts of the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.*, 33, L17706. Doi:10.1029/2006GL026242
- ²¹¹ The Niño3.4 SST anomaly is an average over (5°S–5°N, 170°W–120°W). Data from <http://www.cpc.ncep.noaa.gov/data/indices/>
- The North Atlantic Oscillation index is defined here at the 500 hPa level applying the method described in Barnston, A.G. and Livezey, R.E. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.*, 115, 1083–1126. Data from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh
- The index represents the average sea surface temperature anomaly in the North Atlantic at 0°–70°N, calculated from time series that have been linearly detrended to (partly) filter out the effect of global climate change (Enfield, D.B., et al. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.*, 28, 2077–2080). Data from <http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data>.
- ²¹² Christensen, J.H., et al. 2007. Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- ²¹³ Hibbard, K.A., et al. 2007. A strategy for climate change stabilization experiments. *Eos. Trans. AGU*, 88:20. Doi:10.1029/2007EO200002
- ²¹⁴ Danabasoglu, G. and Gent, P.R. 2009. Equilibrium climate sensitivity: is it accurate to use a slab ocean model? *J. Climate*, 22, 2494–2499. Doi:10.1175/2008JCLI2596.1
- ²¹⁵ Chylek, P., et al. 2007. Limits on climate sensitivity derived from recent satellite and surface observations. *J. Geophys. Res.*, 112, D24S04. Doi 10.1029/2007JD008740
- ²¹⁶ Manabe, S. and Wetherald, R.T. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.*, 24, 241–259.
- ²¹⁷ Chylek, P. and Lohmann, U. 2008. Aerosol radiative forcing and climate sensitivity deduced from the Last Glacial Maximum to Holocene transition. *Geophys. Res. Lett.*, 35, L04804. Doi: 10.1029/2007GL032759
- ²¹⁸ Schwartz, S.E. 2007. Heat capacity, time constant and sensitivity of Earth's climate system. *J. Geophys. Res.*, 112, D24S05. Doi:10.1029/2007JD008746
- ²¹⁹ Knutti, R. and Hegerl, G.C. 2008. The equilibrium sensitivity of Earth's temperature to radiation changes. *Nature Geoscience*, 1, 735–743. Doi:10.1038/ngeo337
- ²²⁰ Köhler, P., et al. 2010. What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity. *Quaternary Science Reviews*, 29, 129–145.
- ²²¹ Roe, G.H. and Baker, M.B. 2007. Why is climate sensitivity so unpredictable? *Science*, 318, 629–632.
- ²²² Hansen, J., et al. 2008. Target atmospheric CO₂: Where should humanity aim? *Open Atmos. Sci. J.*, 2, 217–231. Doi:10.2174/1874282300802010217
- ²²³ Lunt, D.J., et al. 2010. Earth System sensitivity inferred from Pliocene modeling and data. *Nature Geoscience*, 3, 60–64. Doi:10.1038/ngeo706

