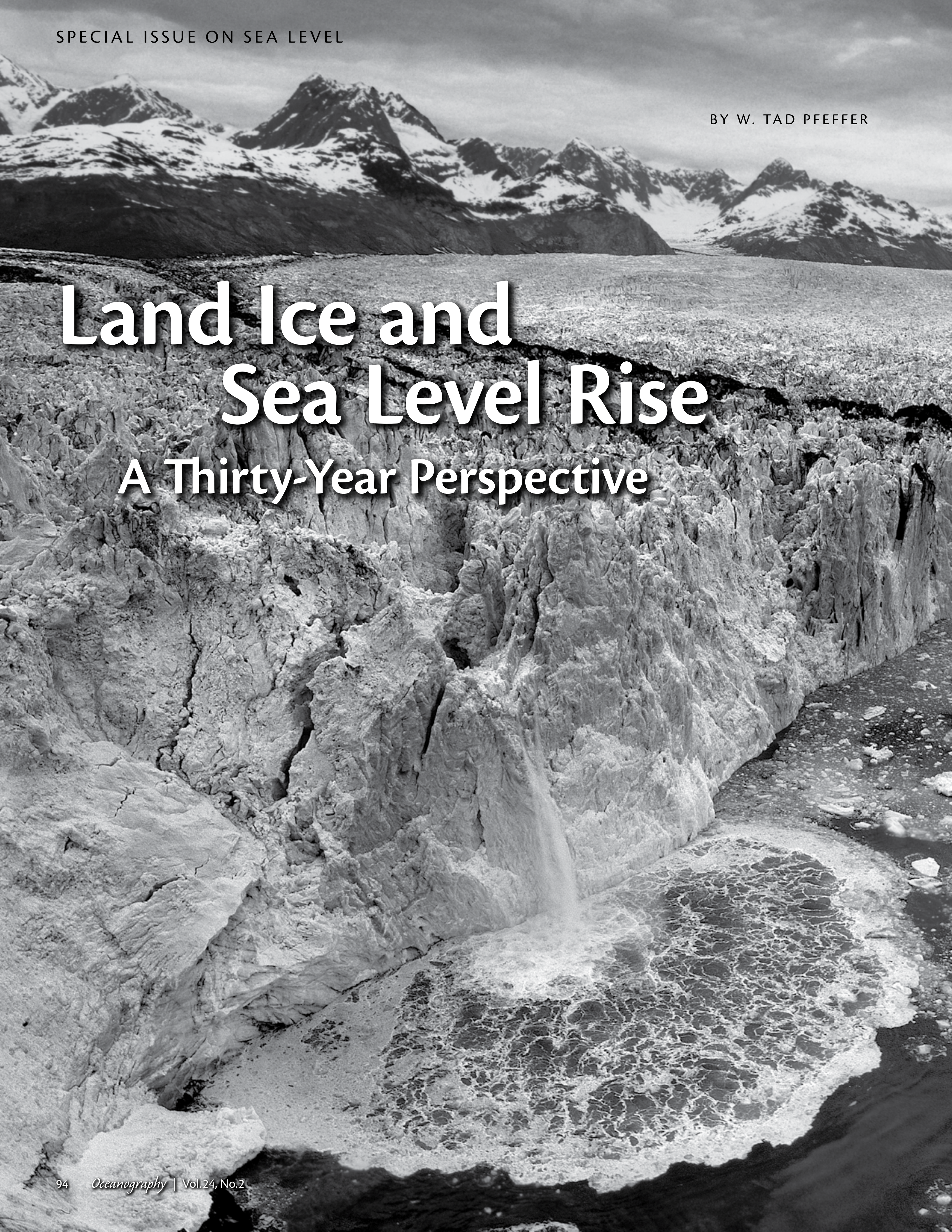
BY W. TAD PFEFFER

Land Ice and Sea Level Rise

A Thirty-Year Perspective



ABSTRACT. The present-day assessment of contributions to sea level rise from glaciers and ice sheets depends to a large degree on new technologies that allow efficient and precise detection of change in otherwise inaccessible polar regions. The creation of an overall research strategy, however, was set in early collaborative efforts nearly 30 years ago to assess and project the contributions of glaciers and ice sheets to sea level rise. Many of the research objectives recommended by those early collaborations were followed by highly successful research programs and led to significant accomplishments. Other objectives are still being pursued, with significant intermediate results, but have yet to mature into fully operational tools; among them is the fully deterministic numerical ice sheet model. Recognized as a crucial tool in 1983 by the first formal working group to be convened to quantitatively evaluate glaciers and ice sheet contributions to sea level in a CO_2-warmed future environment, the deterministic numerical model of glacier and ice sheet behavior has been the ultimate prognostic tool sought by the glaciological research community ever since. Progress toward this goal has been thwarted, however, by lack of knowledge of certain physical processes, especially those associated with interactions of ice with the bedrock it rests on, and interactions of ice with the ocean and calving of icebergs. Over the last decade, when mass loss rates from Greenland and Antarctica started to accelerate, some means of projecting glacier and ice sheet changes became increasingly necessary, and alternatives to deterministic numerical models were sought. The result was a variety of extrapolation schemes that offer partial constraints on future glacier and ice sheet losses, but also contain significant uncertainties and rely on assumptions that are not always clearly expressed. This review examines the history of assessments of glacier and ice sheet contributions to sea level rise, and considers how questions asked 30 years ago shaped the nature of the research agenda being carried out today.

