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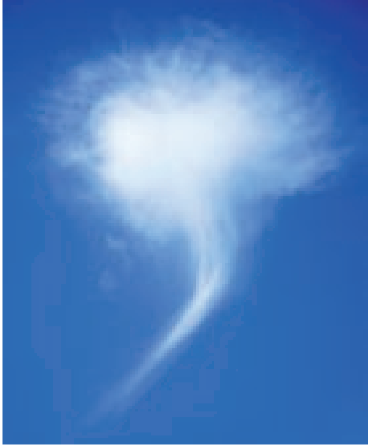
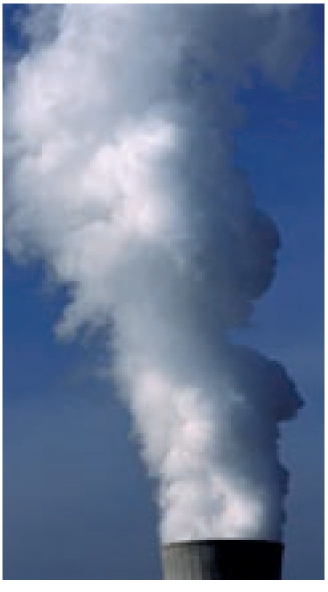


New Climate Science 2006–2009

Markku Rummukainen and Erland Källén



REGERINGSKANSLIET

New Climate Science 2006–2009

A brief review of research into the physical science basis of the climate change issue since IPCC AR4/WG I of 2007

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Erland Källén, Stockholm University

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Preface

In 2007 the Swedish Government established an advisory Commission on Sustainable Development. The Commission comprises a broad range of members from business/industry, independent organisations, research and politics. It is a forum for discussion, analysis and dialogue. The Prime Minister chairs the Commission with the Minister of the Environment as his Deputy. It works in a transparent manner with the intention of stimulating a broader dialogue in society.

Climate change is perhaps the most complex issue facing the international community. At the end of 2009, the countries of the world will gather in Copenhagen to attempt the establishment of a new climate agreement. Science forms the basis of climate policy. Reports from the UN Intergovernmental Panel on Climate Change IPCC, the latest being their fourth assessment report from 2007, have played a vital role in substantiating and clarifying the threats posed by global warming. The IPCC was then able to consider research carried out up to 2006. Since then a considerable amount of new research has been put forward. The question could therefore be asked whether more recent research provides any cause to change or adjust the conclusions drawn by IPCC in 2007.

Against this background, Professors Erland Källén and Markku Rummukainen were asked to carry out an update of the scientific basis concerning climate change. This report presents the more important recent research results. The report has been subject to a limited scientific review process. The authors are responsible for its content.

This report is published with the hope that it will stimulate debate and reinforce the scientific basis of climate policies.

Stockholm, May 2009

/Joakim Sonnegård
Head of the Secretariat
Commission on Sustainable Development

Authors' preface

This report has been written during the period December 2008 – March 2009 as tasked by the Commission on Sustainable Development. The authors bear joint responsibility for the entire contents of this report. The basis of the report is internationally published scientific literature. This report covers climate research within the natural sciences.

We have done our best to provide as representative a picture as possible of the development of knowledge in this field between 2006 and the beginning of 2009. This compilation is probably incomplete. In order to attain a more complete picture, working methods of the type used by IPCC are necessary, in which a large number of researchers are involved. This has not been possible within the framework of our assignment or during the brief period of time at our disposal.

We would like to express our thanks for the many constructive comments provided by the experts who have examined our report: Professor Helge Drange of Bergen University, Professor Eigil Kaas of Copenhagen University and Associate Professor Jouni Räisänen at Helsinki University.

This report is to be referred to as Markku Rummukainen and Erland Källén, 2009: New Climate Science 2006-2009. Commission on Sustainable Development, Swedish Government Offices.

Summary

We know that a large part of the temperature increase during the latter half of the 20th century is very likely due to an increased concentration of greenhouse gases in the atmosphere. We also know that humans are responsible for the rise in greenhouse gas concentrations. In addition, projections of possible future climate change can be made. All these facts are published in the international, peer-reviewed, scientific literature. Furthermore, a comprehensive assessment of published climate science results has recently been made by IPCC, the UN Intergovernmental Panel on Climate Change.

Published scientific research steadily finds new and sometimes unexpected results and aspects that further enhance and deepen our understanding of the climate system. In this report we attempt to summarise climate science results that have appeared in literature since the publication of the most recent IPCC report (the IPCC Assessment Report 4, AR4, published in 2007). We focus on results that have modified or added nuances to the conclusions presented in AR4:

- Greenhouse gas concentrations in the atmosphere continue to increase. Also the rate of increase has accelerated.

- The global average temperature over the last year is about 0.1°C lower than the temperature in the years immediately preceeding it. 2008 is among the ten warmest years since 1850 and the most recent ten-year period is warmer than the previous ten-year period. The temperature trend is still rising.

- Previous analyses of observations of sea-level rise have been subject to further study. The results suggest that the rate of increase has been higher during 1993-2003 than 1961-2003. It is possible that the rate of increase has decreased somewhat since 2003.

- The major Arctic warming trend is likely to be linked to the global warming trend. Now warming has also been found in West Antarctica. This warming is related to the global warming trend.

- Recent studies of land ice sensitivity to atmospheric warming and land ice melting rates suggest that future sea level rise may be higher than levels reported in AR4. The total sea level rise may be around one metre over the next one hundred years. These estimates are still very uncertain.

- A significant change in precipitation has been determined from observations. This change is largely consistent with the expected effects of warming.

- The dramatic reduction in Arctic sea ice cover in 2007 and 2008 could be the first observed threshold effect or "tipping point" in the climate system. Confirmation of this depends on how persistent the sea ice reduction will be over the next few years.

- It may be more difficult to limit global warming to two degrees Celsius than expected. For example, recent research supports emphasizes the possibility that carbon sinks may, with continued climate change, become less effective than previously thought.

The overall assessment is that, in many respects, new research published since 2006 confirms earlier research results concerning ongoing climate change, human influence and possible future climate change. Research published after the AR4 report adds new pieces of knowledge to climate science but there is nothing to suggest a weakening of the conclusions presented in AR4. Rather, we believe that the published results show that some of the effects of continued global warming are more severe than previously thought and that future climate warming may be greater than previously estimated. A more definite update of earlier estimates must, however, await the next IPCC report.

1 Introduction

Basic scientific research forms the foundation of our understanding of global warming and its links to human activities. Through systematic observation, physically-based theories and mathematical modelling, knowledge on causes and effects in the climate system is developed.

The UN Intergovermental Panel on Climate Change IPCC has, since 1990, developed four major knowledge syntheses. The latest was published in 2007 (IPCC 2007, below referred to as AR4) which contains research results published up to 2006. Climate research is an extremely active and dynamic research field. A considerable number of studies have been presented since 2006. These will be covered in IPCC's next Assessment Report planned for 2013-14.

The IPCC process exerts considerable impact, not least due to the carefulness of the assessment process and the broad acceptance it enjoys. Results and new research findings are set in a broad perspective. Both the more robust and the more uncertain knowledge is illuminated. Consequently the IPCC reports are something totally different to specific new research results that are published at a steady rate in scientific journals. All new research must be considered as very preliminary while waiting to be confirmed, made more precise or rejected by future research. The absolutely latest research must first be allowed to mature and be compared with other research results within the field before it can be allowed to affect decision-making processes. At the same time it is, in many ways, unreasonable not to update knowledge during the course of time as decision-making processes are dynamic.

As the IPCC process is so thorough and careful there is time for significant advances within climate research before its next assessment is completed. At the same time, as stated above, there is a fine line between waiting for a sufficient amount of new research results and carrying out an up-dated description of the research situation.

Our study intends to produce a review of new research results concerning the climate system and climate change which have been presented since AR4. This study is limited to issues covered in the IPCC Working Group I, i.e. climate observations, the climate system, climate modelling and climate projections.

2 *Observed climate changes*

Global temperature development 2006-2008

In AR4 it is established that the average global temperature has increased by 0.74°C during the period 1906 to 2005. Eleven of the twelve warmest years during the period 1850-2006 occurred during the twelve years spanning 1995-2006. The two following years, 2007 and 2008, were relatively warm but somewhat cooler than the immediately preceeding ones (see Figure 1).

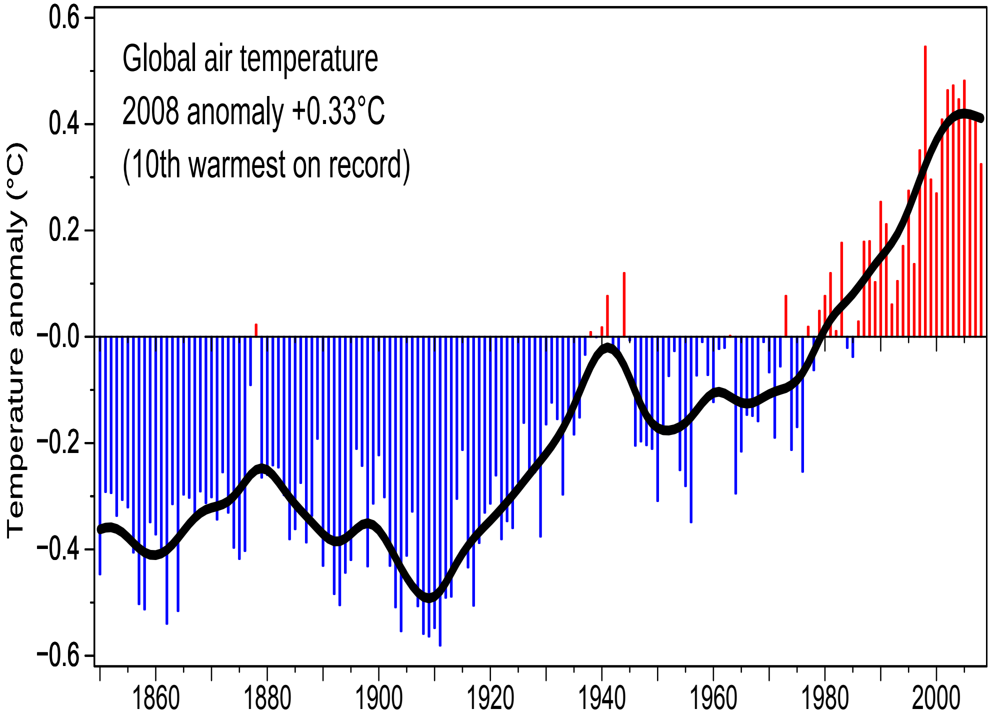

Figure 1. Average global temperature anomalies since 1850
Annual values are shown as deviations from the 1961-90 average[a].

