

Part 1

The Potential for Rapid
Changes to the Weather
and Climate

Introduction to Part 1

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For nearly 100 years following 1897, when Svante Arrhenius first made a quantitative estimate of how human-caused emissions of carbon dioxide (CO₂) would affect the climate, the presumption was that changes in the climate would occur slowly and that, therefore, society would have decades to develop the policies to slow and then stop climate change. When the President's Science Advisory Council advised President Lyndon Johnson in 1965 that climate change was an important emerging issue, there was no urgency expressed to deal with it. Similarly, assessments by the US National Academy of Sciences and various US government agencies summarized scientific understanding in the 1970s and 1980s, changes in climate that could make a difference to the environment and society seemed many decades off, especially in that observations were not convincingly showing any climatic response to the increasing concentrations of CO₂ and other greenhouse gases.

That the Earth's climate could change significantly over quite short periods, however, became particularly evident as a result of analyses of high-resolution ice cores from the Greenland Ice Sheet. Not only did these cores document the long-term changes that were seen in the low-resolution cores drilled in ocean sediments, but they suggested that abrupt changes in climate (at least over Greenland and the North Atlantic) were not even rare events, at least during times when there was substantial glacial ice and meltwater that could, in ways not yet completely understood, lead to rapid changes in ocean conditions.

At the same time, detection and attribution studies aimed at identifying the human 'fingerprint' of climate change found that, indeed, the climate was changing in ways that could only be explained by human activities. Studies brought together in the assessments of the Intergovernmental Panel on Climate Change (IPCC) made clear that both human-caused increases in the atmospheric loading of sulfate aerosols and natural variations in solar radiation and volcanic aerosols were actually countering the warming influences of the increasing concentrations

of greenhouse gases, delaying observation of their strong warming influence. What these studies are suggesting is that there is a stronger potential for changes in the climate (and, in that climate is simply the average of the weather, for changes in the weather) than has been recognized in past scientific assessments.

The three chapters in this section explore various aspects of this issue. In Chapter 1, countering the oft-heard criticisms of media-hyped naysayers that the IPCC's estimates of climate change are too high, Dr A. Barrie Pittock presents ten reasons, each much more soundly argued than the criticisms, that the model-based projections of climate change summarized by the IPCC are likely to be *underestimating* the amount of climate change we can expect. In Chapter 2, Dr Judith Curry summarizes the observational evidence indicating that tropical cyclones (i.e. hurricanes and typhoons) are becoming more intense and destructive than projections with relatively coarse grid models had indicated, suggesting that the pace of increasing damage in coastal regions could continue to accelerate rapidly. In Chapter 3, with the pace of temperature change and of storm intensity both seeming likely to increase more rapidly than had been indicated, Dr Devra Davis and John Topping describe the types of health impacts that the accelerating pace of climate change are likely to cause, making clear that significant effort will need to be put towards enhancing public health infrastructure and practices in order to satisfactorily limit increasing societal vulnerability.

These findings and others from around the world are making it more and more clear that there is an increasing risk that the pace of climate change is accelerating, and that, because of the high degree of environmental and societal vulnerability, the potential for very serious impacts is becoming more and more likely.



Ten Reasons Why Climate Change May be More Severe than Projected¹

A. Barrie Pittock

Uncertainties in climate change science are inevitably large. They arise from questions of data quality, inadequate understanding of the climate system and its representation in climate models and uncertainties about future emissions of greenhouse gases resulting from socio-economic and technical developments. Policies therefore must be based on risk management; that is, on consideration of the probability times the magnitude of any deleterious outcomes for different scenarios of human behavior (Schneider, 2001; Jones, 2004; Kerr, 2005a; Pittock, 2005). We do not insure our house for the coming year because we are certain it will burn down, but because there is a small chance that it might, with serious consequences for our finances. Better flood protection for New Orleans should have been built before 2005 (Fischetti, 2001), not because it was certain New Orleans *would* be flooded in 2005, but because it *might* have been.

When taken together, the ten areas of concern described below, each based on observations and modeling studies, strongly suggest that the risk of more serious outcomes is greater than was understood previously.