THE AGE OF EXPLORATION

A half-century ago, when geophysicists worldwide embarked on the International Geophysical Year (IGY), oceans, glaciers, and ice sheets were still objects of mystery, fascinating objectives of exploration in the nineteenth-century sense almost as much as subjects of twentieth-century scientific inquiry. Oceans and ice sheets were, at that time, among the last blank spots on the map of the world. They had a value simply as objects of discovery, but they also possessed a new quality, given to them in part by the Cold War: their intrinsic scientific value. Science—mostly applied science, like the manned space program, but to some extent scientific knowledge for its own sake—had grown out of World War II and the Cold War to become a part of American culture.

Fields of study that were previously limited to an erudite audience of specialists were suddenly in public view on a daily basis. Science became a larger part of the school day for American children, not only in the exposition of classical disciplinary subjects but also in the description of the exciting activities of individual scientists ("role models" in today's parlance) engaged in the big IGY projects of 1957–1958 and the years that followed. The exploits of a new generation of scientific heroes—oceanographic cruises led by Maurice "Doc" Ewing of Lamont Geological Observatory, Antarctic traverses led by explorer-scientists like Edmund Hillary and Sir Vivian Fuchs—all were followed in minute detail by school children (myself among them) in their *Weekly Readers*. Issues of *National Geographic* showed newly acquired maps of the geography of deep ocean basins and ice sheet interiors. Measurements of the dynamic character of ocean water and glacier ice stimulated both public and scientific imaginations with images of mobile Earth systems—glimpsed also in the emerging science of plate tectonics—and every part of the world seemed to be in motion, unpredictable, poised for change.

Poised for change, but unchanging. The potential for Earth system dynamics to alter conditions for life was evident, but in the 1950s there was not yet a clear sense of the immediacy of the geophysical aspects of environmental change. The evident capacity for change in Earth's climate had been remarked upon briefly in the scientific literature, and, indeed, a discussion of anthropogenically driven melting of glaciers and ice sheets and resultant sea level rise was presented in an IGY popular press document entitled *Planet Earth: The Mystery with 100,000 Clues* (NAS, 1958). The prospect of sea level rise as an environmental change that might require planning or some attempt at accurate projection, however, was not a part of the scientific awakening that marked the 1950s and 1960s. Sigurdur Thorarinsson had written a seminal paper in 1940 (Thorarinsson, 1940) on glacier shrinkage, but it was an anomaly, a prescient piece of work with no immediate followers. Awareness of the implications of the knowledge gained during IGY was not picked up as a continuous thread until the early 1980s, and even today, a half-century later, this awareness is still incomplete.

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In this review, I pursue two objectives: first, provide a summary of the current state of knowledge about land ice contributions to present-day sea level rise and its uncertainties; and second, examine briefly the history of our efforts both to understand glacier contributions to sea level rise and to project those contributions into the future. The evolution of our knowledge of glaciers and sea level over the past three decades is both instructive and remarkable, not only for the great progress made in the resolution of certain problems but also for the recalcitrant nature of others, which remain essentially no better understood today than when they were first identified.

THE FIRST ORGANIZED INVESTIGATIONS OF FUTURE SEA LEVEL RISE

The question of what future sea level might do came hard on the heels of the earliest large-scale investigations of future CO_2-induced atmospheric warming. An early National Academy of Sciences study on climate change entitled *Carbon Dioxide and Climate: A Scientific Assessment* (Charney et al., 1979) made no mention of concomitant sea level rise. By 1983, however, a US Environmental Protection Agency (EPA) study headed by John Hoffman, Dale Keyes, and James Titus, and comprising a group of climatologists, climate modelers, and glaciologists, attempted to assess not only future sea level rise (and its impacts) under conditions of warming climate, but also to understand and project the individual components contributing to sea level rise (Hoffman et al., 1983). Without the extensive array of remote-sensing tools available to polar scientists today, the authors of the study were nearly blind to global-scale conditions around them: individual glaciers and ice caps were known to be shrinking but global net rates of loss from Earth's glaciers and ice sheets were entirely unknown. Likewise, sea level was believed to be rising, but no clear signal could be firmly established (contemporary estimates, based on tide-gauge records, varied from 11 to 30 cm/century). The scientists knew that rising temperatures would lead to warming and thermal expansion of ocean water (although they chose only to consider warming of the upper ocean in that early analysis). They also knew that warming would lead to significant changes in land ice: increased melting would result in greater runoff of water to the ocean, and increased flow of ice toward coastlines would increase the discharge of icebergs to the ocean, while warmer air could create a compensatory effect by increasing snowfall on land. Predicting future land ice mass balance changes quantitatively—that is, representing them in a physically based and complete numerical model—was well beyond the capacity of the scientific community at the time. Furthermore, using models to predict glacier losses required knowledge not only of the balance between accumulation of mass through snowfall and loss through melt and calving of icebergs, but also detailed knowledge of the dynamics of the flow of ice though glacier systems. The study's authors were well aware of the complex dynamic capacities of glaciers and ice sheets, as was the entire glaciological community of the 1970s and early 1980s, and research at that time focused especially on those ice masses, like the West Antarctic Ice Sheet, that rested on bedrock below sea level (see for example, Hughes, 1973; Mercer, 1978; Thomas and Bentley, 1978; Thomas et al., 1979; Denton and Hughes, 1981). The possibility of the removal of protective ice shelves surrounding West Antarctica and subsequent rapid flow of ice off of the land and into the ocean—"uncorking the bottle" in the words of the report—was fully appreciated.