There is no significant interruption of the global warming trend. The last two years are among the warmest years since 1850 and compared to 1991-2000, the entire period since then (2001-2008) has been almost 0.2°C warmer. The reason that each consecutive year does not become warmer than all the previous years concerns

[a] Based on Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J. Geophysical Research 111, D12106, doi:10.1029/2005JD006548. © Copyright 2009, Climatic Research Unit.

the interplay between ongoing warming and temporary internal climate fluctuations in the global system, especially in the world ocean. One reason why 2008 was not warmer than 2007 was probably the La Niña situation that prevailed from mid 2007 to mid 2008, which temporarily cooled the global, surface average temperature slightly[b]. La Niña conditions returned at the end of 2008 and were also in play at the beginning of 2009.

Temperature measurements are available from a large number of measuring stations, but these are unevenly distributed around the globe. It is especially far between measuring stations in the polar areas and over the oceans. This leads to a certain amount of uncertainty in the establishment of the average global temperature. For example while the analysis shown in Figure 1 states that 2008 was the tenth warmest year, an analysis using another possible combination of station data places 2008 as the eighth warmest year[b]. This aspect is further illustrated in Figure 2 which also shows that a new year is not automatically warmer than the previous one, in spite of the fact that the long-term trend is one of warming.

In AR4 it was demonstrated that warming over the last 50-year period is well in line with the increase of greenhouse gas concentrations in the atmosphere. This conclusion is based on temperature trends up to and including 2005. One way of illustrating how global temperature change over the last few years may be compared with global climate simulations for the period 1990-2010 is shown in Figure 3. Here results from 21 different simulations of the global climate, all taken from the database used in AR4, are compared with the observed temperature trend up to and including 2008. In spite of the lack of temperature increase during the last years it can be seen that the curve lies well within the interval produced by the simulations when both growth of greenhouse gas concentrations and natural climate variability have been taken into consideration.

[b] WMO 2009. WMO Statement on the status of the global climate in 2008. WMO-No. 1039, 14 pp.

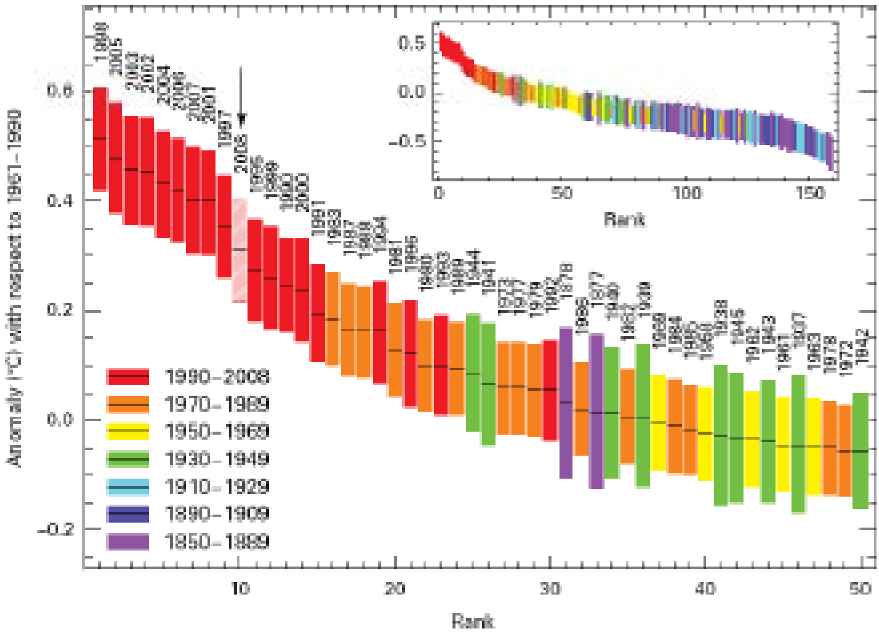

Figure 2. Global surface average temperature (HadCRUT3 data) for the 50 warmest years since 1850
Annual levels are shown as deviations from the average for 1961-90. Length of each annual bar gives an estimate of uncertainty (95%) of analyses[b].

To date climate projections have primarily dealt with the climate response to emissions. These are reported with a large number of projections in AR4. Overall these speak of a global temperature rise of 1.1-6.40C from 1990 to around 2095[c]. Climate models are based on the physical characteristics of the climate system and consequently also describe internal variations that occur, for example, through variations in heat exchange between the atmosphere and oceans. Calculations begin with a realistic, but not the observed, condition of the climate system. Consequently the simulated variability describes a possible course of events, but not necessarily the course of events that will actually occur. This is a way of taking into consideration the unpredictable, natural variability of the climate system. With the help of many such calculations a probablitity description can be established for both climate

[c] In addition to climate models, the underlying assumptions span possible future emissions and uncertainty as to how the carbon cycle will be affected by successive climate changes. Explicit assumptions on climate policies are not included. The figure has been taken from WMO 2009. WMO Statement on the status of the global climate in 2008. WMO-No. 1039, 14 pp., where it is stated that it originates from Met Office/Hadley Centre and Climatic Research Unit, Univ. East Anglia, UK.

change and variability. However, conditions regarding an individual year or even a specific decade cannot be determined.

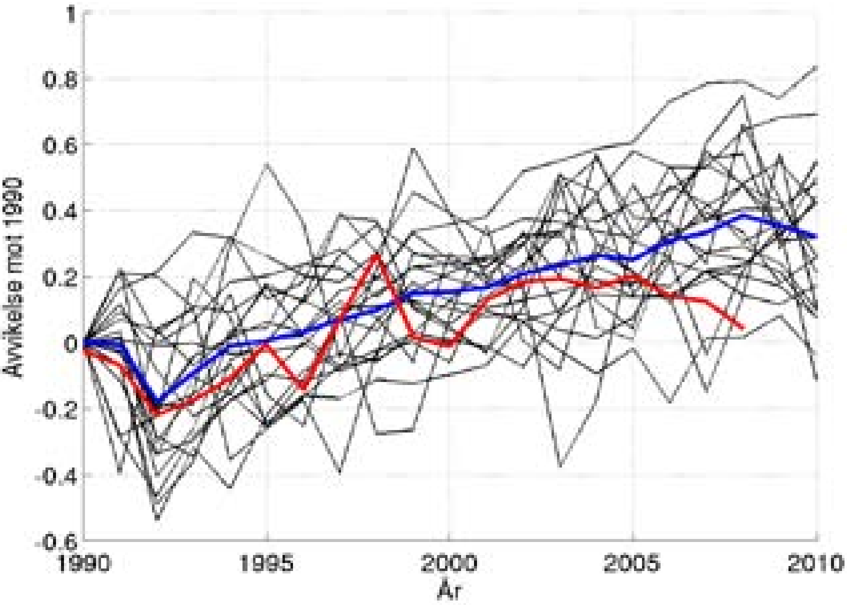

Figure 3. Global climate simulation results for 1990-2010
Calculated global annual average temperatures between 1990 and 2010 (thin lines) from 21 different global climate model simulations used in AR4. The mean value of these calculations is given in the thick blue line. Observed global average temperatures (from HadCRU3) are shown using a thick red line. All calculated temperatures have been normalised to a reference value of 1990. Source: SMHI.

Since AR4, first attempts have been published as concerns short-range climate forecasts, for the next 20-30 years. In these, climate simulations are initialised with regard to the current internal climate variability[2,3]. These results suggest that the next few years will be characterised by a natural climate variability phase that will reduce the global average surface air temperature, at the same time as the underlying warming trend, due to increased greenhouse gas concentrations, will continue. Today there is no cause to question the conclusions on temperature increase that were reported in AR4:

> *Observations of increased global average air and ocean temperatures, widespread melting of ice and snow and a rise in the average global sea level produces an unambiguous picture of the ongoing warming of the climate system.*

Temperature development 2006-2008 in Sweden

In Sweden the period 1991-2005 was considerably warmer than the latest so-called climate normal period, i.e. 1961-90[d]. Also 2007 and 2008 were rather warm. Especially the winter 2007/2008 was very mild (see Figure 4). In parts of eastern Sweden, this was the mildest winter since meteorological measurements began in Sweden, even considering Sweden's longest temperature measurement series from the 18th century. Compared to the previously highest levels, there was a difference of approximately half a degree Celsius in east Svealand. Nevertheless, it is still not possible to unambiguously attribute this regional warming to the global increase in greenhouse gas concentrations. Sweden represents such a small part of the surface of the earth that regional temperature fluctuations from purely natural causes could be a possible explanation for a few warm years. On the other hand, data from Sweden does not contradict the link between increased greenhouse gas concentrations and increasing temperatures.

