André Berger
Fedor Mesinger
Djordje Šijački
*Editors*

# Climate Change

## Inferences from Paleoclimate and Regional Aspects

Springer

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# Logos of the Major Financial Contributors to the Milankovitch Anniversary Symposium, 2009, Belgrade, Serbia

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*This book is dedicated to the memory of Stevan Koički,*
*former Vice-President of the Serbian Academy of Sciences and Arts,*
*the original proposer to UNESCO of the Milankovitch Anniversary*
*Symposium held 2009 in Belgrade*

**Milutin Milankovitch**
a photograph from the year 1926
(Photo Library of the Serbian Academy of Sciences and Arts, Belgrade)

# Preface

Once again, for the third time, in 2009, the Serbian Academy of Sciences and Arts organized an international symposium on the occasion of the birth anniversary of Milutin Milankovitch. As in 2004, the 2009 symposium was held under the patronage of the United Nations Educational, Scientific and Cultural Organization (UNESCO). What were the motives, supported by UNESCO, that led the Academy to organize another Milankovitch symposium 5 years after the second one? Several considerations were behind this move.

Paleoclimate, with its records of numerous drastic climatic changes, is a rich reservoir of real-world information on the patterns of change in the earth's climate system. While in 2004 there were some people skeptical about global warming and also of it being a phenomenon caused by man's activities, in 2009 there were not many left of either kind. Thus, understanding paleoclimate, following in the footsteps of Milankovitch, not only adds to our basic knowledge of the history of the world we live in, but it also adds to our abilities to anticipate future climate changes as the emission of greenhouse gasses by the increasing world population continues with little abatement in sight.

This last point was brought into focus recently by the work of James Hansen and collaborators who pointed out that the information on which way the earth's climate is going should best rely on three sources: observations, results of numerical models, and paleoclimate data. This is because the former two sources have limitations: observations are obtained from the earth's climate system which is now not in equilibrium, and numerical models include processes that are insufficiently understood and thus contain errors, and in their most advanced forms cannot be run for as long as one would wish. Paleoclimate data, on the other hand, are obtained from the time when the earth's climate system was close to equilibrium, such as the time of the maximum extent of the last ice age, and the time when there was no ice cover on the earth, some 40 million years ago.

With this new awareness of the significance of paleoclimate in the context of the climate change in progress, it seemed appropriate to open the 2009 symposium with a brief review of the present climate change situation, especially in view of the post 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Given that the proceedings are being printed about 2 years after the symposium was held, the review paper by Richard Somerville included here has been updated so as to contain information on global climate during the 2 years following the symposium: 2009 and 2010.

The review of the present climatic condition is followed by invited presentations reporting the progress made in the field of paleoclimate science. The session on paleoclimate started on Tuesday, 22 September and ended on Thursday, 24

September, and included 12 papers. The session was subdivided into two main parts. The first one was on glacial–interglacial cycles and the second on modeling the Last Glacial Maximum and the Holocene. Then, additional papers discuss Milankovitch's contribution to the understanding of climate evolution (Aleksandar Petrović), the feedbacks in the climate system (Ray Bates), and the snowball Earth (David Spiegel). Brief remarks on the contributions of Milankovitch made by André Berger in his presentation have been expanded into a full-length paper on the history of the astronomical theory of climate change.

In the first part, Peter Ditlevsen indicates the dynamic origin of the Mid-Pleistocene transition from the 41-ka world to the 100-ka one, and the role of the internal stochastic noise in the period prior to the last five glacial cycles. Andrey Ganopolski and Reinhard Calov apply the model Climber-2 to simulate the last eight glacial–interglacial cycles forced by variations in the astronomical parameters and in the concentration of the major greenhouse gases. André Berger and Qiuzhen Yin discuss the climate associated with the peaks of the interglacials of the last one million years, stressing the difference between the interglacials before and after the Mid-Brunhes Event. Slobodan Marković explains the role of loess sediments in reconstructing the climatic variations in Serbia. Qiuzhen Yin discusses the origin of the strong East Asian summer monsoon seen in the loess of China during MIS-13.

Four papers in the second part demonstrate the power of models in simulating past climates. Bette Otto-Bliesner stresses the role of the astronomical parameters in shaping the last interglacial using experiments with the NCAR Community climate system model. Didier Roche shows the importance of the different forcings in simulating the last deglaciation, whereas André Paul proposes ways to reduce the uncertainty pertaining to the Atlantic meridional overturning circulation of the Last Glacial Maximum by employing paleo-data assimilation techniques.