Predictive numerical models could not be built on the mere appreciation of complexities alone, however, and the study's authors had to settle for a stopgap measure to give them an estimate of land ice losses in projected future climates, which, when added to estimates of thermal expansion, yielded estimates of sea level rise. The stopgap was crude, but simple and expedient. It sidestepped a great deal of well-established glaciological knowledge, valuable for its theoretical insight but useless operationally, in a model that required a complete and deterministic view of the processes involved, plus observational constraints, neither of which were available. The stopgap was as follows: the recent (past century) historical rate of sea level rise was estimated, as well as the fraction of historical rate of sea level rise attributable to thermal expansion, and from those numbers, a range of ratios of land ice-to-thermal expansion contributions were determined. Using this range of ratios, model-determined future thermal expansion could be extrapolated to produce a future total sea level rise, assuming that the ratio remained constant or varied according to clearly defined scenarios.

A crude predictive tool, certainly, and the study's authors were the first to acknowledge this fact: "If estimates based on models of deglaciation had been available, we would have used them" (Hoffman et al., 1983, p. 33). Nonetheless, the tool produced a projection, the first ever sea level projection to explicitly treat thermal expansion and land ice losses resulting from warming due to increased atmospheric CO_2. The projections are startling, especially in comparison to today's projections. The report's summary advised that "sea level will almost certainly rise in the coming decades," with the "most likely" sea level rise lying between 144 and 217 cm by 2100, but it cautioned that a wider range of 56 to 345 cm "cannot be ruled out."

While the report's particular sea level projections are, at this point, essentially a historical curiosity more than a useful scientific product, the working group's presentation of a research strategy for improving knowledge and reducing uncertainties in future studies of sea level rise remain valid and useful today. The ideas detailed in the 1983 report formed the basis of a strategy that, in evolved form and modified by subsequent developments, guided the rapid growth of research that led—through several more ad hoc studies—to the assessments of the Intergovernmental Panel on Climate Change (IPCC) in 1990, 1995, 2001, and 2007 (Houghton et al., 1990, 1996; Church et al., 2001; Lemke et al., 2007), and to the Fifth Assessment, due to be released in 2014.

Despite all of the gains in knowledge in the intervening three decades, however, there are still lessons to be learned from the simple expression of research goals as stated in the 1983 report. The study's authors understood that projections of future sea level could not be accomplished by monitoring alone, that some predictive capacity had to be developed, and that the ultimate goal was the provision of information "in time to be useful to coastal decision-makers." Observational capabilities were nevertheless going to have to be significantly improved if the various sources of sea level rise—for example, increased thermal expansion, increased new water from ice sheets vs. new water from mountain glaciers, increased new water from changing surface mass balance vs. changing iceberg discharge—were to be distinguished from each other. Understanding the mechanisms of sea level rise would be a necessary precursor to understanding sea level forcings and thus enabling projections of sea level rise. A firm knowledge of the physics of glaciers would also be paramount. Underlying all was the assumption that a deterministic quantitative model of glacier and ice sheet behavior, based on physics, constrained by observations, and implemented in a computational scheme, following the highly successful examples set by the emerging field of global atmospheric circulation modeling, should in principle be available for the study of glaciers as well. The motivation, will, and expertise were in place. All that was lacking was the mandate and the funding.

Progress toward the advances sought by the EPA group materialized quickly. Another ad hoc working group was formed, organized this time by Mark Meier, a glaciologist and head of the US Geological Survey's Glaciology

Project Office in Tacoma, Washington, and supported by the National Research Council and the Department of Energy's Carbon Dioxide Research Division. With additional resources and another year's study, the group was able to assemble a clearer picture of land ice losses. They also employed a far more process-oriented method for projecting future losses. The report, entitled *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change* (Committee on Glaciology, 1985), tabulated contemporary estimates of loss rates from Greenland, Antarctica, and glaciers and ice caps, each with assigned uncertainties. One surprising new finding was that the vast majority of the land ice contribution to sea level was coming not from the two ice sheets but from the global aggregate of the world's other land ice, a category collectively referred to as "glaciers and small ice caps." The estimate of the glacier and ice cap losses came about serendipitously. In 1982, Tim Barnett, an oceanographer and geophysicist at Scripps Institution of Oceanography, had contacted Meier with a question: could the world's glaciers and ice caps account for a substantial unexplained increment of sea level rise apparent in the observational record? Losses from Greenland and Antarctica, to the extent that they could be determined, could not explain the observed sea level rise, but glaciers and ice caps exclusive of the ice sheets offered an appealing explanation (Barnett, 1983). They were a small reservoir, but, because of the dynamics characteristic of their size, experienced a high throughput flux. Given their large numbers, might a small flux imbalance in the glacier and ice cap reservoir close the gap in sea level rise? Meier was initially unconvinced: "My first reaction was no, of course not, they're too small." The proposition challenged Meier, however, and the result of some simple calculations, intended originally to demonstrate that glaciers and ice caps were indeed too small to explain the missing sea level rise signal, was a surprise: the loss rate was large, and closed Barnett's gap almost exactly. The analysis, presented at the American Geophysical Union Fall Meeting in 1983 (Meier, 1983) and published in *Science* in 1984 (Meier, 1984), relied upon an assumed relation between a glacier's "mass balance amplitude" and its sensitivity to temperature change. Combined with Meier's best estimate of global glacier and ice cap area, the estimated loss represented approximately one-third to one-half of the observed sea level rise in the previous century—almost exactly that unaccounted for by thermal expansion.

