

**The Role of Warming in Melting Ice and Sea-Level Rise,
and the Possibility of Abrupt Climate Changes**

Testimony of

Dr Richard B. Alley*
Pennsylvania State University

For the hearing entitled

*A Rational Discussion of Climate Change:
The Science, the Evidence, the Response*

Before the

Subcommittee on Energy and Environment
House Committee on Science and Technology
United States House of Representatives
Room 2325 of the Rayburn House Office Building
10:30 a.m., November 17, 2010

*Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the Pennsylvania State University, the Intergovernmental Panel on Climate Change, the National Research Council, the US Climate Change Science Program, or other organizations.

Introduction. My name is Richard Alley. I am Evan Pugh Professor of Geosciences and Associate of the Earth and Environmental Systems Institute at the Pennsylvania State University. I have authored over 200 refereed scientific papers, which are “highly cited” according to a prominent indexing service, and I have made many hundreds of public presentations concerning my areas of expertise. My research is especially focused on the great ice sheets of Greenland and Antarctica, their potential for causing major changes in sea level, the climate records they contain, and their other interactions with the environment; I also study mountain glaciers, and ice sheets of the past. I have served with distinguished national and international teams on major scientific assessment bodies, including chairing the National Research Council’s Panel on Abrupt Climate Change (report published in 2002), and serving the Intergovernmental Panel on Climate Change (IPCC) in various ways, and the U.S. Climate Change Science Program. I had the honor of testifying to the Subcommittee on Investigations and Oversight of the House Committee on Science and Technology in 2007; my testimony today updates and extends the material I presented then.

Background on Climate Change and Global Warming. Scientific assessments such as those of the National Academy of Sciences of the United States (e.g., National Research Council, 1975; 1979; 2001; 2006; 2008; 2010a; 2010b), the U.S. Climate Change Science Program, and the Intergovernmental Panel on Climate Change have for decades consistently found with increasingly high scientific confidence that human activities are raising the concentration of CO₂ and other greenhouse gases in the atmosphere, that this has a warming effect on the climate, that the climate is warming as expected, and that the changes so far are small compared to those projected if humans burn much of the fossil fuel on the planet.

The basis for expecting and understanding warming from CO₂ is the fundamental physics of how energy interacts with gases in the atmosphere. This knowledge has been available for over a century, was greatly refined by military research after World War II, and is directly confirmed by satellite measurements and other data (e.g., American Institute of Physics, 2008; Harries et al., 2001; Griggs and Harries, 2007).

Although a great range of ideas can be found in scientific papers and in statements by individual scientists, the scientific assessments by bodies such as the National Academy of Sciences consider the full range of available information. The major results brought forward are based on multiple lines of evidence provided by different research groups with different funding sources, and have repeatedly been tested and confirmed. Removing the work of any scientist or small group of scientists would still leave a strong scientific basis for the main conclusions.

Ice Changes. There exists increasingly strong evidence for widespread, ongoing reductions in the Earth’s ice, including snow, river and lake ice, Arctic sea ice, permafrost and seasonally frozen ground, mountain glaciers, and the great ice sheets of Greenland and Antarctica. The trends from warming are modified by effects of changing precipitation and of natural variability, as I will discuss soon, so not all ice everywhere is always shrinking. Nonetheless, warming is important in the overall loss of ice, although changes in oceanic and atmospheric

circulation in response to natural or human causes also have contributed and will continue to contribute to changes. The most recent assessment by the IPCC remains relevant (Lemke et al., 2007). Also see the assessment of the long climatic history of the Arctic by the U.S. Climate Change Science Program (CCSP, 2009), showing that in the past warming has led to shrinkage of Arctic ice including sea ice and the Greenland ice sheet, and that sufficiently large warming has removed them entirely.

The large snowfalls that closed much of Washington, D.C. last winter are successfully explained by the accidental “weather” of El Niño and the North Atlantic Oscillation (Seager et al., 2010), and do not undermine our understanding of the long-term effects of warming on snow and ice. The existence of such variability virtually guarantees that any climate record will be “bumpy”, but scientific techniques successfully identify the long-term trends in such bumpy records.

For sea ice (frozen ocean water), the trends in Arctic sea-ice area and volume have been strongly downward. The reports of the National Snow and Ice Data Center (a research institute at the University of Colorado with funding from NSF, NASA, and NOAA) provide up-to-date data; also see Kwok and Rothrock (2009) among many other studies. Note that the observed shrinkage of Arctic sea ice with warming is consistent with (although somewhat faster than) expectations from a great range of climate models. The models generally project shrinkage of Antarctic sea ice once warming becomes notably larger, but for the warming to date some models have projected growth of Antarctic sea ice in response to changing winds and ocean conditions in the very cold Antarctic winter including freshening of the surface waters from increasing precipitation and shrinkage of the land ice, consistent with observations (e.g., Manabe et al., 1992; Turner et al., 2009; Liu and Curry, 2010).

