Changes in Ice:
The 2007 IPCC Assessment

Testimony of

Dr Richard B. Alley*
Pennsylvania State University

Before

Committee on Science
United States House of Representatives
Room 2318 of the Rayburn House Office Building
10:00 a.m., February 8, 2007

*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, 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 170 refereed scientific publications in the areas of ice and climate, which are "highly cited" according to a prominent indexing service, and I have given hundreds of presentations concerning my areas of expertise. My research interests focus especially on glaciers and ice sheets, their potential for causing major changes in sea level, and the climate records they contain. I have been a member of many national and international committees, including chairing the National Research Council's Panel on Abrupt Climate Change and serving on their Polar Research Board. I have contributed to the efforts of the Intergovernmental Panel on Climate Change (IPCC) in various ways, and serve as a Lead Author on Chapter 4 (the Cryosphere), and on the Technical Summary and the Summary for Policymakers of Working Group I of the Fourth Assessment Report. A brief description of the IPCC process as it applies to this testimony is appended, for your information.

Changes in Ice. The newly released report reaffirms the strong scientific evidence that human activities are changing the composition of the planet's atmosphere, and that this is warming the climate and affecting it in other ways. In particular, our chapter documents the increasingly strong evidence for widespread reductions in the Earth's ice, including snow, river and lake ice, sea ice, permafrost and seasonally frozen ground, mountain glaciers, and the great ice sheets of Greenland and Antarctica. Our chapter and others highlight the strong evidence for the dominant role of warming, which is primarily being caused by human activities, in this loss of ice.

I will briefly summarize some of these many aspects, especially focusing my attention on the issue of ice-sheet shrinkage and its possible effect on sea-level rise. I will rely on the recent IPCC report, as well as other materials as needed.

Snow cover has decreased in most regions, as shown by satellite data tied to limited surface observations. Snow melt is shifting earlier into the spring. Declines in April 1 snowpack have been measured in 75% of western North American sites monitored. Impacts of climate change on people will be covered in the WGII report, coming soon, but other sources express great concern about earlier snowmelt in the U.S. West, because the snow pack in many regions is a dominant source of summertime water. Trends in snow cover cannot be explained by changing precipitation (and indeed, in some very cold places snow depth has increased with increasing precipitation), but the overall shrinkage of snow cover can be explained by rising temperature.

Freezing of rivers and lakes generally has been occurring later in the fall, with thawing earlier in the spring, giving longer intervals of open water. Coordinated data collection is scarce, however, and the data set not extensive.

Arctic sea ice, formed by freezing of ocean water, has decreased in area and thickness. The change in the summer has been especially large, with ice lost from an area twice the size of Texas between 1979 and 2005 (decreasing trend in ice area of 7% per decade over that interval). Data sets from satellites, tied to observations from ships submarines, have been especially important in documenting these changes. Although shifts in circulation of the ocean and atmosphere may have contributed to the ice loss, greenhouse-gas warming is likely to have been important. (Any Antarctic sea-ice changes fall within natural variability; cooling associated with the ozone hole may be affecting Antarctic climate, a complex subject beyond the scope of these brief remarks.)

Permanently frozen ground (permafrost) and seasonally frozen ground are not readily monitored globally. However, available reports point to overall warming and thawing of this ice in the ground, in response to rising air temperatures and changes in snow cover.

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). 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.

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.

A paper published in the journal *Science* last week (Rahmstorf *et al*., 2007) compared the projections made in the 2001 IPCC Third Assessment Report to changes that have occurred. The carbon dioxide in the atmosphere has followed expectations closely. Temperature has increased just slightly faster than projected, but well within the stated uncertainties. Sea level is following near the upper edge of the stated uncertainties, however, well above the central estimate. Changes in the ice sheets help explain this.

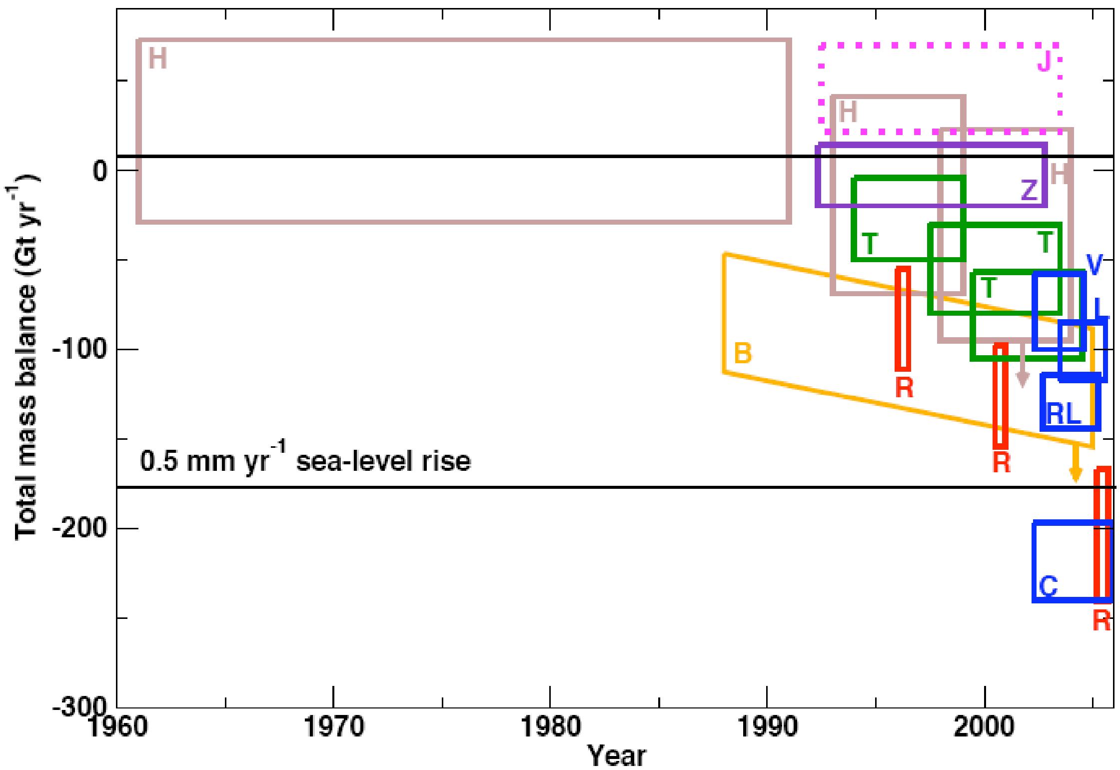
The 2001 IPCC report noted large uncertainties, but presented a central estimate that the combined response of the ice sheets to warming would be net growth, lowering the sea-level rise from other sources averaged over the 21st century, with increase in snowfall on the ice sheets exceeding increase in melting and with little change in ice flow. 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, as noted in the IPCC report and elsewhere (e.g., Alley *et al*., in press; Cazenave, 2006). 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 (see the Figure, below) and parts of Antarctica have accelerated, transferring mass to the ocean and further contributing to sea-level rise. The total contribution to sea-level rise from the ice sheets remains smaller than the contribution from mountain-glacier melting or from the expansion of ocean water as it warms. However, the existence of the ice-sheet contribution, its important ice-flow source, and the large potential sea-level rise from such mechanisms in the future motivate careful consideration.