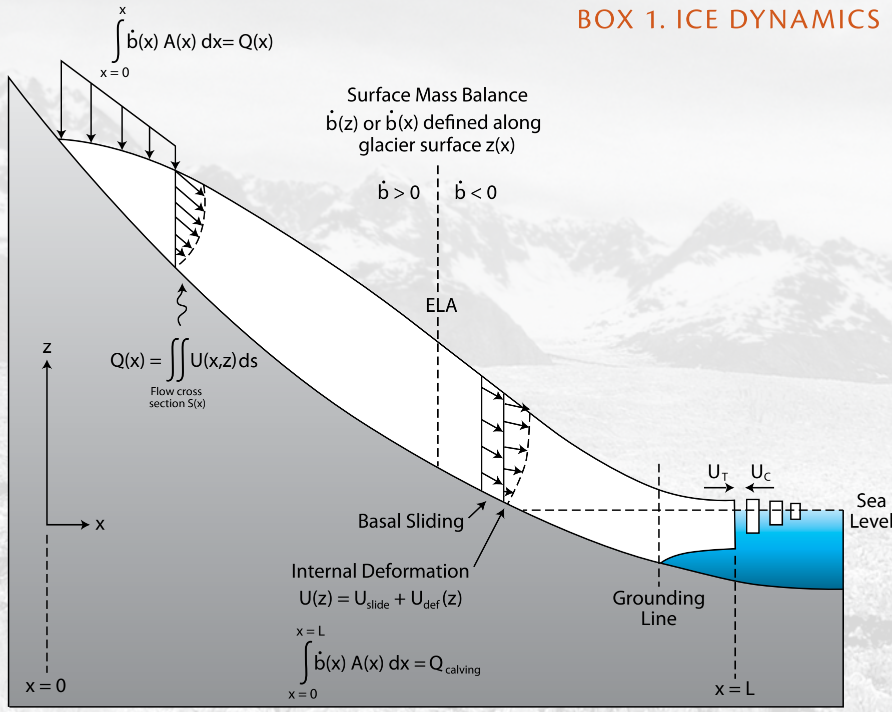
Meier's calculation involved an early encounter with a crucial limitation that has plagued efforts to understand the aggregate changes in glaciers and ice caps to this day: the absence of observations on any but a tiny fraction of the multitude of individual ice bodies scattered across the globe's high-latitude and high-altitude regions. The accounting task alone was daunting: glaciers and ice caps numbered more than 300,000 individual bodies ranging in size over seven orders of magnitude, and they were located on every continent except Australia. Measurements, however, existed on only a handful of glaciers, and even today, records of glacier mass balance of useful duration are kept on only about 100 glaciers worldwide. Finding a scheme for scaling up, or extrapolating, the records from those few measured glaciers to represent the vast unmeasured majority was a perplexing difficulty.

The response to this difficulty was to place a high priority on global glacier mass balance programs, not only for the ice sheets, but for other regions with extensive glacial cover as well, including such areas as coastal Alaska and Patagonia. An international framework was required to coordinate mass balance measurements, and a basic inventory of glaciers had to be completed in order to make available a compilation that contained at least such information as glacier location, size, and elevation for as large a fraction of the world's glaciers and ice caps as could be managed. Meier's problem of extending, or upscaling, the observations

Table 1. Global Land Ice, Major Reservoirs

	Volume (m Sea Level Equivalent)	Area (km^2 x 10^6)	Source
Greenland Ice Sheet	7.3	1.7	Lemke et al., 2007
Antarctic Ice Sheets	56.6	12.3	Lemke et al., 2007
Global Glaciers and Ice Caps	0.6	0.74	Radić and Hock (2010)

BOX 1. ICE DYNAMICS



LAND ICE CONTRIBUTION TO SEA LEVEL

While certain physical processes dominate in ice bodies that are very large, or very cold, or have boundaries in contact with the ocean, all glaciers and ice sheets move mass though their systems in fundamentally the same way. Glaciers exist wherever accumulating snowfall during the course of a year (or some number of years) exceeds the combined losses from melt and runoff, evaporation, or scouring and transport by wind. Ice is a stiff nonlinear fluid, so the excess mass accumulated over time flows downslope from an "accumulation zone," where climatically derived mass flux is net positive, at a rate determined by the thickness of the accumulated ice, the surface slope, and the physical properties of the ice. Downslope flow carries the ice into an "ablation zone" at lower elevations, where it encounters a warmer environment, higher melt rates, and a net negative climatic mass flux. The descending mass is eventually entirely consumed by ablation, and the glacier terminates. If any part of the glacier remains once the descending path reaches the coast, the remaining ice will calve into the ocean as icebergs. In Earth's coldest regions, like Antarctica, melt is absent, and calving constitutes virtually the entire mechanism of glacier loss.