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[d] SMHI Factsheet No. 29, 2006. Changing climate, 8 pp. (http://www.smhi.se/content/1/c6/02/35/52/attatchments/factabladclimate.pdf, 2009-03-29).

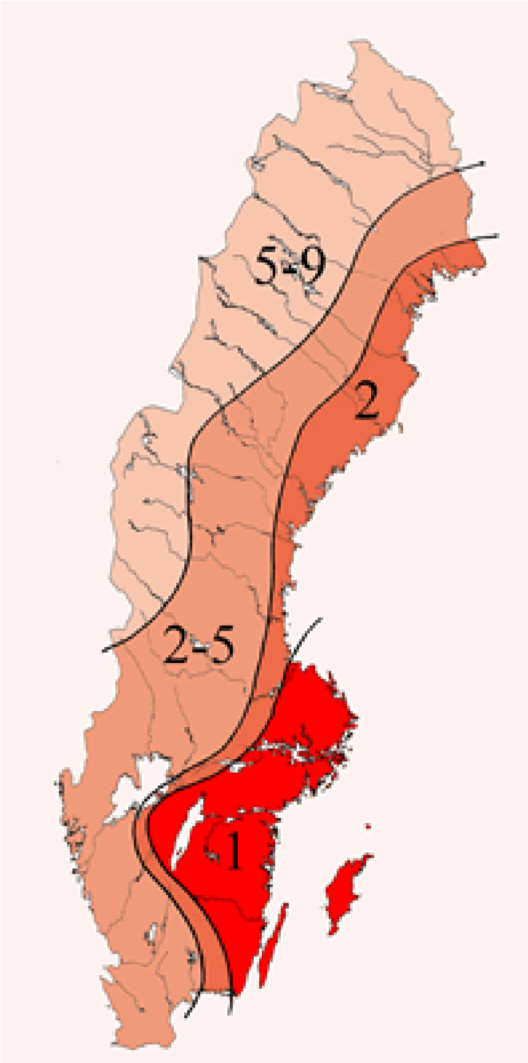

Figure 4. Regional ranking of the winter 2007-08 as concerns mildest winters on record
In east Götaland and east Svealand the 2007-2008 winter was the mildest on record since country wide measurements began about 150 years ago. Along the Norrland coast it was the second mildest winter. In the western parts of Götaland and Svealand plus inner Norrland the winter ranks in place 2-5, and in western and northern Norrland in place 5-9 on the list of mildest winters in Sweden. (Source: www.smhi.se 2008-03-04.)

Global sea levels

The rise in global sea levels is primarily dependent on two factors: the thermal expansion of water when it warms up and the increased supply of water from ice melting on land. Some effect also ensues from changes to the amount of freshwater in rivers and lakes, groundwater or artificial lakes. Observed sea level increases and estimates of how much was contributed by the different factors was summarised in AR4 (see Table 1). AR4 pointed out that there was a difference between the sum of the individual contributions from thermal expansion/ice melting and the observed total rise. This difference is relatively large for the period 1961-2003 while the correspondence is better for the period 1993-2003. Generally the differences lies within the range of uncertainty for the various estimates.

There is some uncertainty in data before and after 1993 because 1993 forms a dividing line between a period of sea level measurements from larger sea ports and the period when data from satellites with altimeters is also available[4]. Analysis of satellite data suggests a somewhat more rapid increase of sea level than data from conventional tide gauge measurements. Studies since AR4 confirm that sea level rise since 1993 has progressed more quickly than over the period 1961-2003[5,6]. As pointed out in AR4, and also confirmed in later research, over shorter periods of time natural variability may speed up or slow down changes to sea level. In the longer perspective the sea level follows the successive global warming.

The arrival of satellite measurements has provided an improved picture of regional variations in sea level change. This information is important in itself and it can also be used to improve comparisons between conventional measurements from only a limited number of locations with model results that provide a large-scale picture of sea level changes. Similar considerations have also been utilised to compare modelled and observed data concerning heat storage in oceans[7]. Previously stated differences decrease considerably when the uneven coverage of measurements is taken into consideration, together with the effect of changes in measurement techniques and other kinds of development of analysis of measurements and models.

Thermal expansion of water is a major component of the rise in sea level. According to AR4 it explains approximately one fourth of the total observed rise between 1961 and 2003. For the period 1993-2003, thermal expansion is responsible for almost half the rise. The rest is caused by melt water from smaller glaciers and, during the latter period, also from the land ice on Greenland and in Antarctica. For the last few years, results suggest that the relationship between the contributions of thermal expansion and ice melting can have changed. While one study shows that sea level rises over the last few years are 70-80% dependent on melting ice[5], another study concludes that the contrubutions of ice melting and thermal expansion are more even[6].

The correspondence between observed sea level rise and the sum of its contributing factors has been further studied. An argument has been laid forward that construction of artificial water reservoirs and increased utilisation of ground water has exerted comparable, but opposite, effects on sea level[4]. Another study has concluded that increased storage of fresh water in artificial reservoirs has countered the rise in sea level over the last 50 years by about 3 cm[8]. This would mean that the total gross effect on sea level of both the thermal expansion and ice melting would be almost 2.3 mm/year (approximately 1.7 mm/year according to Table 1 and in addition just under 0.6 mm/year) during the same period. During the later period 2003-2006, it is stated that some of the water would have been transported from the terrestrial reservoirs back to the sea, corresponding to a global sea level rise of a couple of tenths of a millimetre per year.

Table 1. Observed sea level rise (mm/year) according to different studies
Calculation of anticipated effects of thermal expansion and ice melting is stated in brackets. In AR4 data for 1961-2003 possible changes in fresh water storage are not included.

	1961-2003	1993-2003	2004-2007
AR4	1,8±0,5 (1,1±0,5)	3,1±0,7 (2,8±0,7)	
Ref[4]	1,6±0,2	2,3[x]	
Ref[6]			1,5±1,0
Ref[6]			2,4±1,1
Ref[6]			2,7±1,5
Ref[5]		3,1±0,4 (3±0,5)	2,5±0,4[y] (2,6±0,3[y])

[x] Study does not provide uncertainty estimates.
[y] Relates to 2003-2008.

The discussion concerning sea level clearly illustrates how new results can detail or modify previous results which leads to improved knowledge.

Corrected global temperature data

Temperature statistics are based on underlying observations that have been collected from a number of different sources. Each data source has its characteristic weaknesses and uncertainties. Observation technology changes over time. Observation locations are added, moved or disappear. A great deal of emphasis is placed on studying the accuracy of observational data as this forms the basis of our knowledge concerning ongoing climate change. Data analyses that encompass enormous amounts of complex, compounded observations, are continuously reassessed and evaluated. Since AR4 some systematic biases have been found compared to previous data analyses. These do not alter conclusions as concerns the significance of the current changes, however the realisation does provide relevant improvements of available knowledge.

One aspect of global temperature variations that the climate models have not been able to capture in their simulations of the 20th century climate is the limited, but rapid, temperature fall in the middle of the century. A previously uncorrected effect in observations has now been localised concerning changes to methods for the collection of temperature data out at sea[9]. The change consists of the relative number of measurements that were made by US vessels (measurements at the cooling water intake point of the engines), and UK vessels (measurements using water collection buckets), see Figure 5. During WW II, most of these measurements were made by US vessels, while the proportions were more even before and after the war. These differences in data collection had not previously been noted. However it is well known that different measuring methods do give rise to different systematic errors. These new insights are not expected to change the overall picture of significant, successive warming during the 20th century. However, a correction downwards as concerns temperatures in the mid-1940s is expected, which in turn can be expected to lead to better correspondence between climate model simulations and actual measurements for the same period. In the same article changes to data collection methods during the last few years is also mentioned. There is an increased number of measurements coming from ocean buoys which also leads to systematic deviations that need to be taken into account. Buoy measurements typically give a somewhat lower temperature as compared to measurements from vessels, which should mean a somewhat greater warming trend during the last few years than has been assessed so far.