New evidence suggesting more rapid climate change

(i) The climate sensitivity may be larger than has been traditionally estimated

In its Third Assessment Report (IPCC, 2001) the IPCC assumed that the climate sensitivity (the global warming after a doubling of the pre-industrial CO₂ concentration) is in the range of 1.5°C to 4.5°C. However, recent estimates of the climate sensitivity, mostly based on modeling, constrained by recent or paleoclimatic data, suggest a higher range of around 2°C to 6°C (Murphy et al,

12 *The Potential for Rapid Changes to the Weather and Climate*

2004; Piani et al, 2005; Stainforth et al, 2005; Annan and Hargreaves, 2006; Hegerl et al, 2006; Torn and Harte, 2006). The only exception is a paper by Forster and Gregory (2006), which provides one of the lowest estimates of climate sensitivity, 1.0°C to 4.1°C. However, it is based on only 11 years of data from the Earth Radiation Budget Experiment, and the results may not be representative of longer time scales at which some major feedback mechanisms come into play.

Overall, these estimates throw doubt on the low end of the IPCC (2001) assumed range and suggest a much higher probability of global average surface warmings by 2100 exceeding the midlevel estimate of 3.0°C above pre-industrial that many scientists consider may lead to 'dangerous' levels of climate change (Schellnhuber et al, 2006).

(ii) Global dimming is large but decreasing

Atmospheric particles (aerosols) reduce the amount of sunlight at the Earth's surface. The resulting 'global dimming' has delayed warming of the oceans (Delworth et al, 2005), especially in the Northern Hemisphere. With stricter controls leading to reductions in emissions of particles and precursor compounds (Bellouin et al, 2005; Pinker et al, 2005; Wild et al, 2005), the decreasing atmospheric loading of aerosols is leading to a decreasing cooling influence on the climate. Because aerosols have a short lifetime in the atmosphere, this cooling effect of aerosols is highly responsive to reductions in sulfur emissions (Andreae et al, 2005). In that the highest aerosol loading is in the Northern Hemisphere, reductions in global dimming are likely to have asymmetric effects, leading to greater warming in the Northern Hemisphere and to changes in cross-equatorial flows such as the Australian monsoon (Rotstayn et al, 2006) and the circulation in the Atlantic Ocean (Cai et al, 2006).

By contrast, emissions of CO₂ and other greenhouse gases exert a long-term warming influence because of their long lifetimes and the resulting cumulative effect on their concentrations. As a result, reductions in global dimming will lead to greater warming even if the emissions of greenhouse gases are cut back.

(iii) Permafrost melting and albedo changes

Observations show rapid melting of permafrost, or frozen ground (Nelson, 2003; Arctic Climate Impact Assessment, 2004; Overland, 2006), which is expected to increase (Lawrence and Slater, 2005). Melting changes the reflectivity, or albedo, of the surface (Chapin et al, 2005; Foley, 2005), and this will likely lead to emissions of CO₂ and methane previously stored in frozen soils. These are positive feedback effects that may have been underestimated. Where permafrost is replaced by swampland, methane is likely to be emitted, but where it is replaced by dry soil, CO₂ is more likely to be emitted. Changes wrought by global warming in

the Arctic are complex and pervasive (Hinzman et al, 2005). Increased vegetation cover will tend to further reduce the albedo, especially when there is snow on the ground, but may take up more CO₂ from the atmosphere, at least until the carbon is released by fire.

Satellite data over the period 1984–1999 indicate a significant decreasing trend in surface albedo over high latitudes in the North American region, but this trend is not simulated in climate models (Wang et al, 2006). This suggests that the representation of surface albedo feedbacks in these climate models might be too weak, at least in the studied region.

(iv) Biomass feedbacks are kicking in

Saturation of terrestrial carbon sinks, and potential destabilization of large biospheric carbon pools are possible (Canadell et al, 2007). Observations of soil and vegetation acting as sources rather than sinks of greenhouse gases (Bellamy et al, 2005; Raupach et al, 2006) suggest an earlier-than-expected (Friedlingstein et al, 2001; Matthews et al, 2005) positive feedback in the terrestrial carbon cycle (Gruber et al, 2004; Scheffer et al, 2006). Angert et al (2005) attribute an observed decreased summer uptake of CO₂ in middle and high latitudes to hotter and drier conditions, which cancels out increased uptake in warmer springtimes. This net loss in carbon has been observed at ground level in some regions under extreme warm conditions (Ciais et al, 2005), and such conditions are expected to occur more frequently in the future (Stott et al, 2004).