-
- ²²⁴ Baker, M.B. and Roe, G.H. 2009. The Shape of Things to Come: Why Is Climate Change So Predictable? *J. Climate*, 22, 4574–4589. Doi:10.1175/2009JCLI2647.1
- ²²⁵ Santer, B.D., et al. 2007. Identification of human-induced changes in atmospheric moisture content. *Proc. Natl. Acad. Sci.* 104, 15248–15253. Doi: 10.1073/pnas.0702872104
- ²²⁶ Willett, K.M., et al. 2007. Attribution of observed surface humidity changes to human influence. *Nature* 449, 710–712. Doi:10.1038/nature06207
- ²²⁷ Dessler, A.E. and Wong, S. 2009. Estimates of the water vapour climate feedback during El Niño-Southern Oscillation. *J. Climate*, 22, 6404–6412. Doi:10.1175/2009JCLI3052.1
- ²²⁸ Dessler, A.E. et al. 2008. Water-vapour climate feedback inferred from climate fluctuations. *Geophys. Res. Lett.*, 35, L20704. Doi:10.1029/GL035333
- ²²⁹ Gettelman, A. and Fu, Q. 2008. Observed and Simulated Upper-Tropospheric Water Vapor Feedback. *J. Climate*, 21, 3282–3289. Doi:10.1175/2007JCLI2142.1
- ²³⁰ Chung, E.-S., et al. 2010. An assessment of climate feedback processes using satellite observations of clear-sky OLR. *Geophys. Res. Lett.*, 37, L02702. Doi:10.1029/2009GL041889
- ²³¹ Paltridge, G., et al. 2009. Trends in middle- and upperlevel tropospheric humidity from NCEP reanalysis data. *Theor. Appl. Climatol.*, 98:3–4, 351–359. Doi:10.1007/s00704-009-0117-x
- ²³² Karlsson, J., et al. 2008. Cloud radiative forcing of subtropical low level clouds in global models. *Clim. Dyn.*, 30, 779–788. Doi:10.1007/s00382-007-0322-1
- ²³³ Trenberth, K. and Fasullo, J.T., 2009. Global warming due to increasing absorbed solar radiation. *Geophys. Res. Lett.*, 36, L07706. Doi:10.1029/2009GL037527
- ²³⁴ Clement, A.C., et al. 2009. Observational and Model Evidence for Positive Low-Level Cloud Feedback. *Science*, 325, 460–464. Doi:10.1126/science.1171255
- ²³⁵ Lindzen, R., and Choi, Y.-S. 2009. On the determination of climate feedbacks from ERBE data. *Geophys. Res. Lett.*, 36, L16705. Doi:10.1029/2009GL039628
- ²³⁶ Trenberth, K.E., et al. 2010. Relationships between tropical sea surface temperature and top-of-atmosphere radiation. *Geophys. Res. Lett.*, 37, L03702. Doi:10.1029/2009GL042314.
- ²³⁷ Phillips, O.L., et al. 2009. Drought sensitivity of the Amazon rainforest. *Science*, 323, 1344–1347.
- ²³⁸ Cox, P. and Jones, C. 2008. Illuminating the modern dance of climate and CO₂. *Science*, 321, 1642–1644.
- ²³⁹ Frank, D.C., et al. Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature*, 463, 527–530. Doi:10.1038/nature08769
- ²⁴⁰ Matthews, H.D. and Keith, D.W. 2007. Carbon-cycle feedbacks increase the likelihood of a warmer future. *Geophys. Res. Lett.*, 34, L09702. Doi:10.1029/2006GL028685
- ²⁴¹ Heimann, M. and Reichstein, M. 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* 451, 289–292. Doi:10.1038/nature06591
- ²⁴² Piao, S., et al. 2008. Net carbon dioxide losses of northern ecosystems in response to autumn warming. *Nature* 451, 49–52. Doi:10.1038/nature06444
- ²⁴³ Sitch, S., et al. 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, 14, 2015–2039. Doi:10.1111/j.1365-2486.2008.01626.x
- ²⁴⁴ Sokolov, A.P., et al. 2008. Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. *J. Climate*, 21, 3776–3796. Doi:10.1175/2008JCLI1038.1
- ²⁴⁵ Zaehle, S., et al. 2010. Terrestrial nitrogen feedbacks may accelerate future climate change. *Geophys. Res. Lett.*, 37, L01401. Doi:10.1029/2009GL041345
- ²⁴⁶ Schuur, E.A.G., et al. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience*, 58:8, 701–714. Doi:10.1641/BS80807