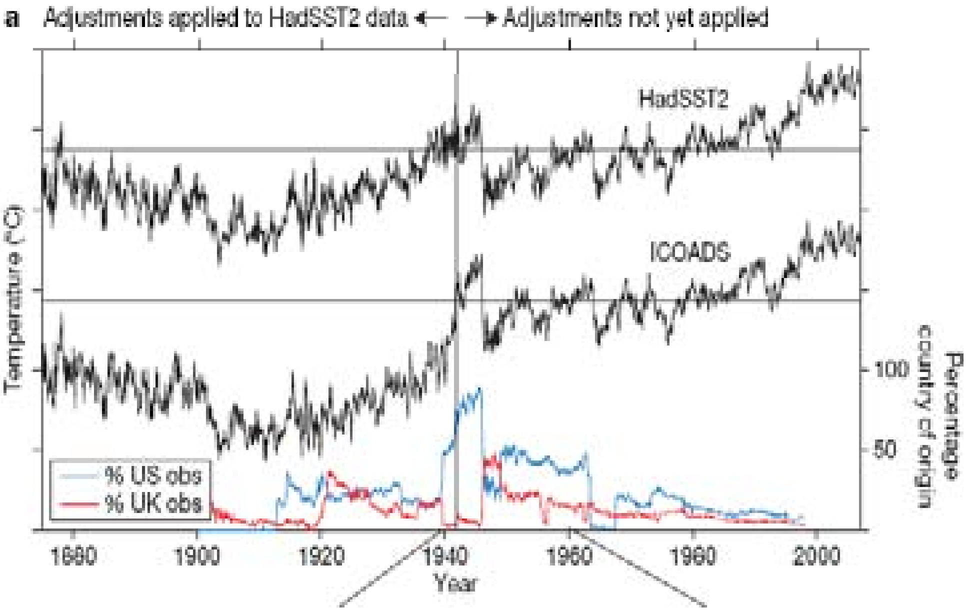

Figure 5. Two sea surface temperature analyses (HadSST2 and ICOADS) plus the relative amount of data collection made by US (blue line) and UK (red line) vessels[e]

Urbanisation effects

In AR4 the effects of urbanisation are stated to influence error limits in the determination of the global average temperature at less than 0.006°C per decade, that is extremely marginal. Sea surface temperatures are not affected at all. Locally, however, urbanisation effects on temperature may be greater. The established picture of global temperature rise has not been changed by these new studies. In two studies it is stated that the urbanisation effects have no large-scale importance [10,11] while a third maintains that trends over land between 1980 and 2002 are perhaps only half as large as previously stated[12]. The latter study is based on metho-

[e] Figure reproduced/adapted with the permission of Macmillan Publishers Ltd: Nature Thompson, D. W. J et al. 2008. A large discontinuity in the mid-twentieth century in observed global mean surface air temperature. Nature 453, 646-650. Copyright 2008.

dology developed in previous work which was discussed in AR4. This study was criticised in AR4 and the method is not considered reliable. In addition it has later been shown[13] that the relationships utilised do not contradict conclusions concerning urbanisation effects as stated in AR4.

Developments in the Arctic and the Antarctic – temperatures

Climate projections in AR4 show that the anticipated regional temperature increase will be greatest in the Arctic area, while a less extreme trend is expected in the Antarctic. At the same time the natural variability is also great in the Arctic.

Warming in the Arctic has continued over the last decade[14] (see Figure 6). Compared to the regional warm period in the 1930s, the mean temperature in the Arctic reached new record heights at the end of the 1900s and the beginning of the 2000s.

In AR4 it was found that the Antarctic was the only continent where no evident global warming has been observed. It was also pointed out that both the thickness of the Antarctic ice sheet and the dominance of ocean around Antarctica means that warming is expected to be slow in this area and natural climate fluctuations can for the time being be expected to dominate observed changes. However, warming has now been observed in the Antarctic as well[15,16] on the western part of the continent, although not as great or as wide-spread as that underway in the Arctic. In contrast to the Arctic area, Antarctica is almost totally covered by a thick sheet of land ice. Warming is not consequently able to be reinforced as it is in the Arctic due to local feedback. The Antarctic Peninsula in turn has already been observed in previous studies to display clear signs of warming.

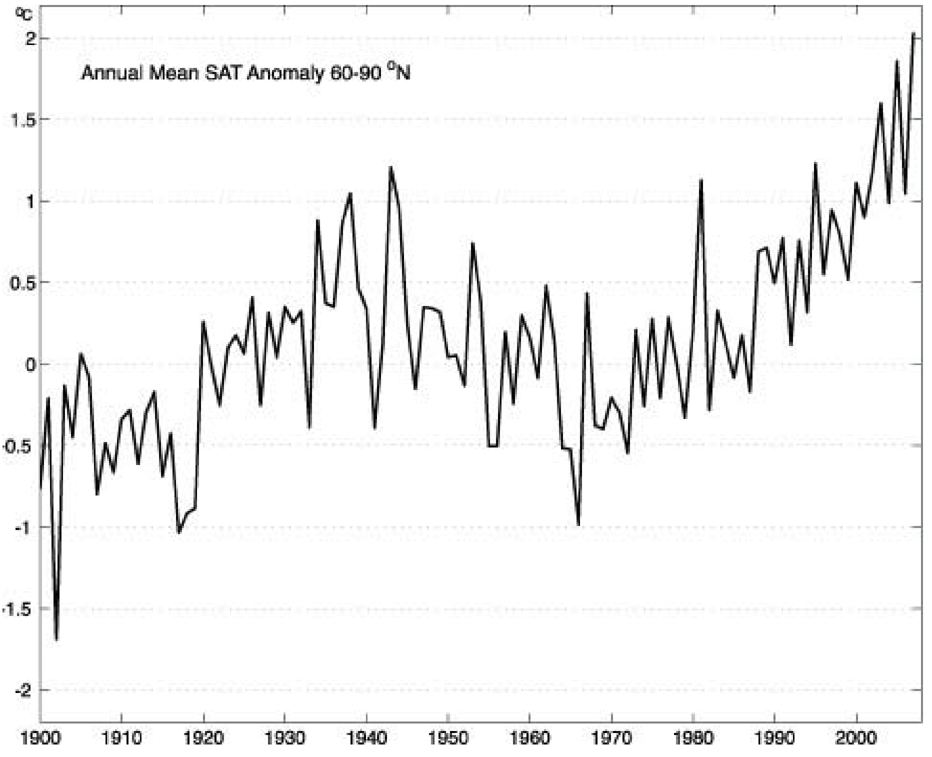

Figure 6. Surface air temperature (SAT) in the Arctic[f]
Stated annual values are deviations from the 1961-90 mean value.

Developments in the Arctic and the Antarctic – sea ice

In line with the regional temperature increase, the Artic sea ice cover has continued to decrease. Over the last 50 years, in the late summer/early autumn, it has decreased by about 30%. In 2007 the sea ice cover was the smallest ever observed in mid-September, around 5.5 million km^2. This is approximately 2 million km^2 less than the year before. The mean trend of decrease over the last 50 years lies around 0.06 million km^2 annually. In 2008 the minimum was slightly higher but still more comparable with the preceeding year than with earlier years (see Figure 7).

The sea ice cover around the Antarctic shows no clear systematic trends of change.

[f] Richter-Menge, J. et al. 2008. Arctic Report Card 2008, See http://www.arctic.noaa.gov/reportcard (2009-04-01).

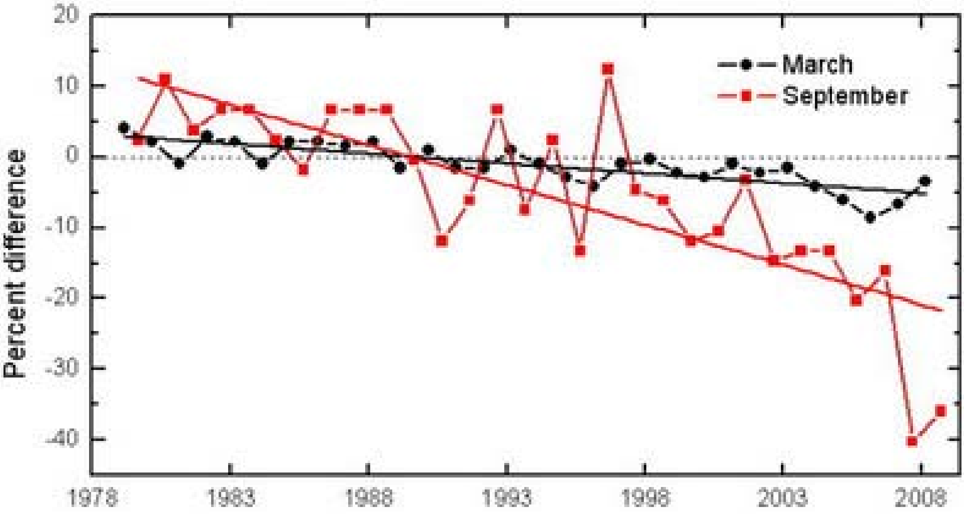

Figure 7. Difference of sea ice cover in the Arctic in March and September relative to the 1979–2007 mean[g]

Developments in the Arctic and the Antarctic – land ice

Greenland's ice has, over the last few years, shown some signs of increased melting[17] as compared with the beginning of the 1970s. Satellite data indicates occasional, unexpectedly rapid ice melting at the beginning of the 2000s[18,19]. The dynamic response of land ice to warming is complex. For example, something that is termed the "lubrication effect" may occur which means that melt water running down from the surface to the base of the glacier through holes and tunnels leads to decreased friction between the glacier and the underlying surface. This lubrication effect may speed up the glacier's slide towards the sea. Observations do not categorically support this [20,21,22] but indicate that there may be stabilising mechanisms in place, alternatively that instead of a lubrication effect the rapid changes observed may depend on locally warm sea water temperatures. Consequently the observed rapid melting episodes may be temporary phenomena.

The Antarctic ice melt is even more uncertain. In principle there are possibilities that the Antarctic ice sheet grows in a warmer climate due to increased snowfall and that melting increases in the parts that lie close to sea level. Which of these effects is dominant is extremely difficult to determine.

[g] Richter-Menge, J. et al. 2008. Arctic Report Card 2008, See http://www.arctic.noaa.gov/reportcard (2009-04-01).

New measurements, which are supported by regional climate modelling, indicate a total ice reduction, which could in addition have been accelerated between 1992 and 2006, the time period to which the study applies[23]. It has also been shown that different parts of Antarctica are affected in different ways. On the continent's eastern side the changes are small or non-existent while parts of western Antarctica and especially the Antarctic Peninsula are losing ice.

Possible acceleration of ice sheet melting would increase the anticipated rise of sea level (see section entitled Sea level rise at page 41).