The beauty of the physics of a glacier is the fact that the glacier is, in principle, able to find a geometry precisely in balance with its environment. In an ideal steady state, the shape and speed of a glacier would be exactly that needed to transport excess mass accumulating at high elevations down though the glacier system, and replace the mass deficit at low elevations, where, in the reverse of the situation at the top of the glacier, annual losses exceed gains. Climate does not remain fixed, of course, perhaps oscillating around a mean state, or in a state of transition to some new state. In any case, the glacier is always responding, but the response lags because of flow dynamics. The interaction between the climatic mass balance, controlled by climate, and expressed through the variable, and the glacier dynamics, expressed through the glacier flux Q, can be written:

$$\frac{dM}{dt} = \int_0^L \rho\left(\dot{b} - \frac{\partial Q}{\partial x}\right)dx + \rho h\,(L)\,(u_T - u_c) \qquad [1]$$

where M is total glacier mass, t is time, $\dot{b}$ is local mass balance (net rate of mass accumulation of ablation), ρ is ice density, h is ice thickness, L is glacier length, u_T and u_c are ice speed and calving speed at the terminus, respectively, and x is the along-flow coordinate. The first term on the right represents the difference between mass balance input or output and along-flow transport, which would appear as a thickness change. The second term on the right represents mass lost to changes in length of the glacier at a marine terminus if the calving speed is not identical to the flow speed. (This term is absent in a land-terminating glacier.) In steady state, the flux divergence in the along-flow direction exactly satisfies the mass coming into (or leaving) the glacier through mass balance, and the glacier satisfies a continuity equation of the form:

$$\frac{\partial Q}{\partial x} - \dot{b} = 0 \qquad [2]$$

All glaciers redistribute mass by internal flow processes to maintain a geometry in equilibrium with their mass balance under steady-state conditions, and to this extent all glaciers experience "dynamics." However, not all glacier dynamics necessarily lead to geometries in equilibrium with their mass balance environments. The velocity field in a glacier may, under certain circumstances, shift, sometimes extremely abruptly, to a pattern and magnitude of flux that does not lead to Equation 2. A glacier surge is the classic example of this behavior. Marine-ending glaciers and the West Antarctic Ice Sheet share this property and can shift, when thinning of marine-grounded ice allows buoyancy forces to become a significant factor in the local force balance (Pfeffer, 2007), to behaviors in which the velocity field and resulting redistribution of mass do not act to restore a geometry in equilibrium with the glacier's climate, but may instead rapidly transfer a large portion of the glacier's mass into the ocean through calving. These fast changes in flow and mass redistribution, referred to as "rapid dynamical changes," figured significantly in the controversy surrounding the treatment of potential future ice sheet contributions to sea level in the IPCC Fourth Assessment. Such rapid phenomena were discussed, especially in view of their recent emergence in observations of Greenland and West Antarctic outlet glaciers. Because of a lack of basic physical knowledge of controlling processes, rapid dynamical changes have not been represented confidently in numerical models, and thus were not a part of the IPCC's consensus evaluation.

of a few glaciers to represent the aggregate behavior of all the world's glaciers depended critically on completion of this inventory.

Such an inventory already existed, albeit in incomplete form. Organized glacier inventory programs dated back to the founding of the International Glacier Commission in 1894, but most organized efforts to collect and maintain information on glaciers at international scales dated, again, from the International Geophysical Year of 1957–1958 and the programs that followed. The modern glacier monitoring and data archival services, including the World Glacier Monitoring Service (e.g., WGMS, 2008) and World Data Center–Glaciology/National Snow and Ice Data Center, can trace their roots to programs such as the Permanent Service on Fluctuations of Glaciers and the World Glacier Inventory, both founded at the Swiss Federal Institute of Technology, and both offshoots of IGY-era initiatives (Wallen, 1981).

At the outset of the International Hydrological Decade in 1965, a program was proposed to track glacier changes and to use glaciers as indicators of climate change. In certain regions of the world, like the European Alps, glaciers were few enough in number to actually be enumerated and cataloged with fairly extensive descriptive data accompanying each glacier. In North America, by contrast, where glaciers were vastly more numerous, more widespread, and less accessible, and fewer people were available to perform the work, a different approach had to be adopted. In Alaska and the US Pacific Northwest, a small selection of seven "index glaciers" were chosen for careful and extended study, while the remaining ice was intended to be characterized by data available from maps and aerial photography. In fact, except for a few regions, most of Alaska and the rest of the United States were never inventoried. Even within the inventoried regions, however, practical realities limited the representative character of the index glaciers.

Given the vast territory of North America, the index glaciers were necessarily selected first for their ease of access and manageability as field sites, and second for their likelihood to reflect climate changes and the aggregate behavior of neighboring glaciers. Even if the inventory was complete, the extreme variability in the population made the result of the upscaling an unsure product. The calculation of glacier and ice cap mass balance thus became a complex multistep problem, consisting of: (1) acquisition of the glacier mass balance data (an exercise in upscaling itself), (2) compilation of the mass balance data, often conducted using different protocols and on different schedules, (3) upscaling of data collected on the tiny sample of measured glaciers to the vastly larger population of unmeasured glaciers, and (4) some infrastructure to allow the entire enterprise to operate on a regular basis, issuing updated assessments of global glacier mass balance as annual measurements came in and as the global inventory improved.