Several papers address the impact of climate change on hydrologic ecosystems and on regional watershed issues. Possible effects of climate change on the aquatic vegetation in river and floodplain habitats are described by Georg Janauer. He also discusses sensible solutions to problems envisaged, so as to include ecohydrology principles and mediating between diverging stakeholder interests. The analysis presented in the paper by Music and coauthors addresses the challenging task of evaluating the uncertainties associated with the projection of climate change impact on hydrological regimes at the watershed scale. Dejan Dimkić and Jovan Despotović analyze the expected changes in stream flows in Serbia by looking at flows of previous years of under and above average temperature and precipitation in available records, and trends projected by the IPCC AR4 report.

Given that an overview of climate change was the symposium's main topic and that it is not only a scientific but also a societal need to understand regional changes that could be expected, regional climate modeling was looked into at some length by a number of invited and contributed papers. Basic issues such as what can be done by running regional climate models (RCMs) and other not fully understood problems are extensively reviewed by René Laprise and collaborators, in a paper presented by Dragana Kornić. The paper by Fedor Mesinger and coauthors discusses the issues of the domain size and lateral boundary conditions in view of the possible desirability of attempting to improve the RCMs on a large scale. They include a summary of the very recent results obtained by Katarina Veljovic, as well as the earlier results of Michael Fennessy and Eric Altshuler, arguing that if a small improvement on a large scale were to be achieved, a still greater improvement on a small scale should be expected. How well a specific polar region problem, that of open water, can be dealt with is looked into by Sandra Morelli and Flavio Parmiggiani. Finally, of the papers included here, one that focuses on the climate changes to be expected in the region of Southern Europe and the Mediterranean, thus including the symposium venue, is that of Aleksandra Kržič and collaborators.

The 17 papers published in this volume were, of course, typically submitted some months and, in some cases, even up to more than a year after the symposium itself, and all have gone through a customary peer-review process. Thus, it is expected that they contain "added value" compared to the actual presentations at the symposium. The editors hope that having the collection in one volume will be appreciated by the readers.

As to the symposium itself, at the opening session, the participants were addressed by the Serbian Vice Premier and Minister for Science and Technology, Božidar Đelić; by the President of the Academy, academician Nikola Hajdin; by Dr. Patricio Bernal, Assistant Director-General of UNESCO for the Intergovernmental Oceanographic Commission, on behalf of the UNESCO, that extended its patronage to the symposium; and finally by Professor André Berger, Chairman of the International Scientific Committee. The following evening participants enjoyed a very nice reception at the City Hall, hosted by Dragan Đilas; on the penultimate day, they were received by Their Royal Highnesses Crown Prince Alexander and Crown Princess Katherine, at the White Palace, located on the outskirts of Belgrade on a plateau offering a view of the city; all three of these events were accompanied either by fine music performed by acclaimed Belgrade musicians, or, at the White Palace reception, by a colorful traditional Serbian folk dance group. The symposium dinner, on the last evening, organized on a ship cruising the rivers Sava and Danube, offering a night view of downtown Belgrade, its Kalimegdan Park and Fortress, with its walls and towers reflecting off the waters of the two rivers, provided a fitting conclusion for the Belgrade part of the program.

On the last day of the program, Saturday, 26 September, the participants visited the Milankovitch family home in Dalj, Croatia, which is an impressively refurbished building made into a Milankovitch Science Center. An afternoon session was held, with several talks and a concluding discussion. At the final coffee break with refreshments served in the renovated garden of the Milankovitch family home, on the bank of Danube, the participants enjoyed the colorful view of the Danube with a wide vista of the plains to its north, and many places mentioned in Milankovitch's entertaining and inspiring autobiographical writings.

The symposium was possible because of the financial contribution made by UNESCO. Generous contributions toward organizing the symposium were also made by several Serbian sponsors: the Electric Power Industry of Serbia, the Ministry for Environment and Spatial Planning of Serbia, Hydrometeorological Institute of Serbia, the Agency for the Protection of the Environment of Serbia, and last but not least, by the Dalj hosts, County of Erdut, Croatia, and the Milankovitch Science Center, Dalj.