The North Atlantic meridional overturning circulation

Global warming may lead to changes in the current patterns of the oceans. In AR4 model simulations indicated that the strength of the Gulf Stream would be reduced by a larger global warming. In the Nordic countries, global warming would still dominate in spite of decreased warmth brought in with the Gulf Stream. In AR4 individual studies were also reported in which observations suggested signs of a decrease in the strength of the Gulf Stream. Yet later studies in turn indicate, however, that the variability of ocean circulation from year to year is so great that data from individual years is not sufficient to establish possible long-term trends[24]. In a study covering ten years from 1995 to 2005, no significant changes were found in the waters around Iceland and the Faro Islands[25].

Thousand year perspective

Historical climate changes before the instrumental measurement period (i.e. before around 1850) can be estimated with the help of paleoclimatological data. In AR4 paleoclimatology was covered in detail. For example, it was concluded that the temperature rise at the end of the 1900s was unique in a perspective of at least 1300 years back. Research during recent years has confirmed this conclusion as well as the conclusions stated in AR4[26]. However, the choice of the statistical method used and the selection of data has also been criticizied[27]. Several studies over the last few years do, however, indicate that this criticism is neither robust nor especially justified[28,29,30,31,32]. Temperature levels at the end of the 1900s have not been exceeded for any longer period over the last thousand years and perhaps even as far back as the last 1700 years – since 300 AD.

3 Emissions of greenhouse gases and particles in the atmosphere

Greenhouse gas concentrations are rising, particle levels more uncertain

The atmospheric concentration of carbon dioxide has continued to rise. Between July 2007 and June 2008 the carbon dioxide level measured at just under 384 ppmv[h]. As was already noted in AR4, global emissions have increased more rapidly since 2000 than previously. Even the rate of increase of atmospheric carbon dioxide level accelerated at the beginning of the 21st century, which was linked to increased emissions but may also be partially connected to a weakening of natural carbon sinks[33]. However it is unclear how permanent the more rapid increases of the last few years are[34].

One related aspect is that, while the pace of increase of the atmosphere's methane level decreased from the beginning of the 1980s, a global turning point was observed in 2007[35]. This could be temporary, at the same time as it appears to differ from previous temporary increases around 1998 which may have been caused by the effect on the then strong El Niño on methane exchange in ecosystems, and around 2002-2003 when there was an increase on the northern hemisphere. The increase of the methane level over the last few years probably depends more on larger net emissions than on, for example, changes in atmospheric chemistry. There are certain reasons to believe that the net emissions have increased in the northern hemisphere rather than in the southern.

As concerns particles in the atmosphere, the latest research provides somewhat varied results as concerns global changes. Over Europe, regional decreases have been clearly documented[36], while levels are increasing in, for example, southeast Asia[37]. Satellite measurements support a decrease of particle amounts since the 1980s[38]. However, these conclusions are indicative in light of the uncertainty inherent in satellite measurements. A compilation of land-based observations between 1973 and 2007 indicate the varied, regional changes mentioned above[39], while compilations relating to the global land area as a whole indicate a rise[40]. Black carbon – soot – has received considerable attention[41,42]. Calculations show that it may be causing a considerable regional warming effect in Southeast Asia. Possibly also soot particles deposited on ice and snow in the Arctic contribute to Arctic warming.

[h] http://cdiac.esd.ornl.gov/pns/current_ghg.html (2009-03-27).

4 Are humans responsible for climate change?

In AR4 it is definitely shown that the temperature of the earth's surface has increased during the 20th century and that several other related changes in climate have become evident. Some examples include increased melting of the sea ice in the Arctic, increased occurrence of heat-waves and droughts, increasing ocean temperatures and rising sea levels. Later research findings have extended detection (i.e. identification of significant changes in climate) to even more aspects of the climate system. Examples of this are changes in the humidity in the atmosphere, a more extensive rise in temperature in the Antarctic than was previously discussed, changes in river flow and river systems as well as changes in precipitation over land. While detection concerns identifiying significant changes, attribution means taking an additional step. Attribution is defined as a determination of the most likely causal connections between a conceivable influence and a verified change.

The Arctic

In AR4 there is no clear conclusion as to a causal relationship between human influence on the global mean temperature and the rapid Arctic warming. However, the research in recent years point clearly in this direction.

The long-term trend in Arctic warming and the reduction of sea ice is probably a consequence of global warming during the same period. The melting sea ice itself contributes to the increase in Arctic warming. When the sea ice melts during the summer months a smaller amount of solar radiation is reflected back into space and the Arctic area retains more heat. Moreover, a new study[16] shows that it is not possible to explain Arctic warming during recent decades as a result of natural climate variations. Nevertheless, a mere successive warming does not suffice to explain the rapid sea ice cover reduction that occurred in 2007 and 2008. This is also dependent on unusual conditions in the atmosphere and the sea which may fit within natural variations.

It has been shown[43] that warming in the Arctic is greatest at a height of approximately three kilometres and that changes in atmospheric heat transport may explain a considerable amount of Arctic warming. It is difficult to investigate the warming over the Arctic Ocean basin. There is a lack of conventional data from weather balloons and data studies are based on satellite measurements. By means of a special method of meteorological analysis called re-analysis, satellite data is combined with information from other observational data in the immediate surroundings of the Arctic. The use of this method has been criticised with reference to different observation data that indicates that the results may be due to systematic biases in the re-analysis[44,45,46]. The authors of the study in question consider that, within the framework of the uncertainty of the method, the results hold up[47]. These results do not contradict human effect on climate as an explanation of drastic Arctic warming. Rather, they underline the complexity of cause and effect in the Arctic region.

The Antarctic

Climate change in the Antarctic[15] can, to a certain extent, be associated with global warming[16]. The pattern in temperature variations and warming of parts of the Antarctic continent may be explained as a combined result of anthropogenic global warming and changes in atmospheric circulation patterns which have been observed in the southern hemisphere. The latter may, in turn, depend on the current warming, but may also have been affected by the thinning of the ozone layer in the Antarctic[48].

Precipitation changes

The amount of water vapour in the atmosphere increases in a warmer climate. In AR4 reference was made to studies that showed a significant increase in the water vapour content of the atmosphere over the last 20 year period, which may lead both to a considerable precipitation increase in the mean and to more intensive rainfall. At the same time, dry areas will become even drier. However, in AR4 there are no studies that show precipitation trends from observations over the last 50 years. Now trends can be identified[49] after dividing the earth into latitude belts. In general, precipitation has decreased over sub-tropical areas while it has increased over middle latitudes.

A later study of satellite data indicates that precipitation increases in parity with the water vapour content of the atmosphere,[50,51] which would be stronger than the conclusions of many earlier studies with regard to both measurements and simulations using climate models.

Tropical cyclones

Tropical cyclones are formed in the sub-tropical areas of the Atlantic, Pacific and the Indian Oceans. These cyclones gain energy from warm sea water. When they blow in over land they die out quickly. Sea surface warming can thus affect the strength and the frequency of tropical cyclones.

In AR4 it was established that the number of severe tropical cyclones in the tropical and sub-tropical parts of the Atlantic has increased since the 1970s and that this trend corresponds to increasing sea surface temperatures [52,53]. There is no clear trend in other parts of the tropics which may depend on a lack of data coverage. On average, throughout the entire tropical area, no trend is evident in the number of tropical cyclones.

Later studies of tropical cyclone data provide no clear picture of a rising trend. For example, it has been reported that the number of tropical cyclones reaching the continental USA has, in fact, decreased concurrently with the increase in sea surface temperatures[54]. This may depend on increasing upper level winds in tropical areas which may lead to a reduced frequency of tropical cyclones. Continued global warming could lead to such wind changes in parts of the tropical areas[55]. However, it is not clear whether it is this phenomenon that is the cause of the above-mentioned decrease in tropical cyclones observed.

Projections of future changes in the intensity and the number of tropical cyclones are very uncertain. The number of tropical cyclones could decrease in a future climate with warmer sea surface temperatures[56], but at the same time they could become more intensive[57]. Both studies start from the projections of change to large-scale circulation patterns that are presented in AR4 but they use more detailed limited area models to simulate tropical cyclones. It is thus not possible to draw general conclusions about future tropical cyclones. It is possible that more intensive tropical cyclones will occur when global warming continues, but on the other hand the total number of tropical cyclones may decrease.

Warming of the troposphere and cooling in stratosphere

Warming of the earth's surface is the clearest temperature signal today. In what is known as the free atmosphere (the troposphere) there is also warming, but the signals are not as clear. The tropospheric warming pattern does not quite agree with what would be expected on grounds of physical reasoning. This has been the focus of an intensive discussion in scientific literature. In 2008 a number of studies clarified why the discrepancies appear so great. These studies present new analyses of observational data that agree much more closely with physical/theoretical model results than has earlier been the case.

Humidity, temperature and wind data have been available via radiosoundings (weather balloons) since the 1950s. However, one basic problem is the lack of sufficient numbers of reliable observations in the free atmosphere, particularly in the tropics. One special problem with temperature measurement by radiosondes in the upper troposphere is the effect of solar radiation. The sun's rays heat both the balloon and the temperature sensor. The temperature that is registered must therefore be corrected for systematic errors connected to solar radiation. These corrections have been made in different ways and it has been difficult to assess the reliability of the radiosonde temperature measurements in the upper troposphere. Since the end of the 1970s, satellite data has increased geographical cover. Satellite data, in turn, is characterised by limited accuracy of measurement and quite coarse vertical resolution.