-
- ²⁴⁷ Repo, M.E., et al. 2009. Large N₂O emissions from cryoturbated peat soil in tundra. *Nature Geoscience*, 2, 189–192. Doi:10.1038/ngeo434
- ²⁴⁸ Raes, F., et al. 2010. Atmospheric chemistry climate feedbacks. *J. Geophys. Res.*, in press. Doi:10.1029/2009JD013300
- ²⁴⁹ CMIP3 Publications list, available at http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php (last read 29 April 2010)
- ²⁵⁰ Taylor, K.E. 2009. A summary of the CMIP5 experiment design. (See http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html (last read 29 April 2010))
- ²⁵¹ Moss, R.H., et al. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463, 747–756. Doi:10.1038/nature08823
- ²⁵² Heines, K., et al. 2009. Decadal climate prediction (project GCEP). *Phil. Trans. R. Soc. A*, 367 925–937. Doi:10.1098/rsta.2008.0178
- ²⁵³ Hawkins, R. and Sutton, E. 2009. The potential to narrow uncertainty in regional climate predictions. *Bull. Am. Meteorol. Soc.*, 90, 1095–1107. Doi:10.1175/2009BAMS2607.1
- ²⁵⁴ Swanson, K.L. 2009. Long-term natural variability and 20th century climate change. *Proc. Natl. Acad. Sci.*, 106, 16120–16123. Doi:10.1073/pnas.0908699106
- ²⁵⁵ Chen, D. and Cane, M.A. 2008. El Niño prediction and predictability. *Journal of Computational Physics*, 227, 3625–3640. Doi:10.1016/j.jcp.2007.05.014
- ²⁵⁶ Chen, D., et al. 2004. Predictability of El Niño over the past 148 years. *Nature*, 428, 733–736. Doi:10.1038/nature02439
- ²⁵⁷ Diaz, H.F., et al. 2001. ENSO variability, teleconnections, and climate change. *Int. J. Climatol.*, 21, 1845–1862. Doi: 10.1002/joc.631
- ²⁵⁸ Hermanson, L. and Sutton, R.T. 2009. Climate predictability in the second year. *Phil. Trans. R. Soc. A*, 367, 913–916. Doi:10.1098/rsta.2008.0181
- ²⁵⁹ Smith, D.M., et al. 2007. Improved surface temperature prediction for the coming decade from a global climate model. *Science*, 317, 796–799.
- ²⁶⁰ Keenlyside, N.S., et al. 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature* 453, 84–88. Doi:10.1038/nature06921
- ²⁶¹ Boer, G.J., 2009. Changes in interannual variability and decadal potential predictability under global warming. *J. Climate*, 22, 3098–3109. Doi:10.1175/2008JCLI2835.1
- ²⁶² Rummukainen, M. 2010. State of the art with regional climate models, *WIRE (Wiley Interdisciplinary Reviews: Climate Change) Advanced Review* 1:1, 82–96. Doi:10.1002/wcc.008
- ²⁶³ van der Linden, P., and Mitchell, J.F.B. (eds.) 2009. *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project*. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. 160pp.
- ²⁶⁴ Christensen, J.H., et al. 2008. On the need for bias correction of regional climate change projections of temperature and precipitation, *Geophys. Res. Lett.*, 35, L20709. Doi:10.1029/2008GL035694
- ²⁶⁵ Mearns, L.O., et al. 2005. NARCCAP, North American Regional Climate Change Assessment Program, A multiple AOGCM and RCM climate scenario project over North America. Preprints of the American Meteorological Society 16th Conference on Climate Variations and Change. 9–13 January, 2005. Paper J6.10, American Meteorological Society, Washington, DC, 235–238.
- ²⁶⁶ Mearns, L.O. and NARCCAP team 2009. The North American Regional Climate Change Assessment Program (NARCCAP): overview of Phase II results. *IOP Conf. Series: Earth and Environmental Science* 6 (2009) 022007. Doi:10.1088/1755-1307/6/2/022007
- ²⁶⁷ Fu, C.B., et al. 2005. Regional Climate Model Intercomparison project for Asia. *Bull. Am. Meteorol. Soc.*, 86:2, 257–266. Doi:10.11/BAMS-86-2-257
- ²⁶⁸ Giorgi, F., et al. 2009. Addressing climate information needs at the regional level: The CORDEX framework. *WMO Bulletin*, 58:3, 175–183.
- ²⁶⁹ Lenton T.L., et al. 2008. Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci.*, 105, 1786–1793. Doi: 10.1073/pnas.0705414105
- ²⁷⁰ Schellnhuber, H.J. 2009. Tipping elements in the Earth System. *Proc. Natl. Acad. Sci.*, 106, 20561–20563. Doi: 10.1073/pnas.0705414105