Glaciers and ice caps occur primarily in mountainous areas, and near but distinct from the Greenland and Antarctic ice sheets. On average, the world’s glaciers were not changing much around 1960 but have lost mass since, generally with faster mass loss more recently. Glacier melting contributed almost an inch to sea-level rise during 1961-2003 (about 0.50 mm/year, and a faster rate of 0.88 mm/year during 1993-2003). Glaciers experience numerous intriguing ice-flow processes (surges, kinematic waves, tidewater instabilities), allowing a single glacier over a short time to behave in ways that are not controlled by climate. Care is thus required when interpreting the behavior of a particular iconic glacier (and especially the coldest tropical glaciers, which interact with the atmosphere somewhat differently from the great majority of glaciers). But, ice-flow processes and regional effects average out if enough glaciers are studied for a long enough time, allowing glaciers to be quite good indicators of climate change. Furthermore, for a typical mountain glacier, a small warming will increase the mass loss by melting roughly 5 times more than the increase in precipitation from the ability of the warmer air to hold more moisture. Thus, glaciers respond primarily to temperature changes during the summer melt season. Indeed, the observed shrinkage of glaciers, contributing to sea-level rise, has occurred despite a general increase in wintertime snowfall in many places (Lemke et al., 2007). An erroneous paragraph about Himalayan Glaciers in the IPCC assessment from Working Group II in 2007 was identified by a distinguished scientific team with ties to the IPCC (Cogley et al., 2010), and this in no way changes the reality that strong glacier melting has been occurring, with more warming

expected to cause more melting (Meehl et al., 2007).

Ice-sheet changes. The large ice sheets of Greenland and Antarctica are of special interest, because they are so big and thus could affect sea level so much. Melting of all of the world's mountain glaciers and small ice caps might raise sea level by about 1 foot (0.3 m), but melting of the great ice sheets would raise sea level by just over 200 feet (more than 60 m). We do not expect to see melting of most of that ice, but even a relatively small change in the ice sheets could matter to the world's coasts; roughly 10% of the world's population lives within 10 m of sea level (McGranahan et al., 2007).

Data collected recently show that the ice sheets very likely have been shrinking and contributing to sea level rise over 1993-2003 and with even larger loss by 2005 and more recently, as noted in the IPCC report and updated elsewhere (e.g., Allison *et al.*, 2009). Thickening in central Greenland from increased snowfall has been more than offset by increased melting in coastal regions. Many of the fast-moving ice streams that drain Greenland and parts of Antarctica have accelerated, transferring mass to the ocean and further contributing to sea-level rise.

Measurements of mass loss from the ice sheets rely on multiple techniques, implemented by multiple groups. Techniques include repeatedly "weighing" the ice sheets using the GRACE gravity satellites, measuring changes in surface elevation using radar or laser altimeters from satellite or aircraft, and comparing snow delivered to the ice sheets (estimated from measurements on the ice or from atmospheric models) to loss of ice by melting or flow into the ocean; the results are checked against changes in the ocean level (together with estimates of sea-level rise from other sources) and against changes in Earth's rotation caused by the water moving from ice sheets into the ocean (e.g., Allison et al., 2009; Cazenave et al., 2009; Lemke et al., 2007). To date, sea-level rise has been controlled more by mountain-glacier melting and expansion of ocean water as it warms, but ice sheets have the greatest potential to increase their contribution in the future.

Ice-sheet behavior. An ice-sheet is a two-mile-thick, continent-wide pile of snow that has been squeezed to ice under the weight of more snowfall. All piles tend to spread under their own weight, restrained by their own strength (which is why spilled coffee spreads on a table top but the stronger table beneath does not spread), by friction beneath (so pancake batter spreads faster on a greased griddle than on a dry waffle iron), or by "buttressing" from the sides (so a spatula will slow the spreading of the pancake batter). Observations in Greenland have shown that meltwater on top of the ice sheet flows through the ice to the bottom and reduces friction there. More melting in the future thus may reduce friction further, speeding the production of icebergs or exposing more ice to melting from warmth at low altitude, and thus speeding the increase in sea level (Parizek and Alley, 2004).