Other factors that may lead to a more rapid global warming include reduced sequestration of root-derived soil carbon (Heath et al, 2005), overestimates of responses to ambient CO₂ increases (Kilronomos et al, 2005), and forest and peat fires (Page et al., 2002; Aldhous, 2004; Langmann and Heil, 2004; Westerling et al, 2006) exacerbated by land clearing and draining of swamps. Based on data from one forest fire in Alaska, Randerson et al (2006) suggest that increased surface albedo following boreal forest fires may in fact outweigh the increase in radiative forcing due to the CO₂ emitted in the fires. However, the general applicability of this result remains highly uncertain.

The recent high growth rates in the atmospheric CO₂ concentration reported by Francey (2005) appear to be persisting through 2004–2005 (David Etheridge, CSIRO, personal communication, 2006) and may be linked to the regional surface observations (Langenfelds et al, 2002). Present indications are that emissions, sea level rise and global surface temperatures are all tracking along the highest of the range of estimates from the IPCC's Third Assessment Report (Rahmstorf et al, 2007).

(v) Arctic sea ice is retreating rapidly

Rapid recession of arctic sea ice has been observed, leading to an acceleration of global warming as reduced reflection of sunlight increases surface heating (Gregory et al, 2002; Comiso and Parkinson, 2004; Lindsay and Zhang, 2005; NASA, 2005; Stroeve et al, 2005; NSIDC, 2005, 2006; Comiso, 2006; Overland, 2006; Serreze and Francis, 2006; Wang et al, 2006). Some scenarios have the summertime Arctic Ocean becoming ice-free by the end of the century. Comiso (2006) notes that the average area of perennial ice has recently been declining at a rate of 9.9 per cent per decade, with large inter-annual variability of ice cover. There have also been longer seasonal melt periods, for the sea ice as well as the Greenland Ice Sheet and other land areas, especially since 2002. Serreze and Francis (2006) argue that the Arctic is presently in a state of 'preconditioning', setting the stage for larger changes in coming decades. They state that 'extreme sea ice losses in recent years seem to be sending a message: the ice-albedo feedback is starting'.

How serious and irreversible this and other potential 'tipping points' in the climate system may be is a complex question, discussed thoughtfully in a review by Walker (2006). If a positive ice-albedo feedback kicks in to accelerate regional or global warming, it might contribute to other parts of the climate system also reaching critical points, notably the Greenland Ice Sheet and the North Atlantic thermohaline circulation (see below).

(vi) Changes in air and sea circulation in middle and high latitudes

Different rates of warming at low and high latitudes in both hemispheres have led to increasing sea level pressure in the middle latitudes and a poleward movement of the middle latitude westerlies (that is, a more positive 'northern or southern annular mode') (Cai et al, 2003; Gillett et al, 2003; Marshall, 2003). This partly explains the observed and projected drying trends in winter rainfall regimes in Mediterranean-type climatic zones in both hemispheres (Pittock, 2003).

This change has also strengthened the major surface ocean circulations, including the Antarctic Circumpolar Current (Cai et al, 2005; Cai, 2006; Fyfe and Saenko, 2006). These changes will significantly affect surface climate, including sea surface temperatures and storminess (Fyfe, 2003), and may already have accelerated melting in Antarctica (Carril et al, 2005; Marshall et al, 2006) and preconditioned the South Atlantic for the formation of tropical cyclones (Pezza and Simmonds, 2005).

The strengthening of the annular modes, if due to enhanced greenhouse gas forcing alone, appears to have been under-predicted in climate models (Gillett, 2005), but may be explained by the additional forcing effects of stratospheric ozone depletion (Cai and Cowan, 2007) that has now leveled off and may decline on a timescale of several decades.