In AR4 it was observed that the warming trend of the last 50 years in the lower part of the troposphere agrees well with surface observations. In the upper part of the troposphere warming is not as evident, while in the stratosphere a cooling is observed. While the latter agrees with what would be expected of an increasing greenhouse effect, the lack of warming in the upper troposphere, especially in tropical areas, does not agree with what is expected of an increasing greenhouse effect. In the tropics there is intensive heat transport from the surface up to the upper troposphere via cloud formation and subsequent release of heat as the water vapour becomes drops of water and ice crystals. This condensation process generates huge amounts of heat. A surface warming should give rise to increased vertical heat and transfer and in connection with cloud formation, provide for a large temperature increase in the upper troposphere.

By means of a thorough quality control of radiosonde data and corrections of systematic errors in temperature measurements from the tropical upper troposphere, a new picture of a warming trend in the free atmosphere has evolved. There is a warming over the tropics that is in agreement with satellite data and model simulations[58]. A new method based on wind observations[59] shows likewise a warming trend in the upper troposphere which closely agrees with results from physical/theoretical calculations and model simulations. The advantage of wind observations is that they are not affected by solar radiation effects in the upper troposphere and thus are not burdened with the same error sources as temperature data from radiosondes.

In other words improved quality control of radiosonde data and expanded model-observation comparisons has led to improved concordance between observations and model simulations in the upper troposphere than what was presented in AR4.

5 *Natural climate forcing factors*

Althoug it appears all the more evident that most of climate change observed today is anthropogenic, the climate is of course also affected by natural factors. The prevailing climate is on each occasion a combination of external influences as well as the internally generated variations of the climate system. To what extent the different factors are known and understood differs. The role of solar effects in climate change during the 1900s is one such issue. In AR4 it was stated that changes in solar radiation have caused a distinguishable, but very limited, warming effect during the same period in which the human influence on climate has increased. Also hypotheses such as a connection between changes in the sun's magnetic field, cosmic radiation and cloud formation, are discussed in AR4. The conclusion is that possible such interplay has probably not affected climate development during the 1900s to any great extent. This is further confirmed by later research.

The sun and climate change today

A possible connection between the variations in the global mean temperature and what is known as the sunspot cycle was discussed early on in modern climate change research. Some researchers found correlations between them, but could not give any physical explanation based on physical science. According to later research, the global mean temperature swings 0.2°C between the maximum and minimum of the sunspot cycle[60]. Furthermore it was proposed in the same study that, in order to explain the effect on mean temperature of such minor differences in solar radiation that occur during a sunspot cycle, the same amplification mechanisms must be in play that amplify the warming effect of the increasing concentration of greenhouse gases in the atmosphere. In any case, no important increase in incoming solar radiation has been observed during recent decades[61]. These results are generally in line with what was presented in AR4.

The search for rapid changes in cloud cover when there are temporary increases in incoming cosmic radiation has not provided any unambiguous results to support a hypothesis of such a connection[62]. The satellite data now used includes more cloud characteristics than those used in earlier studies and also more geographical regions have been studied. Although laboratory studies indicate[63] that cosmic radiation that ionizes atmospheric molecules may lead to new cloud condensation nuclei, studies of atmospheric data do not show that this is of global importance. More indirectly this is supported by studies[64] that indicate that the amount of incoming cosmic radiation has not changed during the recent decades in the way that the hypotheses would expect, when the global mean temperature has increased.

Research on historical and pre-historical climate periods supports the idea that the sun is a natural climate forcing factor. For example there is one study[65] which, among other things, deals with the connection between solar variability, temperature variations and monsoon circulations. This study states that historical links between these were broken after the middle of the 1900s. This is interpreted as resulting from an overriding increasing anthropogenic climate effect. There also are studies using climate models that come to similar conclusions[66].

The latest research confirms the result that solar variations cannot have played any large or important role in climate development in recent decades. Some hypotheses that have been proposed are too complex to be tested with observation data available.

6 *Climate projections*

Sea level rise

One area of research where a great deal has happened over the last few years is the assessment of how the global sea level may rise during this century and beyond. In many cases the estimates put forward in AR4, i.e. a global increase in sea level of 18-59 cm between 1990 and 2095, have been extended towards even larger values. However, it should be remembered that this interval in AR4 did not include a possible acceleration of land ice melting, for which the available data was deemed to be too uncertain. Even in light of the more recent research the overall assessment of the sea level rise presented in AR4 still appers valid. Nevertheless the risk of a considerably greater rise is now more emphasised.

There are calculations that show that the global sea level may rise by up to 0.8 metres by 2100 if the land ice melt rate speeds up[67]. The same study also shows that a sea level rise of more than 2 metres by 2100 is physically unreasonable. Also, a rise of 2 metres would require that all the relevant uncertainties acted in the same direction.

In a study that focused on the minimum expected rise in sea level, a rise of 0.5 metres is suggested[68]. Strictly speaking, this research concerns how much mountain glaciers and suchlike (continental ice sheets are not included) will continue to contribute to the sea level rise due to the global warming that has already taken place. This is calculated at 0.18 metres which, together with an expected continued thermal expansion[5], would give a global rise in global sea level of at least 0.5 metres up to 2100. An assumption of a continued warming and its effect on mountain glaciers over the next 100 year would increase this estimate to about 0.7 metres.

Part of the argumentation for a considerably larger sea level rise than that projected earlier is inferred from knowledge about prehistorical climate periods in connection with the most recent ice age (sea level rise of the order of 0.7-1.5 m over 100 years)[69,70] and climate periods even farther back in time[71,72]. An extrapolation[73,74] of the observed sea level rise over the last 100 years leads to comparable conclusions, as does simplified modelling calibrated using knowledge about past sea level data[75]. One disadvantage of using historical periods are the large differences back then compared to today in the basic characteristics of the climate system, for example the distribution of the amounts of ice between the northern hemisphere and that in the Antarctic. Possible non-linear connections and links within the climate system may be different depending on the base climate state.

Tipping points

Tipping points (see Figure 8) are defined as critical threshold values in the climate system. Exceeding a tipping point significantly influences a climate effect, for example leading to an intensive melting of ice or a sudden release of greenhouse gases from ecosystems. The part of the climate system thus affected is called a tipping element. Tipping points have long been discussed in connection with climate change, using terms such as "abrupt change". An oft-quoted example is a possible "collapse" of the Gulf Stream[i] which would cause consequences for climate development over the North Atlantic and in neighbouring regions. Other examples are a possible melting of land ice on Greenland or in parts of the Antarctic (e.g. the West Antarctic Ice Shelf, WAIS)[76,77], which would further increase sea level rise. Another example is a possible change of the rainforests of the Amazon into savannah, the escape of methane gas from thawing permafrost areas[78,79,80] or from hydrates[81]. If the latter should happen, the consequence could be a greatly increased greenhouse gas amounts in the atmosphere and consequently an even greater climate change than according to most projections until now. Alternatively, an even greater reduction of emissions would be required to stabilize the climate.

There is a considerable lack of quantitative knowledge about where the different tipping points are located in terms of size and pace of global and regional climate.

[i] Actually, one means a change in the large-scale ocean circulation in the North Atlantic.

Figure 8. Various potential tipping elements in the earth system[82]

Expert assessments are one way of addressing these issues[82]. Here both the probability that continued global warming might lead to the reaching of tipping points and the level of knowledge on ensued changes in related climate effects are adressed. Such assessments lead to the conclusion that tipping points are a relevant issue. The most immediate tipping points in the climate system are proposed to be the receding sea ice cover in the Arctic and a melting of the Greenland ice sheet. The effects of the latter on the global sea level were discussed previously in the section on Climate Projections. Projections of sea ice cover changes in the Arctic are discussed below.

During the late summer and early autumn of 2007, record low levels were measured in the Arctic sea ice[83]. The sea ice cover was almost 50% less than the average for the period from 1950 to 1970[84]. In AR4 the ongoing decrease of the Arctic sea ice cover was discussed quite extensively. A clear downward trend is documented for the period since the middle of the 1900s. Even so, the drastic decrease in 2007 was a complete surprise. It has even been referred to as a tipping point[85]. There is an argument for the possibility that a critical threshold has been reached in the case of the Arctic sea ice cover. However, there also are researchers who argue against this point of view[86]. The extent of the sea ice depends on the energy balance in the Arctic during the ice melting season, the extent of the ice cover during the previous winter and circulation patterns in the atmosphere and in the ocean[87,88]. In 2007 several of these factors were combined which resulted in a markedly accelerated summer melting[89]. 2008 was another year when there was very little late summer sea ice in the Arctic, even though the rapid melting did not begin until August. In some years the different factors at play work together while in other years the circulation in the atmosphere, for example, may be different and may prevent rapid melting from occurring. How things will be during a particular year is more or less impossible to predict. Consequently the Arctic sea ice cover will continue to vary from year to year. It is, however, probable that the decreasing sea ice cover trend will continue with further global warming (see Figure 9)[90].