Some early gothic cathedrals suffered from the "spreading-pile" problem, in which the sides tended to bulge out while the roof sagged down, with potentially unpleasant consequences. The beautiful solution was the flying buttress, which transfers some of the spreading tendency to the strong earth beyond the cathedral. Ice sheets also have flying buttresses, called ice

shelves. The ice reaching the ocean usually does not immediately break off to form icebergs, but remains attached to the ice sheet while spreading over the ocean. The friction of these ice shelves with local high spots in the sea floor, or with the sides of embayments, helps restrain the spreading of the ice sheet much as a flying buttress supports a cathedral. The ice shelves are at the melting point where they contact water below, and are relatively low in elevation hence warm above. Ice shelves thus are much more easily affected by climatic warming than are the thick, cold central regions of ice sheets. Rapid melting or collapse of several ice shelves has occurred recently, allowing the “gothic cathedrals” behind to spread faster, contributing to sea-level rise. Many additional ice shelves remain that have not changed notably, and these contribute to buttressing of much more ice than was supported by those ice shelves that experienced the large recent changes, so the potential for similar changes contributing to sea-level rise in the future is large.

Although science has succeeded in generating useful understanding and models of numerous aspects of the climate system, similar success is not yet available for ice-sheet projections, for reasons that I would be happy to explore with the committee. We do not expect ice sheets to collapse so rapidly that they could raise sea level by meters over decades; simple arguments point to at least centuries. However, the IPCC (2007) is quite clear on the lack of scientific knowledge to make confident projections of ice-sheet behavior. The changes in ice-sheet flow that have been contributing to sea-level rise were not projected in the 2001 assessment (see Lemke et al., 2007), part of the reason why best-estimate projections of sea-level rise have fallen below observations (Rahmstorf et al., 2007). For 2007, the IPCC noted that the sea-level-rise projections provided excluded contributions from “future rapid dynamical changes in ice flow” (Table SPM-3) “because a basis in published literature is lacking” (page SPM14), so that it was not possible to “provide a best estimate or an upper bound for sea level rise” (page SPM15). (The 2007 report also noted a similar difficulty arising from lack of knowledge of feedbacks in the carbon cycle, referring to the possibility that warming will cause much release of methane and carbon dioxide from soils in the Arctic, sediments under the sea, or elsewhere, contributing to more warming.)

In the absence of an assessed estimate of sea-level rise, various “back-of-the-envelope” estimates have been provided. Without in any way representing an assessed projection, these estimates show that a meter or more of sea-level rise this century, with additional and probably faster rise beyond that, falls within the realistic scientific discussion (e.g., Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009).

Tipping Points, and Abrupt Climate Change. A golden retriever leaping to the side will force a canoe to lean, but usually the canoe will remain upright. If an ice chest slides across the seat towards the retriever, this positive feedback will cause the canoe to lean further. In exceptional circumstances a tipping point may be crossed, leading to an abrupt change as the canoe dumps the dog, ice chest, and paddlers into the water.

Much scientific and popular discussion has focused on the possibility that human-caused climate change may force the Earth to cross one of its tipping points. Paleoclimatic history shows clearly that very large, rapid and widespread changes occurred repeatedly in the past

(e.g., National Research Council, 2002; CCSP, 2008). An ice-sheet collapse, a large change in the circulation of the North Atlantic Ocean, a rapid outburst of methane stored in sea-floor sediments, a sudden shift in rainfall patterns, or others are possible based on available scientific understanding (CCSP, 2008).

The available assessments, and in particular that of the U.S. Climate Change Science Program (CCSP, 2008), do not point to a high likelihood of triggering an abrupt climate change in the near future that is large relative to natural variability, rapid relative to the response of human economies, and widespread across much or all of the globe. However, such an event cannot be ruled out entirely, and rapidly arriving regional droughts seem more likely than the others considered, with potentially large effects on ecosystems and economies.

Projections of warming from a given release of greenhouse gas generally include a best estimate, the possibility of a somewhat smaller or somewhat larger rise, and the slight possibility of a much larger rise; because of the way feedbacks interact in the climate system, very large changes remain possible if unlikely, and are not balanced by an equal probability of very small changes (e.g., Meehl et al., 2007). The possibility of an abrupt climate change gives a similar shape to the uncertainties about damages from whatever warming occurs, with a chance of very large impacts.

Synopsis. With high scientific confidence, human CO₂ and other greenhouse gases are having a warming influence on the climate, and the resulting rise in temperature is contributing to changes in much of the world's ice. Shrinkage of the large ice sheets was unexpected to many observers but appears to be occurring, and the poor understanding of these changes prevents reliable projections of future sea-level rise over long times. Large, rapid changes in the ice sheets, or in other parts of the Earth system, may be unlikely but cannot be excluded entirely, and such an event could have very large effects.

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