(vii) Rapid changes in Antarctica

Rapid disintegration of ice shelves around the Antarctic Peninsula, and subsequent acceleration of outlet glaciers point to the role of surface meltwater in ice shelf disintegration (Scambos et al, 2000; Rignot et al, 2004; Thomas et al, 2004; Cook et al, 2005; Dupont and Alley, 2006) and to the role of ice shelves in retarding glacier outflow. The Larsen B Ice Shelf collapsed spectacularly in 2002, following Larsen A and the Prince Gustav Channel Ice Shelf both collapsing in 1995. Satellite observations clearly document that the sequence of the Larsen B Ice Shelf collapse involved the sudden disappearance of surface meltwater pools, followed immediately by the opening of crevasses and the break-up of the ice shelf over a period of a few weeks. Paleo-data indicate no previous collapse of the Larsen B Ice Shelf in the Holocene (the period since the last glaciation) although some other small ice shelves have shown earlier retreats (Hodgson et al, 2006).

Warm intermediate-depth water may also be penetrating below ice shelves and outlet glaciers such as Pine Island Glacier in West Antarctica, melting the ice from the bottom, weakening the floating ice, and reducing resistance to glacier outflow (Bindschadler, 2006).

Strengthening and warming of the Antarctic Circumpolar Current (Cai et al, 2005; Carril et al, 2005; Fyfe and Saenko, 2006) may accelerate Antarctic ice sheet disintegration by enhancing local warming, preventing sea ice formation, and undercutting ice shelves (Goosse and Renssen, 2001; van den Broeke et al, 2004; Carril et al, 2005). This hypothesis is supported by an observed link between the Southern Annular Mode (which is responding to anthropogenic forcing) and local warming, especially along the east coast of the Antarctic Peninsula (Marshall et al, 2006).

Recent modeling of the effect of global warming on the West Antarctic Ice Sheet does not appear to incorporate any of the above mechanisms (Greve, 2000; Gray et al, 2005).

Some indirect observations suggest that Antarctic sea ice extent is already in decline (Curran et al, 2004), although shorter direct observations are less clear. Radar observations (Zwally et al, 2005) and satellite gravity surveys show Antarctica to be losing mass (Velicogna and Wahr, 2006), while a major recent study suggests that the expected increase in snowfall in central Antarctica due to greater moisture in the lower atmosphere (Krinner et al, 2007), which might have contributed to a slowing of sea level rise, has not occurred (Monaghan et al, 2006). This is despite observed warming of the Antarctic winter troposphere (Turner et al, 2006).

(viii) Rapid melting and faster outlet glaciers in Greenland

The Greenland Ice Sheet is at a generally lower latitude than Antarctica and has widespread marginal surface melting in summer. The area of surface melting

has rapidly increased in recent years, notably since 2002 (NASA, 2003, 2006). Penetration of this meltwater through moulins (crevasses and tunnels in the ice) to the lower boundary of the ice is thought to have lubricated the flow of ice over the bedrock and led to accelerated glacier flow rates (Alley et al, 2005; Fountain et al, 2005; Hansen, 2005; Dowdeswell, 2006; Kerr, 2006; Rignot and Kanagaratnam, 2006; Thomas et al, 2006). Melting of tidewater glaciers from the bottom, pushing back the grounding line, may also be contributing to acceleration of flow (Bindschadler, 2006; Kerr, 2006).

Outlet glaciers have accelerated rapidly in recent years, with Rignot and Kanagaratnam (2006) reporting from satellite radar interferometry that widespread acceleration occurred south of 66°N between 1996 and 2000, expanding to 70°N in 2005. Accelerated discharge in the west and, particularly, in the east more than doubled the outflow from 90 to 220 cubic kilometers per year. Thomas et al (2006), using laser altimeter measurements, report that net mass loss from Greenland more than doubled between 1993/4–1998/9 and 1998/9–2004.

These observational results indicate mass losses considerably faster than were modeled by glaciologists using models that did not take account of the recently identified mechanisms of meltwater lubrication and tidewater glacier undercutting (Huybrechts and de Wolde, 1999; Greve, 2000; Ridley et al, 2005). Indeed, Hansen (2005) suggests that various other positive feedbacks may come into play as the ice sheet slumps, most notably that more precipitation on the ice sheet interior will fall in summer as rain rather than snow, thereby accelerating the effect of surface melting and bottom lubrication. At present marginal areas are slumping, but the high plateau is still accumulating mass. This may change in the future.