-
- ²⁷¹ Smith, J.B., et al. 2009. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proc. Natl. Acad. Sci.*, 206:11, 4133–4137. Doi:10.1073/pnas.0812355106.
- ²⁷² Holland, M.M., et al. 2006. Future abrupt reductions in the Summer Arctic sea ice. *Geophys. Res. Lett.*, 33, L23503. Doi:10.1029/2006GL028024
- ²⁷³ Notz, D. 2009. The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss. *Proc. Natl. Acad. Sci.*, 106, 20590–20595. Doi:10.1073/pnas.0902356106
- ²⁷⁴ Hoffmann M. and Rahmstorf, S. 2009. On the stability of the Atlantic meridional overturning circulation. *Proc. Natl. Acad. Sci.*, 106, 20584–20589. Doi:10.1073/pnas.0909146106
- ²⁷⁵ Ramanathan, V., et al. 2005. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proc. Natl. Acad. Sci.*, 102, 5326–5333. Doi:10.1073/pnas.0500656102
- ²⁷⁶ Patricola, C.M. and Cook, K.H. 2008. Atmosphere/vegetation feedbacks: A mechanism for abrupt climate change over northern Africa. *J. Geophys. Res.*, 113, D18102. Doi:10.1029/2007JD009608
- ²⁷⁷ Cook, K. H. and Vizi, E.K. 2006. Coupled Model Simulations of the West African Monsoon System: Twentieth- and Twenty-First- Century Simulations. *J. Climate*, 19, 3681–3703.
- ²⁷⁸ Levermann, A., et al. 2009. Basic mechanism for abrupt monsoon transitions. *Proc. Natl. Acad. Sci.*, 106, 20572–20577. Doi:10.1073/pnas.0901414106
- ²⁷⁹ Malhi, Y., et al. 2009. Exploring the likelihood and mechanism of a climate-change induced dieback of the Amazon rainforest. *Proc. Natl. Acad. Sci.*, 106, 20610–20615. Doi:10.1073/pnas.0804619106
- ²⁸⁰ Shakhova, N., et al. 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic shelf. *Science*, 327, 1246–1250.
- ²⁸¹ Archer, D., et al. 2009. Ocean methane hydrates as a slow tipping point in the global carbon cycle. *Proc. Natl. Acad. Sci.*, 106, 20596–20601.
- ²⁸² Khvorostyanov, D.V., et al. 2008. Vulnerability of permafrost carbon to global warming. Part I: model description and the role of heat generated by organic matter decomposition. *Tellus B*, 60, 250–264.
- ²⁸³ Kriegler, E., et al. 2009. Imprecise probability assessment of tipping points in the climate system. *Proc. Natl. Acad. Sci.*, 106, 5041–5046. Doi:10.1073/pnas.0809117106
- ²⁸⁴ Unger, N., et al. 2010. Attribution of climate forcing to economic sectors. *Proc. Natl. Acad. Sci.*, 107:8, 3382–3387. Doi:10.1073/pnas.0906548107
- ²⁸⁵ Den Elzen, M.G.J. and van Vuuren, D.P. 2007. Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. *Proc. Natl. Acad. Sci.*, 104:46, 17931–17936. Doi:10.1073/pnas.0701598104
- ²⁸⁶ Matthews, H.D. and Weaver, A.J. 2010. Committed climate warming. *Nature Geoscience*, 3, 142–143. Doi:10.1038/ngeo813
- ²⁸⁷ Matthews, H.D. and Caldeira, K. 2008. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, 35, L04705. Doi:10.1029/2007GL032388
- ²⁸⁸ Allen, M.R., et al. 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 458, 1163–1166. Doi:10.1038/nature08019
- ²⁸⁹ O'Neill, B.C., et al. 2010. Mitigation implications of mid-century targets that preserve long-term climate policy options. *Proc. Natl. Acad. Sci.*, 107:3, 1011–1016. Doi:10.1073/pnas.0903797106
- ²⁹⁰ Matthews, H.D., et al. 2009. The proportionality of global warming to cumulative carbon emissions. *Nature*, 459, 829–832. Doi:10.1038/nature08047
- ²⁹¹ Meinshausen, M., et al. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458, 1158–1162. Doi:10.1038/nature08017
- ²⁹² Solomon, S., et al. 2009. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci.*, 106:6, 1704–1709. Doi:10.1073/pnas.0812721106
- ²⁹³ Schwartz, S.E., et al. 2007. Quantifying climate change – too rosy a picture? *Nature Reports Climate Change*. Doi:10.1038/climate.2007.22

-
- ²⁹⁴ Knutti, R. 2008. Why are climate models reproducing the observed global surface warming so well? *Geophys. Res. Lett.*, 35, L18704. Doi:10.1029/2008GL034932
- ²⁹⁵ Jones, C., et al. 2009. Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience*, 2, 484–487. Doi:10.1038/ngeo555
- ²⁹⁶ “The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

Physical Climate Science since IPCC AR4

A brief update on new findings between 2007 and April 2010

This report provides an update of the IPCC Fourth Assessment Report (AR4), focusing on the physical climate system that in the IPCC work is addressed by its Working Group I. The report considers progress in understanding of the human and natural drivers of climate change, climate observations, attribution, key climate feedback, as well as ocean acidification. Recent developments and near future prospects of climate modelling are also discussed in brief. Some of the key findings that the recent literature brings forth include:

- Parts of the Greenland and Antarctic ice sheets have shown rapid melt over recent years.
- Solar cycle effects on global temperatures are small compared to anthropogenic forcing
- More emerging research on the "other CO₂ problem", ocean acidification
- Climate change may have significant effects on natural carbon sinks

The report is written by four leading Nordic climate scientists: Markku Rummukainen, Jouni Räisänen, Jens Hesselbjerg Christensen and Halldór Björnsson on behalf of the Nordic ad hoc Group on Global Climate Negotiations. The Nordic ad hoc Group on Global Climate Negotiations prepares reports and studies, conducts meetings and organises conferences to support the Nordic negotiators in the UN climate negotiations. The overall aim of the group is to contribute to a global and comprehensive agreement on climate change with ambitious emission reduction commitments.