Programs such as the World Glacier Inventory (WGMS) and National Snow and Ice Data Center (NSIDC) have taken on the role of building the global glacier inventory, a task that is still incomplete but is progressing, and working collaboratively with a number of individuals and other groups toward streamlining and automating aspects of the inventory and data archival process. The problem of upscaling involves determining multipliers by which measured mass balances judged to be representative of a region are scaled to estimate the total glacier mass balance for the region. Sparse observations and complex spatial climatic gradients obviously make the determination of appropriate scale factors difficult, but additional complexities add even more uncertainty. Because of dynamic effects, the responses of large glaciers differ from those of small glaciers, and observations focused on logistically simpler small glaciers do not give a clear picture of large glacier response. The different characteristics of land- and ocean-terminating glaciers add an even greater element of uncertainty, and mass balance observations on nearby land-terminating glaciers constrain only a portion of the balance of ocean-terminating glaciers.

Despite these limitations, several upscaling approaches have been developed. Kaser et al. (2006) summarize their comparative results through 2004 and discuss the details and relative merits of different approaches. The most recent globally complete assessment applies only to the period ending in 2005 (Dyurgerov and Meier, 2005); refinements have been made to this assessment (Cogley, 2009a), and in one study the series has been extended one year to 2006 (Dyurgerov, 2010). The extended world glacier inventory (WGI-XF, Cogley, 2009b) is estimated to be only approximately 29% of the global total glacier volume (Radić and Hock, 2010). Glacier mass balance data are still being collected, although on an extremely limited (and declining) number of glaciers. The resources for compilation and upscaling, and the number of individuals with the expertise to do the work, are few so that updated global assessments for glaciers and ice caps are now more than five years out of date and are at risk of becoming only more outdated and a greater source of uncertainty in the future.

The National Research Council/Department of Energy (NRC/DOE) 1984 workshop established a clear baseline of contemporary changes and a robust basis for future projections, but the basis of knowledge from which the group was obliged to work was still severely limited. Like the EPA group, the NRC/DOE workshop authors addressed the limitations of their assessment in a summary of recommended research priorities (Committee on Glaciology, 1985). The summary is remarkable for its insight: later investigations confirmed the importance that the workshop authors assigned to their recommendations, and all of the items listed persist as critical tasks. In addition to recommendations concerning better predictive capability in climate modeling and better knowledge of thermal expansion, the workshop recommendations that specifically concerned glaciological problems included studies connected with the dynamics of marine-based ice. The summary also recommended further study of oceanic heat transport across the Antarctic continental shelf, particularly in West Antarctica and the Antarctic Peninsula, and heat transport beneath the large Antarctic ice shelves. Ocean-ice shelf interactions were also emphasized, with priority given to measurements of basal melt rates, iceberg calving rates, and investigation of the processes controlling iceberg calving and the seaward position of ice shelves.

Ice streams also figured prominently in the NRC/DOE report, a reflection in part of the attention that had been focused on fast-moving Antarctic and Greenland ice within the research community in recent years (e.g., Hughes, 1977; Lingle, et al., 1981). Investigations of ice stream mechanics and dynamics were still in their infancy, though. In addition to recommending that research be conducted to determine what factors control whether an ice stream flows in a fast or slow mode, the workshop authors recommended simply that observations be collected on ice stream characteristics, including dimensions, slopes, and speeds.

Observation played a critical role in the NRC/DOE recommendations. Modern remote sensing was on the horizon in the early 1980s, and the report's authors knew technology would soon be available that would make feasible faster acquisition of higher-precision topographic data across larger swaths of polar regions than ever before, if missions were properly designed. Measurements of iceberg calving in both Antarctica and Greenland were also deemed critical, although in those days velocity measurements were still limited to photogrammetric or ground-based means. Radar interferometry, GPS, the GRACE gravity mission, and other modern techniques were still in an unseen future.

The 1984 NRC/DOE workshop report was a substantial advance beyond the limited observational and analytical scope of the preceding EPA report, but once again, implicit in the discussion of recommended research goals was the assumption that the end product of the community's collective effort would be a deterministic model into which observations, theory, and computational capacity would be poured and out of which would flow robust and reliable projections of sea level rise:

These tasks will require continued observation, theory, and modeling studies of basal sliding of glaciers and ice streams using data from deep ice cores and improvement in ice-dynamics models so that they incorporate realistic sliding laws as well as varying ice properties in addition to temperature and meltwater effects. (Committee on Glaciology, 1985, p. 67)

THE IPCC ERA

The body of information concerning ice on Earth's surface, and knowledge of the geometry, environment, and rates of change of the Greenland and Antarctic ice sheets, in particular, grew enormously over the next 25 years. Scientific initiatives, recommended by the early working groups to study the surface mass balance of glaciers and ice sheets as well as the dynamics of marine-based ice, were undertaken in successive stages, and the accumulating knowledge was reported in the four IPCC (Intergovernmental Panel on Climate Change) assessments of 1990, 1995, 2001, and 2007 (Houghton et al., 1990, 1996; Church et al., 2001; Lemke et al., 2007). During the years between the first and fourth IPCC assessments, the estimates of contemporary mass losses from land ice sources held to very consistent, but very uncertain, values: Greenland and Antarctica were not clearly gaining or losing mass, but Greenland was more likely slightly losing mass and Antarctica was more likely gaining mass. Glaciers and ice caps, to the extent that changes could be inferred on the basis of the very small number of glaciers being sampled, were losing mass to the ocean at a rate equivalent to roughly 0.5 mm yr^{-1}.