Simulations and paleo-climatic data indicate that Greenland and Antarctica together contributed several meters to sea level rise at 130,000 to 127,000 years ago, a time when global temperatures were about the same as presently projected for 2100 (Overpeck et al, 2006; Otto-Bliesner et al, 2006). Overpeck et al (2006) conclude that peak rates of sea level rise may well exceed 1 m per century, and that this may be strongly related to warming of the upper 200 m of the ocean producing rapid thinning of ice shelves (and, presumably, tidewater glacier outlets) from below.

(ix) Tropical cyclones may already be more intense

Some observational analyses point to a rapid intensification of tropical cyclones over recent decades (Emanuel, 2005a; Webster et al, 2005; Hoyos et al., 2006). However, modeling of tropical cyclone behavior under enhanced global warming conditions (Knutson and Tuleya, 2004; Walsh et al, 2004) suggests only a slow increase in intensity that would not yet be detectable given natural variability. This is more in line with the analysis by Trenberth (2005).

The record hurricane season of 2005 in the Caribbean region has prompted debate on whether the modeling or more extreme observational analyses are more likely correct (Emanuel, 2005b; Kerr, 2005b; Pielke et al, 2005; American Meteorological Society, 2006; Anthes et al, 2006; Klotzbach, 2006; Witze, 2006). While the observations have their limitations (Landsea, 2005; Pielke, 2005), and have been revised in new analyses, it is also clear that the modeling to date has not been at sufficient horizontal resolution to capture the details of tropical cyclone behavior (Schrope, 2005), nor perhaps the effects of subsurface warming of the ocean. According to Pezza and Simmonds (2005), the first recorded South Atlantic hurricane may be linked to global warming.

(x) Variations in the North Atlantic Ocean circulation and salinity

The North Atlantic has a complex current system, with the largely wind-driven Gulf Stream splitting into the North Atlantic Current that heads north-east into the Norwegian Sea, and a subtropical recirculating arm, known as the Azores and Canary Currents, that turns south. Relatively warm, but highly saline, surface water in the northern arm tends to sink to a depth of several kilometers in three regions – the Labrador Sea, south of Iceland and between Greenland and Norway. The north-flowing arm transports heat from low latitudes to high latitudes, tending to warm northwestern Europe.

Bryden et al (2005) report a significant slowing of this regional sinking, or 'meridional overturning' circulation, supporting other observations discussed by Quadfasel (2005), Schiermeier (2006) and Levi (2006), although these commentators raise questions about the representativeness of the limited data set used by Bryden et al (2005). Bryden et al found that the northward transport in the Gulf Stream at 25°N was unaltered, but there was an increase in the southward flowing surface waters and a corresponding decrease in the southward flowing North Atlantic Deep Water between 3000 and 5000 m in depth.

However, Bryden is reported (Kerr, 2006) as later finding that there were other large variations in flow, suggesting that the earlier reported slowing might in fact be part of the natural variability of the system (see also Bryden et al, 2006).

Any slowdown occurred despite the impact of aerosol-induced cooling, which acts to protect the overturning. The Cai et al (2006) and Delworth and Dixon (2006) studies suggest that without the 'protective' effect of aerosols the slowdown would be 10 per cent greater, indicating a future acceleration of slowdown as aerosols decrease.

Such changes have long been projected in climate models, but most models suggest that significant slowing or collapse of this heat transport system is not likely until well into the 21st or 22nd centuries (Kerr, 2005a), if at all. The slowdown in overturning could be related to observed significant freshening of the surface waters in the Arctic Ocean (Curry et al, 2003) due to increased precipitation

(Josey and Marsh, 2005), increased river inflow (Peterson et al, 2002; Labat et al, 2004), and recently increased ice-melt from Greenland and other glaciers (Rignot and Kanagaratnam, 2006; Swingedouw et al, 2006; Thomas et al, 2006).

Paleo-climatic records, and records over the last millennium (Lund et al, 2006) suggest that a tight linkage exists between the Atlantic Ocean circulation, temperatures in the North Atlantic region and the hydrologic cycle.