April 2012

*André Berger*
*Fedor Mesinger*
*Djordje Šijački*

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(3) Vladimir Janković
(4) Silvio Gualdi
(5) Didier M. Roche
(6) Sandra Morelli
(7) J. Ray Bates
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(22) André Paul
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(24) Georg A. Janauer
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Collage design by Duško Ćosić.

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# Part I

# Climate Change at Present

# Science, Politics, and Public Perceptions of Climate Change

Richard C. J. Somerville

**Abstract**

Recent research has demonstrated that climate change continues to occur, and in several aspects, the magnitude and rapidity of observed changes frequently exceed the estimates of earlier projections, such as those published in 2007 by the Intergovernmental Panel on Climate Change in its Fourth Assessment Report. Measurements show that the Greenland and Antarctic ice sheets are losing mass and contributing to sea-level rise. Arctic sea ice has melted more rapidly than climate models had predicted. Global sea-level rise may exceed 1 m by 2100, with a rise of up to 2 m considered possible. Global carbon dioxide emissions from fossil fuels are increasing rather than decreasing. This chapter summarizes recent research findings and notes that many countries have agreed on the aspirational goal of limiting global warming to 2°C above nineteenth-century "preindustrial" temperatures, in order to have a reasonable chance for avoiding dangerous human-caused climate change. Setting such a goal is a political decision. However, science shows that achieving this goal requires that global greenhouse gas emissions must peak within the next decade and then decline rapidly. Although the expert scientific community is in wide agreement on the basic results of climate change science, much confusion persists among the general public and politicians in many countries. To date, little progress has been made toward reducing global emissions.

## Introduction

The comprehensive Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), published in 2007, authoritatively evaluates climate change science published in the peer-reviewed research literature up to about mid-2006. Viewed from the perspective of what is known in late 2010, the report is thus inevitably somewhat out of date.

In 2007, at the time of the publication of AR4, climate scientists already understood from the most recent research that "observational data underscore the concerns about global climate change. Previous projections, as summarized by IPCC, have not exaggerated but may in some respects even have underestimated the change" (Rahmstorf et al. 2007).

Now, in 2011, more recent research has demonstrated that climate change continues to occur, and in several

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aspects, the magnitude and rapidity of observed changes frequently exceed the estimates of earlier projections, including those of AR4. In addition, the case for attributing much observed recent climate change to human activities is even stronger now than at the time of AR4.

Several recent examples, drawn from many aspects of climate science, but especially emphasizing atmospheric phenomena, support this conclusion. These include temperature, atmospheric moisture content, precipitation, and other aspects of the hydrological cycle.

Motivated by the rapid progress in research, a recent scientific synthesis, *The Copenhagen Diagnosis* (Allison et al. 2009), has assessed recent climate research findings, including:

- Measurements show that the Greenland and Antarctic ice sheets are losing mass and contributing to sea-level rise.
- Arctic sea ice has melted far beyond the expectations of climate models.
- Global sea-level rise may attain or exceed 1 m by 2100, with a rise of up to 2 m considered possible.
- In 2008, global carbon dioxide emissions from fossil fuels were about 40% higher than those in 1990.
- At today's emissions rates, after just 20 more years, the world will no longer have a reasonable chance of limiting warming to less than 2°C.

*The Copenhagen Diagnosis* also cites research supporting the position that, in order to avoid dangerous climate disruption, global emissions must peak and then start to decline rapidly within the next 5–10 years, reaching near-zero well within this century.

*The Copenhagen Diagnosis* is available at http://www.copenhagendiagnosis.org. A somewhat updated version has been formally published recently (Allison et al. 2011).

This chapter summarizes the rapid recent progress in climate change research and relates it to recent developments in the politics and public perceptions of climate change.

## The Intergovernmental Panel on Climate Change and Its 2007 Report

We can begin by looking back at the last IPCC report and asking some key questions:

1. What is the Intergovernmental Panel on Climate Change and how does it work?
2. Were the main conclusions in the IPCC Fourth Assessment Report (AR4), published in 2007, correct?
3. How has climate science changed since the scientific papers that were assessed in AR4?

IPCC was founded in 1988. The history of IPCC has been documented by Bolin (2007). To date, IPCC has produced four major Assessment Reports (ARs). The average interval between reports is about 6 years:

1990: First AR (FAR)
1995: Second AR (SAR)
2001: Third AR (TAR)
2007: Fourth AR (AR4)

In 2013, the Fifth AR (AR5) is expected. During the 20 years since the publication of the First Assessment Report, great progress has been made in climate change science. As an example, much more observational data have become available, and computer simulations of the climate system have made great advances in physical comprehensiveness and realism and also in computational resolution.