After the enormous sea level rise values projected for 2100 by the 1983 EPA study (Hoffman et al., 1983), the

1984 NRC/DOE projections (Committee on Glaciology, 1985) dropped to much smaller, but still substantial, values. The subsequent IPCC projections evolved considerably over the course of the four assessments. Estimates of projected sea level rise grew slightly, but uncertainties remained high. As with the estimates of contemporary loss rates, it remained unclear whether Greenland or Antarctica would act as contributors to future sea level rise, or whether increased precipitation might dominate, and the ice sheets might actually serve as sinks. And the question of marine-based ice dynamics continued to hang over all considerations of ice sheet change, unexpressed so far in observations, but clearly a possibility that could not be dismissed.

THE PROBLEM OF RAPID DYNAMICS

In 1978, John Mercer of Ohio State University published a paper proposing that CO_2-forced warming could cause a rapid loss of ice from the West Antarctic Ice Sheet and a consequent rapid 5-m sea level rise (Mercer, 1978). His hypothesis, based on newly emerging global temperature projections from global circulation models, growing knowledge of the dynamics of marine-based ice and ice sheet-ice shelf interactions, and Mercer's own research on past changes in ice sheets and sea level, was among the earliest expressions of "rapid dynamic changes," which he first termed simply "rapid deglaciation" but was upgraded by later writers to "collapse," "disintegration," and other terms suggestive of runaway catastrophic processes. These deglaciation processes have been seen before in the geologic record. For example, during the retreat of the Laurentide Ice Sheet in the early Holocene (Fairbanks, 1989), Mercer's rapid deglaciation formed a prototype for changes in land ice that could be triggered by climate, but once initiated, were capable of transferring water from land to ocean much faster than by melting alone. The importance of this type of dynamics—"fast dynamics," to distinguish it from the dynamics that acts on all glaciers and ice sheets as mass flows from high elevations to low—was apparent to all researchers involved in projecting sea level rise, starting with the first EPA working group in 1983 (Hoffman et al., 1983).

In the IPCC Assessments, rapid dynamics were dealt with at varying levels of detail, but the inclusion of dynamics in projections was invariably blocked by the same obstacle, repeated over and over, from the First Assessment in 1990 to the Fourth Assessment in 2007: the inability of numerical models to represent the relevant processes. At the time of the 1990 First Assessment (Houghton et al., 1990), the first-generation work had been done on the Siple Coast Ice Streams (Alley et al., 1987; Bentley, 1987), and their potential to exert major changes on ice sheet mass balance was obvious. But as far as quantitative projections were concerned, in the words of the report, "A comprehensive model of the ice streams and their interaction with the main body does not yet exist, unfortunately."

Table 2. Estimated present-day rate of loss, sea level equivalent (mm yr^{-1})

Year	Study		Source		
			Greenland Ice Sheet	Antarctic Ice Sheets	Glaciers and Ice Caps
1984	NRC/DOE (Committee on Glaciology, 1985)	Rate of Loss	−0.3 to +0.5	−1.2 to 0.0	+0.2 to +0.8
		Period of Observation	Last Century	Last Century	Last Century
1990	IPCC First Assessment (Houghton et al., 1990)	Rate of Loss	−0.7 to +0.3	0.0 to +0.1	~ +0.5
		Period of Observation	Mixed Dates	Mixed Dates	1900–1961
1995	IPCC Second Assessment (Houghton et al., 1996)	Rate of Loss	−0.3 to 0.0	−1.0 to +1.0	+0.2 to +0.6
		Period of Observation	Mixed Dates	Mixed Dates	Mixed Dates
2001	IPCC Third Assessment (Church et al., 2001)	Rate of Loss	0.0 to +0.1	−0.2 to 0.0	+0.2 to +0.4
		Period of Observation	1910–1990	1910–1990	1910–1990
2007	IPCC Fourth Assessment (Lemke et al., 2007)	Rate of Loss	+0.14 to +0.28	−0.14 to +0.55	+0.55 to +0.99
		Period of Observation	1993–2003	1993–2003	1993–2003

(Houghton et al, 1990, Section 9.4.6, p. 273). By the time of the 1995 Second Assessment (Houghton et al., 1996), the Larsen and Wordie Ice Shelves on the Antarctic Peninsula had broken up (events anticipated by Mercer), and the potential for rapid dynamics, expressed in the Second Assessment as "the possibility of 'collapse'" was a central issue for discussion. Once again, however, the inability to model the processes involved inhibited progress. This time, however, a useful question was raised, if not answered: Could the dynamic processes responsible for rapid changes be affected by climate changes on time scales as short as one century? If this question could be answered without resorting to high-order glaciological models, it might be possible to decide whether dynamic changes were critical in projecting sea levels on the next-century scale or the next-millennium scale—two very different issues from policy and planning perspectives. In any case, the question was never pursued.