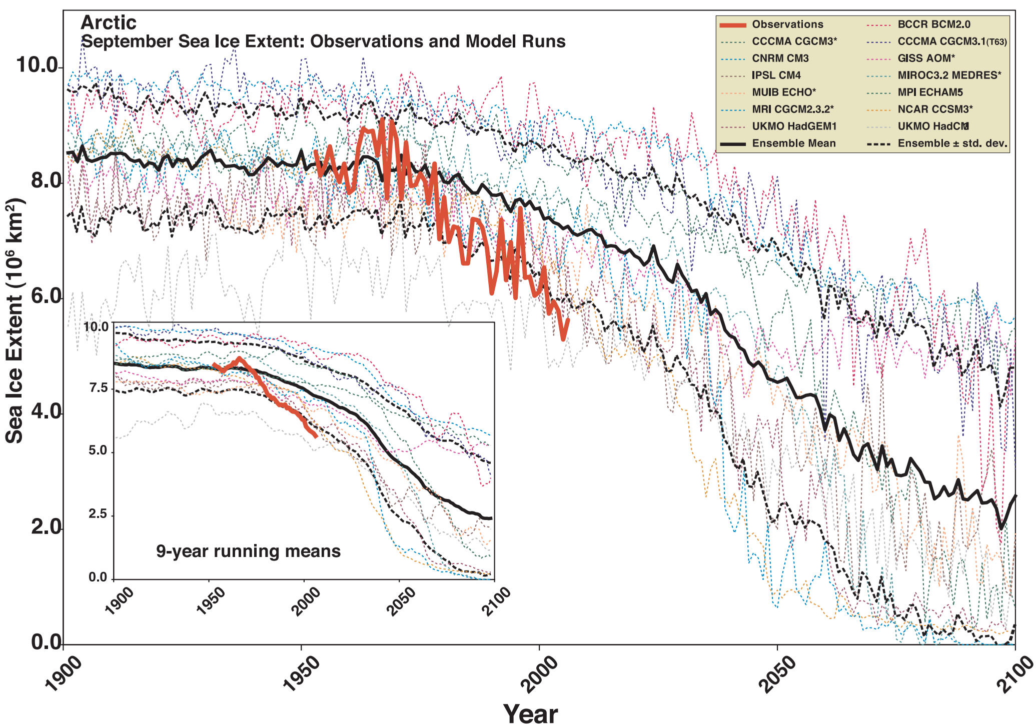

Figure 9. Simulations of historical and future changes in the Arctic sea ice cover[91]

Several models from CMIP3[1] have been analysed. The red curve shows the trend observed up to and during 2006.

Projections of future sea ice melting have been made using climate models under assumptions of increasing greenhouse gas concentrations[91]. Simulations clearly show a continuously shrinking sea ice, yet no simulation has succeeded in capturing the dramatic melt episode in 2007-2008. Overall, also the rate of melting over the last decades is greater than in the model simulations. It is not clear why the models underestimate the rate of melting. The energy balance in the Arctic is sensitive to a number of factors that are less than fully understood. Examples of such factors are cloud cover, heat transports in the atmosphere and in the ocean[92] and the thickness of the sea ice[93]. The amount of multi-year sea ice in the Arctic Ocean basin has greatly decreased; a 50% decrease is shown over the last 50 years[94]. This decrease means that one-year ice formed every winter is more widespread. One-year ice is thinner than multi-year ice and therefore it melts more readily during the summer[95]. Consequently a continued decrease of the Arctic sea ice cover can be expected. It is very difficult to predict when the Arctic will become ice free in the summer, but it could happen at some time towards the middle of the century[90,91].

7 *How extensive could climate change become?*

Climate sensitivity

Climate sensitivity is a measure of the temperature increase due to a change in the atmospheric carbon dioxide concentration (it is also possible to think in terms of carbon dioxide equivalents – if with some caution). Changes to carbon dioxide levels influence the greenhouse effect which in turn leads to changes to the surface air temperature etc. In AR4 the climate sensitivity due to a doubling of the carbon dioxide level is concluded to lie somewhere between 2 and 4.5°C with a best estimate at around 3°C. It is further stated that it is unlikely that climate sensitivity is less than 1.5°C, while levels higher than 4.5°C cannot be ruled out. In studies during the last few years adjustments both upwards and downwards have been proposed. A brief summary of the climate system's radiation balance and the factors affecting it is given in Appendix A as a background for the discussion below.

One new study shows how previous estimates of climate sensitivity from complex models can be compiled into very simple model. One strong conclusion is that uncertainty in the direction of higher climate sensitivity is more probable than uncertainty in the direction of lower climate sensitivity[96], which is already indicated in AR4. At the same time the established picture of climate sensitivity has been questioned as concerns the uncertainty regarding the slower responses of the world ocean[97]. The argument is that ocean temperatures in general have already adapted to the change in the radiation balance so far and consequently the temperature on the surface of the earth will not increase especially much if current carbon dioxide levels were to not to change (that is climate sensitivity is rather low than high). This is not consistent with the discussion in AR4 that indicates that the oceans are currently not in energy balance. The author of the study that proposed low climate sensitivity has later stated[98] that he underestimated climate sensitivity. His revised results are close to the results reported in AR4. Studies that take proxy data from the last 700 years as a point of departure also frame a picture of climate sensitivity in line with the interval stated in AR4[99], although stating a somewhat broader span.

One special aspect of climate sensitivity has also been highlighted. The accepted definition does not consider possible, more long-term effects of warming. If the feedback concerning the melting land ice is included, which is a possible if still uncertain consequence of global warming, climate sensitivity may be around 6°C in spite of estimates of cloud and ocean effects being approximately the same as in the studies that underline the AR4 estimate.

One aspect of aerosols that has received increased attention is the warming from airborn black carbon particles (soot) that occurs at a few kilometres above the surface of the earth[37,42]. These are primarily found in tropical areas, largely as a result of burning of fuel wood. In addition to their effects on temperature and their harmful effects on human health, soot may also contribute to a change in tropical precipitation patterns. This phenomenon may have affected the monsoon rains over India and parts of the Himalayas during the last few decades[42]. Locally, in heavily polluted areas, the warming effect from soot may exceed warming caused by the enhanced greenhouse effect.

The warming due to enhanced greenhouse effect leads to more water vapour in the atmosphere which in turn reinforces the warming. This is in fact the strongest feedback effect that is known, and is consequently central to climate change estimates. In AR4 it has been stated that especially satellite measurements show that the atmospheric water vapour content increased at the end of the 1900s in pace with increasing temperatures. This has been confirmed in later studies[100,101,102]. The exception is one study[103] that shows that water vapour has decreased in the upper part of the tropical troposphere. This is supported by a special dataset, one of the so-called re-analyses, from NCEP/NCAR. It is known that this re-analysis has weaknesses in the processing of satellite data and that in the tropics, humidity information comes from radiosonde data only. In spite of the lack of a humidity increase in the tropical upper troposphere, this re-analysis shows a warming trend the equivalent of that in other re-analyses, for example ERA-40. Furthermore when how the atmospheric water levels respond to temperature variations is examined[104], a good agreement is achieved between observations and climate model simulations. This supports the AR4 estimates of climate sensitivity.

Unavoidable contiued warming

Research over the last few years has also dealt with what the ultimate lowest level – unavoidable – global temperature rise is. In AR4 it was stated that if greenhouse gas concentrations had stabilised at the levels that had been reached in around 2000, the earth would still become an additional half a degree Celsius warmer.

New estimates of aerosol radiative effects show that the associated uncertainty may be greater than that stated in AR4[105,106.] According to these studies aerosol radiative effects are greater than previous calculations have shown. In that case we would have a larger, unavoidable continued warming ahead of us than so far has been expected. However it has also been asserted that calculations of future climate change have not been very much affected by aerosol uncertainty as the increased greenhouse gas forcing is so much more dominant that that of aerosol forcing[107].

A further perspective of the unavoidable, continued warming is applied when not only the climate's but also society's inertia[108] is included, i.e. that it takes time to achieve a sizeable reduction of emissions. It is hardly surprising that the conclusion is that continued temperature rises will then be greater. Just as expected are the results that assumption of decided emission reductions decrease climate change to a considerable degree, perhaps as much as by half of the original temperature change interval. For a number of scenarios that include established emission decreases, future warming is almost halved up until 2100 as calculated from 1990. This means a warming decrease of 0.3-3.4°C compared to various baselines. Remaining warming after 1990 is within the interval 0.5-4.4°C. The expected continued global warming therefore to a first degrees depends on emissions.

A more complete picture is gained when a difference is made between long-term climate forcing (carbon dioxide emissions) and climate forcing that disappears rapidly (anthropogenic particles) or fades away relatively quickly (e.g. methane emissions). If the climate forcing by particles is greater than that stated in AR4[109], greenhouse gas emissions to date may cause unavoidable temperature increases of at least 2.4°C as compared with pre-industrial temperature levels. These 2.4°C consist partially of the warming already observed while the rest is the part that has so far been masked by the oceans' slower response and the net cooling effect of anthropogenic atmospheric particles. At the same time it must be remembered that such anthropogenic greenhouse gas additions to the atmosphere as of methane and tropospheric ozone, like particles, could be reduced relatively efficiently[110]. This means, in turn, that even if it were confirmed that the climate forcing by particles were underestimated in AR4, this does not have to mean that the committed warming is at least 2.4°C, if methane and tropospheric ozone levels were to decrease at around the same pace as particle levels.

The fact that climate change caused by anthropogenic emissions is more or less irreversible for a long period of time into the future is, in itself, nothing new. Nevertheless, the more recent research has shed additional light on this fact[111].

Carbon sinks can be affected when the climate changes

It is well-established that the natural carbon sinks in the ocean and in the land biosphere take up approximately half of the gross, annual anthropogenic emissions of carbon dioxide. AR4 described how these sinks can, as time goes on, become less efficient, which for a given emission development would provide a positive feedback with an even larger temperature increase as a result[112]. The terrestrial sink could even become transformed into a source instead.

The fact that the ability of ecosystems to bind carbon can be weakened by continued global warming is supported by later studies[113,114,115,116,117,118]. For example, extensive drought can affect terrestrial carbon sinks. As has already been stated in AR4, this may enhance global warming as compared to a situation with stable carbon sinks. This would in turn decrease the volume of "allowable emissions" if the climate is to be stabilised over time.