The Working Group I (physical science) part of AR4 was written by 152 scientists called "Lead Authors." Twenty-two of the 152 are called "Coordinating Lead Authors." These are the scientists who led the writing teams for each of the 11 chapters. I was a Coordinating Lead Author for AR4. In this discussion, however, I am speaking as an individual scientist, not on behalf of IPCC or any other organization. In this chapter, I shall refer to the Working Group I (WGI) portion of the IPCC report only, and I shall not consider the reports of IPCC Working Groups II and III, which deal with adaptation, impacts, mitigation, and other issues.

There were several diversity criteria in choosing the 152 Lead Authors in WGI of AR4:

The Lead Authors included younger as well as older scientists. At the time of their appointment, 25% of the Lead Authors had earned a Ph.D. within the last 10 years.

The Lead Authors were not a clique composed of authors of earlier IPCC reports. In fact, 75% of them had not been previous IPCC authors.

The Lead Authors were not overwhelmingly representatives of a few developed countries. Fully 35% of them were from developing countries and countries with economies in transition.

The 152 Lead Authors were chosen by IPCC from about 700 nominations by governments.

The WGI portion of the 2007 IPCC report (AR4) is about 1,000 pages long and took 3 years to write. During the writing, more than 30,000 review comments, from both governments and individuals, were received on three separate drafts. The authors' written responses to every review comment are in the public record. The open and transparent nature of the IPCC process, the multiple stages of peer review, and the credentials of the authors all contribute to the stature of the report.

We can start with the iconic figure depicting the atmospheric $CO_2$ concentration as a function of time, as measured since 1958 (Fig. 1). This is the famous "Keeling curve." This graph shows that the relentless upward trend in the amount of $CO_2$ in the atmosphere continues. In fact, the concentration now is increasing more rapidly than before. Charles David Keeling, who began these observations in 1958, died in 2005. However, the meticulous measurements that he undertook, initially made with an instrument that he invented, are now being continued by others at several stations in an international network.

## The International Scientific Congress in Copenhagen in March, 2009

There were two noteworthy climate meetings in Copenhagen in 2009. The more famous one, the United Nations Framework Convention on Climate Change (UNFCCC) meeting, was held in Copenhagen in December 2009. This was the 15th Conference of the Parties (COP15). The UNFCCC was the document to which the countries that had ratified it were parties. The primary scientific input to the COP15 negotiations was, of course, AR4, the Fourth Assessment Report of