Discussion

The above lines of evidence (supported by well over 100 recent scientific papers), while not definitive and in some cases controversial, suggest that the balance of evidence may be swinging toward more extreme global warming and sea-level rise outcomes. While some of the observations may be due merely to natural fluctuations, their conjunction and in some cases positive feedbacks (from permafrost melting, biomass changes, arctic sea ice retreat, and melting of Greenland) are causes for concern. Some of the links between major elements of the climate system are shown in Figure 1.1. Several of these links indicate positive feedbacks. Overall they illustrate the need to consider the whole system, not just its individual parts in isolation.

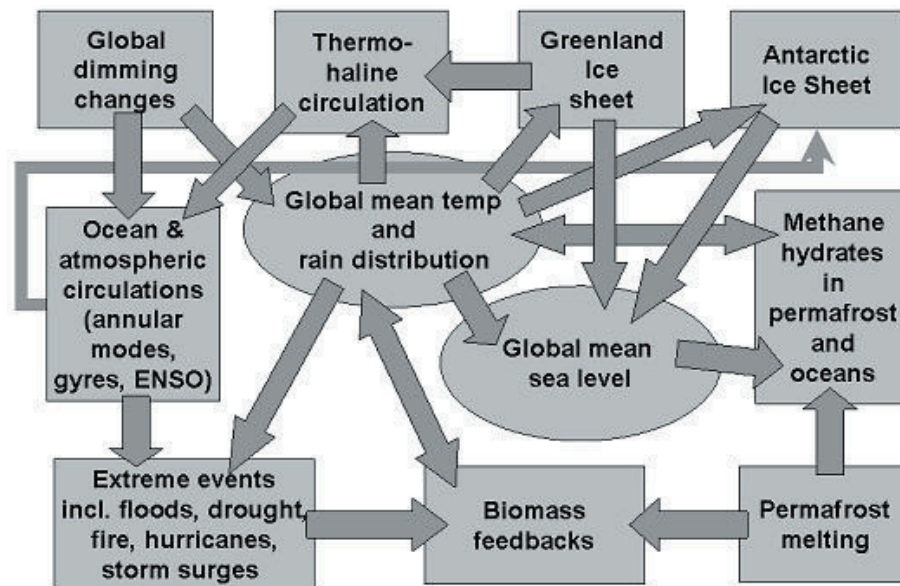


Figure 1.1 Links between parts of the climate system including feedbacks that may accelerate climate change and its impacts

The observations and linkages suggest that critical levels of global warming may occur at even lower greenhouse gas concentrations and/or anthropogenic emissions than was considered justified in the IPCC (2001) report. The observed changes in Greenland and Antarctica suggest that a more rapid rise in sea level may be imminent, as has been observed in recent years (Church and White, 2006; Rahmstorf, 2007). Indeed, Rahmstorf et al (2007) find that emissions, global surface temperature and sea level rise are all increasing at rates at the very highest end of the IPCC range. Several of the points above suggest rapidly occurring regional impacts are imminent. Taken together, these recent developments increase the urgency of further improving climate models, and of taking action to reduce emissions in order to avoid the risk of unacceptable levels of climate change (see also National Research Council, 2002; Pittock, 2006; Schellnhuber et al, 2006; Steffen, 2006; *Time Magazine*, 2006).

A responsible risk management approach demands that scientists describe and warn about seemingly extreme or alarming possibilities, for any given scenario of human behavior (such as greenhouse gas emissions), if they have even a small probability of occurring. This is recognized in engineering design (for instance for the safety of dams and bridges) and in military planning (where large resources are devoted to guarding against, and deterring, hopefully unlikely threats) and this practice is also commonplace in the insurance sector. The object of policy-relevant advice must be to avoid unacceptable outcomes, not to determine the most likely outcome.

The recent developments discussed above might simply mean that the science is progressing. However, it also may suggest that up until now many scientists have consciously or unconsciously downplayed the more extreme possibilities at the high end of the uncertainty range in an attempt to appear moderate and 'responsible' (that is to avoid scaring people). However, true responsibility requires providing evidence of what must be avoided: to define, quantify and warn against possible dangerous or unacceptable outcomes.

Notes

- 1 This paper is an expansion of an article published in *EOS*, 'Are scientists underestimating climate change?', vol 87 (34, 22 August 2006) © American Geophysical Union.

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22 *The Potential for Rapid Changes to the Weather and Climate*

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