A regional weakening of the ocean sink has been noted in the Southern Atlantic around Antarctica since the beginning of the 1980s[119]. It has been speculated that the cause could be changes in the regional wind climate that has altered the exchange of carbon dioxide between the ocean and the atmosphere. Wind changes, in their turn, are assumed to depend on anthropogenic warming or, as mentioned previously, also on the stratospheric ozone depletion over the Antarctic[48]. This carbon sink strength weakening is expected to continue in pace with temperature increases. This is an example of a change (weakening) of the physical carbon dioxide sink. As concerns the biological ocean sink (plankton), this could become a little more efficient[120,121]. According to new studies, the efficiency of the carbon sinks decreased somewhat at the beginning of the 2000s, especially the ocean sink.

The 350 ppm debate

What is known about the climate system from measurements, studies of previous climate events and experiments with climate models is fundamental to discussions and decisions on wich measures to take. The scientific knowledge base is a necessary precondition in order to assess how different measures may affect future climate. In AR4 it is emphasised that we know enough to be able, with a great deal of certainty, to state that increased greenhouse gas concentrations have affected the global climate. We also know that future carbon dioxide levels can cause climate changes that will seriously, negatively affect major parts of the population of the earth. Research after AR4 has added to the knowledge on the climate system and there is not much that counters the conclusions drawn in AR4. Quite the opposite, results tend to show that the effects of warming are greater that what had been previously assessed and that future changes may be greater than what was previously shown. The urgency of taking measures to decrease emissions and adapt ourselves to climate change has consequently become greater rather than less acute when compared to the knowledge available just few years ago.

The so-called 350 ppm debate provides an illustrative example[71,72,122]. This is based, among other things, on climate episodes in the distant past. If land ice were to react considerably more rapidly than what has been assumed, it could be relevant to include this in the definition of climate change sensitivity which could increase the estimates of it to around 6°C. Consequently a call was made to stabilise the atmosphere's carbon dioxide level at, initially, around 350 ppm, in order to later reduce it down even further. In addition it was argued that there should be an upper limit on the "acceptable" global warming of 1.7°C, which would be lower than the EU's 2°C target.

All climate stabilisation goals are linked to a probability of success, or, in other words, a risk that the goal will not be met, for a given future emission pathway. This is inherent because of the uncertainty concerning climate sensitivity and beacause of changes that might occur to the capacity of the carbon sinks[123]. These aspects have been discussed in this report. Consequently it is no simple matter to take decisions on climate goals. Science does, however, provide points of departure as guidance in these decisions[124,j].

[j] EU Climate Expert Group 'EG Science' 2008. The 2°C target. Information reference document 55p. (http://ec.europa.eu/environment/climat/pdf/brandure_2c.pdf 2009-04-06).

8 Conclusions

Climate research has, over the last 2-3 years further extended knowledge about the climate system. Below is a summary of the points that may be considered to indicate a modification or to add nuances to the knowledge of the climate system as compared to what was reported in AR4:

1. Greenhouse gas concentrations in the atmosphere continue to increase. The concentration of carbon dioxide in 2008 amounts to 384 ppm. The pace of increase is faster than earlier. There are also indications that the concentration of methane has once again begun to rise after staying of a constant level for a period of several years.

2. The global mean temperature in 2008 was about 0.1°C lower than in the immediately preceeding years. A temperature difference of 0.1°C is within the limits of uncertainty that is linked to global temperature analyses and is also within the characteristic year-to-year variability that is due to the atmosphere-ocean interaction. 2008 still belongs to the top ten warmest years since 1850 and the latest ten year period is warmer than the previous decade. The temperature trend is one of increase.

3. Data on sea level rise has been further studied for the periods 1961-2003 and 1993-2003. Results indicate that the pace of rise has been higher during the later period. When also data from the last few years is considered , it appears that the pace of rise has again become a little slower, but it remains higher than during the 1900s.

4. A marked decrease in the Arctic sea ice cover occurred during the late summers of 2007 and 2008. The large-scale warming trend in the Arctic is probably closely connected to global warming. Also the western part of the Antarctic has been observed to show signs of warming which is also linked to global temperature rises.

5. Generally speaking, later estimates of climate sensitivity lie within the uncertainty range reported in AR4.

6. New studies of land ice sensitivity to warming and consequently their melting rate indicates that the sea level may rise by more than what was stated in AR4. Estimates are made at around one metre of rise over the 21st Century. These studies are, however, characterised by considerable uncertainty. It is also shown that it is physically unreasonable for the global mean sea level to rise more than two metres during the next 100 years.

7. A significant change in precipitation during the period 1950-2000 has been established from observations. This is in line with what is anticipated as a result of greenhouse gas warming, at the same time as the observed trend exceeds model simulation results.

8. Examples of possible tipping points and elements in the climate system have been published. The dramatic decrease in sea ice in the Arctic (see Point 4 above) may be an example of such a feature if it becomes lasting. In that case this will be the first example of an observed tipping point.

9. New research indicates that it may be more difficult than previously assessed to limit global warming to a maximum of 2°C. It could be that the climate forcing by particles has been underestimated, which would mean that the actual greenhouse gas warming is greater than has been stated to date. Later research also supports concerns that carbon sinks may become less efficient in the future.

Research is a continuous process. IPCC aims to, at regular intervals, assess the state of knowledge on climate change. New IPCC assessment reports are published every 6-7 years. It takes time to conduct such an extensive review of the research. It is often not enough to use single newly published works to establish new knowledge; instead a broad and overall examination of an issue is necessary in order to be able to draw conclusions.

It has not been possible to compile this report with the same weight and scope as characterises a report by IPCC. We have used our knowledge and a mapping of the literature that has been published since 2006 to look into the new developments in some of the research fields considered in AR4. Our overall assessment is that new research that has been carried out since 2006 confirms previous results concerning ongoing climate trends, human impact on climate and possible future climate changes. The state of knowledge has not changed to any important degree. Some nuances have been added and research has continued to illuminate areas where previously there had been a lack of satisfactory background material.

The conclusions in the physical science basis part of the IPCC report from 2007 hold up well in the light of new research results published during the last 2-3 years. In certain areas previous estimates have been confirmed, in others adjustments have been made. Within yet others a more nuanced picture has been developed. The state of knowledge within climate research is not static; however its primary foundations appear, even in the light of the latest research, to be robust.

Appendix A: Summary of the earth's radiation balance and the factors that affect it

The temperature of the earth is determined by a balance between incoming radiation from the sun and outgoing thermal radiation to space. The outgoing radiation is primarily dependent on the temperature of the earth. Higher temperatures lead to increased thermal radiation. Through the atmosphere's greenhouse effect, a great deal of the thermal radiation is caught in the lower parts of the atmosphere. Consequently it becomes warmer on the earth's surface than it would have been without the greenhouse effect. A change in the concentration of greenhouse gases in the atmosphere influences this effect. If, for example, carbon dioxide levels are increased, more thermal radiation is trapped and the temperature of the earth's surface rises. Warming of the atmosphere's lower layers also affects the amount of water vapour and cloud formation which in turn further changes the radiation balance. Temperature increase leads to increased amounts of water vapour which reinforces the heating of the earth surface. Water vapour is namely actually the most important of the greenhouse gases.

The changes to cloud cover caused by changes to the climate system's energy and radiation balance are complex. For example, different changes in the cloud cover exert different effects on the radiation balance.

- The clouds affect incoming solar radiation by reflecting it. More clouds lead to increased reflection and consequently a cooling effect while less cloud exerts the opposite effect. Increase or decrease of clouds in the lower layer of the troposphere – at a height of 1-2 km – is especially effective in this sense.

- Increased cloud cover also leads to an increase of the clouds' contribution to the greenhouse effect, which means a surface warming effect. Increased cloud cover at higher levels in the troposphere – at a height of 5-12 km – is especially effective in this sense.

These opposing effects partially cancel each other out. Even if the net effect is small in relationship to the total radiation effects of clouds, it is important. How cloud cover changes with enhanced greenhouse effect is determined by complex interplay between changes to evaporation, temperature, ice clouds and water droplet clouds as well as in the circulation patterns in the atmosphere. Changes to cloud cover are the single greatest uncertainty in our understanding of climate system sensitivity to changes in the radiation balance. After this come changes to the total reflection of solar radiation, also called albedo. In addition to cloud cover, albedo is also influenced by ice cover and other characteristics of the earth's surface. As the extent of ice and snow cover decreases the warmer it becomes, here is yet another positive feedback mechanism in the climate system.

Finally there is a slowness to react (inertia) in the climate system that is controlled by the oceans. An imbalance between outgoing thermal radiation and incoming solar radiation on ocean surfaces affects ocean temperatures very slowly. It takes hundreds of years to achieve radiation balance over oceans after an increase of greenhouse gas concentrations. This is because of the extremely slow exchange of the water masses close to the surface and those in the ocean depths.

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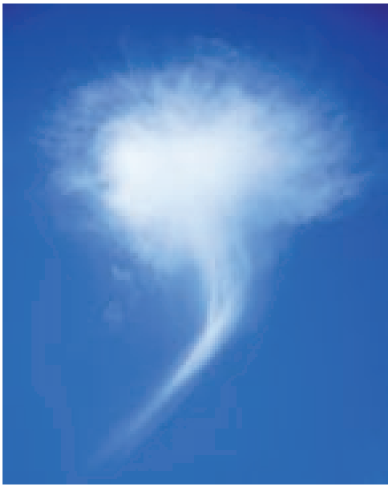

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