An ice-sheet is a two-mile-thick, continent-wide pile of snow that has been squeezed to ice. 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 at a site 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 and the increase in sea level.

Some early gothic cathedrals suffered from the "spreading-pile" problem, the sides tending 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 islands, 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.

Although science has succeeded in generating useful understanding and models of numerous aspects of the climate, 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 report is quite clear on the lack of scientific knowledge to make confident projections.

Synopsis. In summary, with high scientific confidence, changes are occurring in much of the world's ice. These are being caused primarily by warming. That warming is largely being caused by greenhouse gases being released to the atmosphere by human activities. 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.



Recently published estimates of the mass balance of the Greenland ice sheet through time (Alley *et al.*, in press). A Total Mass Balance of 0 indicates neither growth nor shrinkage, and -180 Gt yr^{-1} indicates ice-sheet shrinkage contributing to sea-level rise of 0.5 mm/year (1 inch in about 50 years), as indicated. Each box extends from the beginning to the end of the time interval covered by the estimate, with the upper and lower lines indicating the uncertainties in the estimates. A given color is associated with a particular technique, and the different letters identify different studies. Two estimates have arrows attached, because those authors indicated that the change is probably larger than shown. The dotted box in the upper right is a frequently-cited study that applies only to the central part of the ice sheet, which is thickening, and misses the faster thinning in the margins.

References Cited

Alley, R.B., M.K. Spencer and S. Anandakrishnan. Ice-sheet mass balance: Assessment, attribution and prognosis. In press. *Annals of Glaciology*.

Cazenave, A. 2006. How fast are the ice sheets melting? Science 314, 1250-1252.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker and R.C.J. Somerville. 2007. Recent observations compared to projections. *Science*, Sciencexpress, 10.1126/science.1136843

The Intergovernmental Panel on Climate Change (IPCC) Assessment. The IPCC was founded by the United Nations Environment Programme and the World Meteorological Organization in 1988 (this information is summarized from the publications of the IPCC, which are widely available including at www.ipcc.ch). The Panel is charged to assess the best scientific information on climate change, in a comprehensive, objective, open and transparent way. The panel is divided into three working groups. Working Group I assesses the scientific aspects of the climate system and climate change. Working Group II assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. Working Group III assesses options for limiting greenhouse gas emissions and otherwise mitigating climate change.

The IPCC reports are written by teams of authors, who are nominated by governments and international organizations. Author selection is based on expertise relative to the specific task. Experts come from universities, research centers, business and environmental associations, and other organizations from more than 130 countries. Procedures are enforced to ensure that the results of the IPCC process are policy-relevant. A rigorous review process is used throughout the process. Specialists review a first draft of the report, and governments, authors and independent experts review a second draft, with special review editors for each chapter ensuring that balance is maintained and that all review comments are properly addressed. For our chapter, chapter 4 (the Cryosphere) of Working Group I of the Fourth Assessment Report, which in near-final draft had 47 pages, 255 references, and 23 figures involving 41 panels, the 2 coordinating lead authors, 9 lead authors (informed by 44 contributing authors), and 2 review editors addressed over 1000 comments from the expert review alone. As one of the shorter chapters, we were not the busiest. The Third Assessment Report in total involves more than 2500 expert reviewers, 800 contributing authors, and 450 lead authors.

The report from Working Group I was condensed into a Technical Summary, and then into a Summary for Policymakers. The Summary for Policymakers was approved line-by-line by governments in plenary from January 29 to February 1 in Paris, and was released to the public on February 2, 2007. The Technical Summary and the full report will follow later in the spring, as will reports from Working Groups II and III. The approximately 1000-page main report from Working Group I is being copy-edited and formatted for publication, with a limited number of small changes in specific wording for clarity based on the results of the Paris plenary.