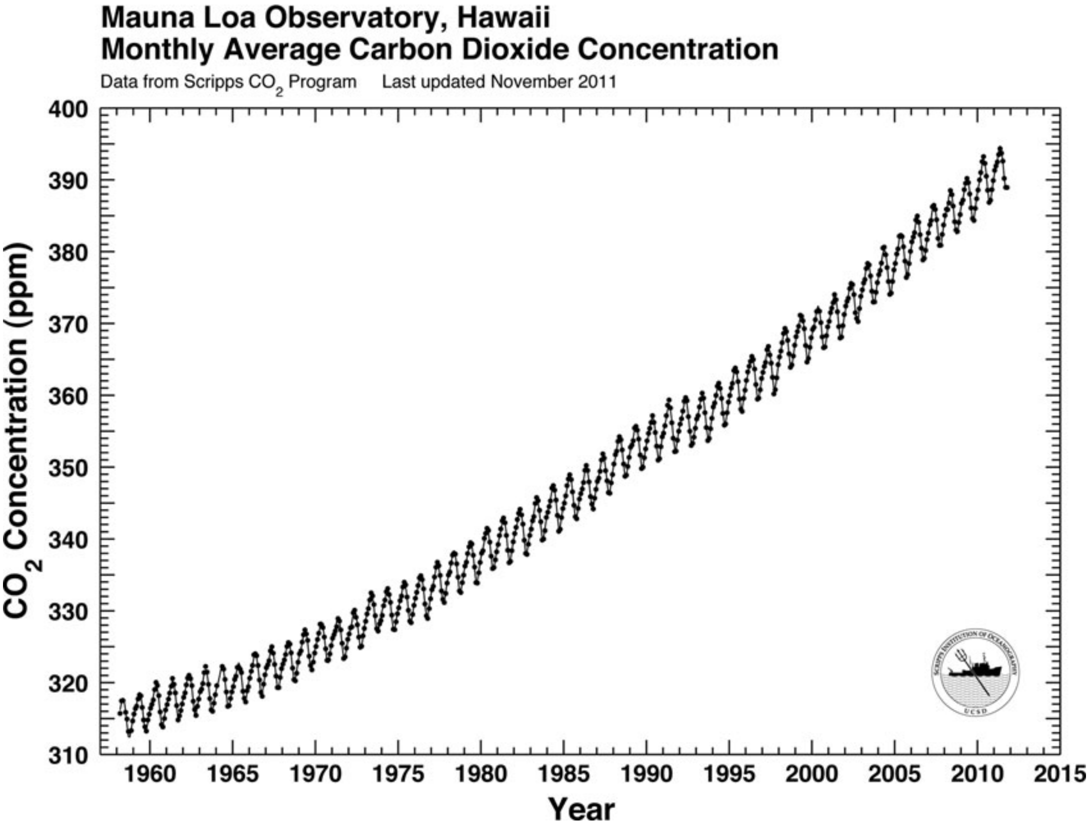

**Fig. 1** The Keeling curve, showing atmospheric carbon dioxide amounts as a function of time since 1958 (credit: Scripps Institution of Oceanography $CO_2$ Program)

the Intergovernmental Panel on Climate Change (IPCC), published in 2007. This report and many other recent IPCC documents are available at http://www.ipcc.ch and are also published by Cambridge University Press.

However, new scientific developments occur continually. Since the publication of the AR4 IPCC report, new knowledge has emerged that furthers our understanding of climate change, including the impacts of human influence on the climate. To bring this new knowledge together, about 9 months before COP15, an international scientific congress, called Climate Change: Global Risks, Challenges and Decisions, was held, also in Copenhagen, from 10 to 12 March 2009. One must keep in mind that the AR4 IPCC report was published in 2007 and the most recent papers that it assesses were published in 2006.

The Copenhagen congress in March 2009 covered more recent research results, but the conclusions of this meeting did not go through any procedure resembling the long IPCC process of multiple drafts and extensive review. Nor did the March 2009 Copenhagen meeting report have the full participation of many expert authors, as did the IPCC. This fact illustrates the inevitable trade-off between the slow and painstaking IPCC process and faster but less thorough summaries and assessments of recent science.

We now consider some of the key results presented at the March 2009 Copenhagen meeting. Temperature is the single most important climate variable. Let us first consider recent temperature trends. IPCC in 2007 concluded, “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.”

The 2007 IPCC Fourth Assessment Report (AR4) described “an unambiguous picture of the ongoing warming of the climate system.” This trend is continuing. Small year-to-year differences in global average temperatures are unimportant in evaluating long-term trends. During a warming trend, a given year is not always warmer than all the previous years, because the ongoing warming is sometimes temporarily masked by internal climate variability, a normal and natural phenomenon. For example, 2008 was slightly cooler globally than 2007, in part, because a La Niña occurred in 2008 (NASA Goddard Institute for Space Studies 2009). Such natural events can lead to slight temporary cooling. Solar output was also at its lowest level of the satellite era, another temporary cooling influence.

Quantitatively, the global average temperature in 2008 was only about 0.1°C less than in the years immediately preceding it. Such a small difference over such a short time is not statistically significant in evaluating trends. It is noteworthy that 2008, while at the time it may have been the coolest year since 2000, remains one of the ten warmest years since instrumental records began in mid-nineteenth century and the most recent 10-year period is still warmer than the previous 10-year period. The long-term trend is clearly still a warming trend (NASA Goddard Institute for Space Studies 2009).

Our knowledge of the causes of this trend has also improved. IPCC said in 2007, “Most of the observed increase in globally averaged temperatures since the mid-twentieth century is ‘very likely’ due to the observed increase in anthropogenic greenhouse gas concentrations.” Science never provides absolute certainty. Here, “very likely” is calibrated language used by IPCC to express the degree of scientific uncertainty or the possible range of given scientific findings. In this terminology, used consistently in AR4, “very likely” means at least 90% probable.

Thanks to recent research, we have learned that by far the greatest part of the observed century-scale warming is due to human rather than natural factors (Lean and Rind 2008). These scientists analyzed the role of natural factors (e.g., solar variability and volcanoes) vs. human influences (e.g., added man-made greenhouse gases and aerosols) on temperatures since 1889. They found, for example, that the sun contributed only about 10% of surface warming in the last century and a negligible amount in the last quarter century, thus contributing far less than had been estimated in earlier assessments.

Recent research has also clarified our understanding of a warming trend in the atmosphere above the lowest layers near the Earth’s surface. By reducing errors in temperature measurements, a warming in the tropical upper troposphere, 10–15 km above the surface, is now apparent in observations, thus reconciling different measurement data and model simulations (Thorne 2008). A new method based on wind observations (Allen and Sherwood 2008) shows a similar warming trend in the upper troposphere, consistent with model results.

The climatic roles of clouds, and of small liquid or solid particles ("aerosols") in the atmosphere, are among the subjects where intensive research is occurring and progress is being made, but only the results of future research can settle several interesting and important scientific questions. AR4 affirmed this conclusion, and it is still true.

In the 2007 IPCC Fourth Assessment Report (AR4), projections were made that future climates would generally have more precipitation at high latitudes and less in the subtropics, where many major deserts exist. However, at that time, no observational studies could be cited defining precipitation trends on a 50-year time scale. Now, such trends have been identified in measurements. For example, Zhang et al. (2007) found that precipitation has been reduced in the subtropics but has increased in middle latitudes, consistent with model projections of human-caused global warming.

Recent research and new observations have decisively settled the question of whether a warming climate will lead to an atmosphere containing more water vapor and, if so, whether the additional water vapor will add to the greenhouse effect, augmenting the warming. The answers to both these questions are yes. Water vapor does become more plentiful in a warmer atmosphere (Dessler et al. 2008). Satellite data show that atmospheric moisture content over the oceans has increased since 1998, with human causes being responsible (Santer et al. 2007).

Recent research has also found that precipitation tends to increase as atmospheric water-vapor content increases (Wentz et al. 2007; Allan and Soden 2008). These conclusions strengthen those of earlier studies.

In the remainder of this section, I briefly summarize several important findings from recent research. Further details, and citations of many of the original papers in the peer-reviewed literature, on which these summary statements are based, may be found in *The Copenhagen Diagnosis* (Allison et al. 2009, 2011).

Only a small fraction of the heat gained by the planet in recent decades is stored in the atmosphere. By far, the largest portion of heat stored is to be found in the ocean. Recently developed observational advances, such as the deployment of a widespread fleet of thousands of autonomous instrumented floats, have greatly improved our knowledge of ocean heat content. Current estimates indicate that ocean warming is about 50% greater than had been previously reported by the IPCC.

Increased melting of the large polar ice sheets contributes to the observed increase in sea level. Observations of the area of the Greenland ice sheet that has been at the melting point temperature for at least 1 day during the summer period shows a 50% increase during the period 1979–2008. The Greenland region experienced an extremely warm summer in 2007. The whole area of south Greenland reached the melting temperatures during that summer, and the melt season began 10–20 days earlier and lasted up to 60 days longer in south Greenland.

In addition to melting, the large polar ice sheets lose mass by ice discharge, which also depends on regional temperature changes. Satellite measurements of very small changes in gravity have revolutionized the ability to estimate loss of mass from these processes. The Greenland ice sheet has been losing mass at a rate of about 179 Gt/year since 2003.

One of the most dramatic developments since the last IPCC report is the rapid reduction in the area of Arctic sea ice in summer. A new minimum in Arctic sea ice was observed only a few months after the publication of AR4. In summer 2007, the minimum area covered by sea ice in the Arctic decreased by about 2 million square kilometers as compared to previous years. In 2008, the decrease was almost as dramatic, as it is at the time of the final submission of this manuscript in September of 2011. This decreasing ice coverage is important for climate on a larger scale for several reasons, including that an ice-free ocean is far less reflective and so absorbs more heat than an ice-covered ocean. Thus, the loss of Arctic sea ice triggers a strong feedback that amplifies the warming.

The global carbon cycle is in strong disequilibrium because of the input of $CO_2$ into the atmosphere from fossil fuel combustion and land-use change. Fossil fuels presently account for about 85% of total emissions, and land-use change, for about 15%. Total emissions have grown at about 2% per year since 1800. However, fossil fuel emissions have accelerated since 2000 to grow at about 3.4% per year, an observed growth rate that is at or even somewhat beyond the upper edge of the range of growth rates in IPCC scenarios. Total $CO_2$ emissions are responsible for two-thirds of the growth of all greenhouse gas radiative forcing.

The IPCC in the TAR (2001) attempted to assess scientific evidence available at the time in terms of "reasons for concern." The resulting visual representation of that synthesis, the so-called burning embers diagram, shows the increasing risk of various types of climate impacts with an increase in global average temperature. Using the same methodology, the same diagram of reasons for concern has been updated by several authors (Smith et al. 2009). Although there inevitably is some subjectivity in any such exercise, the results are provocative and disquieting.

Several conclusions follow from the updated "burning embers diagram" and associated recent findings. First, the risks of climate change impacts now tend to appear at lower global average temperature increases. Second, a 2°C limit of warming relative to preindustrial temperatures, which was widely thought in 2001 to be sufficient to avoid serious risks, now appears to be less adequate. Third, the risks of large-scale discontinuities are now considered to be greater than previously thought.

In summary, although a 2°C rise in temperature above preindustrial remains the most commonly quoted limit for avoiding dangerous climate change, there is now a serious case to be made that this level of warming nevertheless carries significant risks of harmful impacts for society and for the environment.

According to the IPCC analysis in AR4, atmospheric $CO_2$ concentration should not exceed 400 ppm $CO_2$ if the global temperature rise is to be kept within 2.0–2.4°C. Today, the mean $CO_2$ concentration is above 385 ppm and is rising by 2 ppm/year. The 2007 concentration of all greenhouse gases, both $CO_2$ and non-$CO_2$ gases, was about 463 ppm $CO_2$ equivalents. Adjusting this concentration for the cooling effects of aerosols yields a $CO_2$-equivalent concentration of 396 ppm. A recent study estimates that a concentration of 450 ppm $CO_2$ equivalents (including the cooling effect of aerosols) would give only a 50–50 chance of limiting the temperature rise to 2°C or less.

Thus, atmospheric $CO_2$ concentrations are already at levels predicted to lead to global warming of between 2.0 and 2.4°C. The conclusion from both the IPCC and subsequent analyses is blunt and stark—immediate and dramatic emission reductions of all greenhouse gases are urgently needed if the 2°C limit is to be respected.

Humanity is now committing future generations to a strongly altered climate. Even beyond the current century, there are major implications for longer-term climate change. Higher temperatures and changes in precipitation caused by $CO_2$ emissions from human activity are largely irreversible on human time scales. Atmospheric temperatures are not expected to decrease for many centuries to millennia, even after human-induced greenhouse gas emissions stop completely (Matthews and Caldeira 2008; Solomon et al. 2009; Eby et al. 2009).

An analysis of several decades of data in the western United States suggests that as much as 60% of the hydrological changes in this region are due to human activities. This trend, if sustained, has profound consequences for the future water supply of this already water-stressed part of the world (Barnett et al. 2008).

One complex climate model that had been modified to include recent advances in understanding of the carbon cycle, natural climate factors, and other elements then produced twice as large a global average temperature increase at the end of the twenty-first century as it had before the model was modified: 5.2°C in the new model run compared to 2.4°C for the older version of the model (Sokolov et al. 2009).

Many recent aspects of observed climate change reveal a more rapid pace than had been foreseen by recent model projections. Thus, recent revisions of projected climate change exceed earlier estimates, and it is increasingly clear that the projections reported in the IPCC Fourth Assessment Report in 2007 may well have underestimated the pace of current climate change. This conclusion of Rahmstorf et al. (2007), which appeared after AR4 was published, could stand as a conclusion for this entire survey of the results of climate change science:

> Overall, these observational data underscore the concerns about global climate change. Previous projections, as summarized by IPCC, have not exaggerated but may in some respects even have underestimated the change, in particular for sea level.

## How *The Copenhagen Diagnosis* Came to Be Written

*The Copenhagen Diagnosis* (Allison et al. 2009) is a report published online in November 2009. It is available for download at http://www.copenhagendiagnosis.com and http://www.copenhagendiagnosis.org. A group of 26 climate scientists wrote *The Copenhagen Diagnosis*. All are active researchers. They come from eight countries and include three women and several younger scientists. I am one of the 26 scientists who wrote this