By 2001, rapid dynamics had been thoroughly explored as a theoretical matter by many researchers, but no clear understanding of the processes controlling dynamics had emerged, and certainly no validated model existed. The position of the authors of the Third Assessment's report on changes in sea level (Church et al., 2001) remained essentially unchanged: major loss of grounded ice, and accelerated sea level rise, was considered very unlikely during the twenty-first century. Contrary opinions were circulating in the scientific literature, but no consensus existed. The only position IPCC could endorse was that rapid dynamics had a realistic chance of influencing sea level within the next century.

Not long before the release of the IPCC Fourth Assessment in 2007, observations of a distinctly different character started to emerge from the hazy Antarctic and Greenland mass loss signals. Where previously it had been unclear whether the data from the ice sheets indicated net gain or net loss, Rignot and Kanagaratnam (2006) showed that the net rate of mass loss from Greenland had more than doubled from about 80 GT yr^{-1} in 1996

Table 3. Projected contribution to sea level by 2100 (cm)

Year	Study	Source (*1983 EPA did not separate land ice sources*)			
1983	EPA (Hoffman et al., 1983)	Low	Mid-Range Low	Mid-Range High	High
		+56.2	+144.4	+216.6	+345.0

Year	Study	Source		
		Greenland Ice Sheet	Antarctic Ice Sheets	Glaciers and Ice Caps
1984	NRC/DOE (Committee on Glaciology, 1985)	+10 to +30	−10 to +100	+10 to +30
1990	IPCC First Assessment[1] (Houghton et al., 1990)	+0.5 to +3.7	−0.8 to 0.0	+2.3 to +10.3
1995	IPCC Second Assessment[2] (Houghton et al., 1996)	+6	−1	+16
2001	IPCC Third Assessment[3] (Church et al., 2001)	0 to +7	−7 to +2	+3 to +23
2007	IPCC Fourth Assessment[4] (Lemke et al., 2007)	+8 to +17	−14 to −3	+2 to +12

[1] Projection to 2030 using BAU Forcing Scenario; NOTE: 1990 Projection to 2030 only.
[2] Projection using IS92a Forcing Scenario.
[3] Using Forcing Scenario CGCM1 GS; 1990–2100.
[4] Total land ice contribution 4 to 23 cm; with "scaled-up ice sheet contribution," add ca. 10 to 20 cm.
NOTE: Highest ("fastest burn") emission scenario only for each Assessment chosen for comparison.

to about 220 GT yr^{-1} in 2006, with some two-thirds of the increase coming from increased outflow through outlet glaciers terminating at Greenland's coast. A collection of other reports, using a variety of satellite-based methods, verified Rignot and Kanagaratnam's finding, and in Antarctica, a variety of observations (e.g., Zwally et al., 2005; Rignot and Thomas, 2002; Velicogna and Wahr, 2006) showed a comparable rise, with a net loss growing to about 200 GT yr^{-1} by 2003. The Fourth Assessment's evaluation was that the ice sheets were "very likely" contributors to sea level during the period 1993–2003, and each was assigned an average rate during this period of 76 ± 25 GT yr^{-1} or 0.21 ± 0.07 mm yr^{-1} sea level equivalent (SLE).

Mass loss from glaciers and ice caps during the same period was assessed at 280 ± 79 GT yr^{-1}, or 0.77 mm yr^{-1} SLE. Oddly, none of the major assessments have considered a sea level contribution arising from rapid dynamic response from glaciers and ice caps, despite broad awareness of this possibility within the research community. In the few arctic regions where it is measured, for example, in Svalbard (Blaszczyk et al., 2009), calving from marine-ending glaciers constitutes about 50% of the total ablation, a calving fraction comparable to that observed in Greenland. Measured by ice volume, roughly 90% of the glacier and ice cap category is located immediately adjacent to coasts, with only 10% in land-locked interior locations like the Alps or Himalayas. Because proximity to the coast alone does not determine susceptibility to rapid dynamic effects—connections through marine-grounded outlets are required—knowledge of the potential for rapid dynamic discharge from glaciers and ice caps hinges on mapping of marine outlets. For most of the world's glaciers and ice caps, this potential remains unknown.

Once again, a crucial piece of information—in this case, the global fraction of glacier and ice cap volume drained though marine outlets—is missing, one of the many pieces of the glacier and ice cap puzzle that will remain unknown unless and until a global inventory is completed.

In their discussion of sea level rise and rapid dynamics, the authors of the IPCC Fourth Assessment (AR4) were faced with a dilemma: the consensus knowledge that formed the core of the IPCC reports acknowledged the potential importance of rapid dynamic changes in the ice sheets especially, but they still had no workable means for including such dynamics in predictive models. Up through the last three assessments, that lack of capacity hadn't been a critical issue because the ice sheets appeared to be stable (or at least not obviously changing), and the capacity for rapid dynamic changes in the glaciers and ice caps had never been considered. The state of affairs entering the Fourth Assessment was thus not a great deal different than had been expressed at the time of the Third Assessment. This time, however, reports of significant accelerations in loss from the ice sheets were arriving soon enough to be discussed in the Fourth Assessment (e.g., Lemke et al., 2007, Section 4.6.2.2) but far too late for the research community to

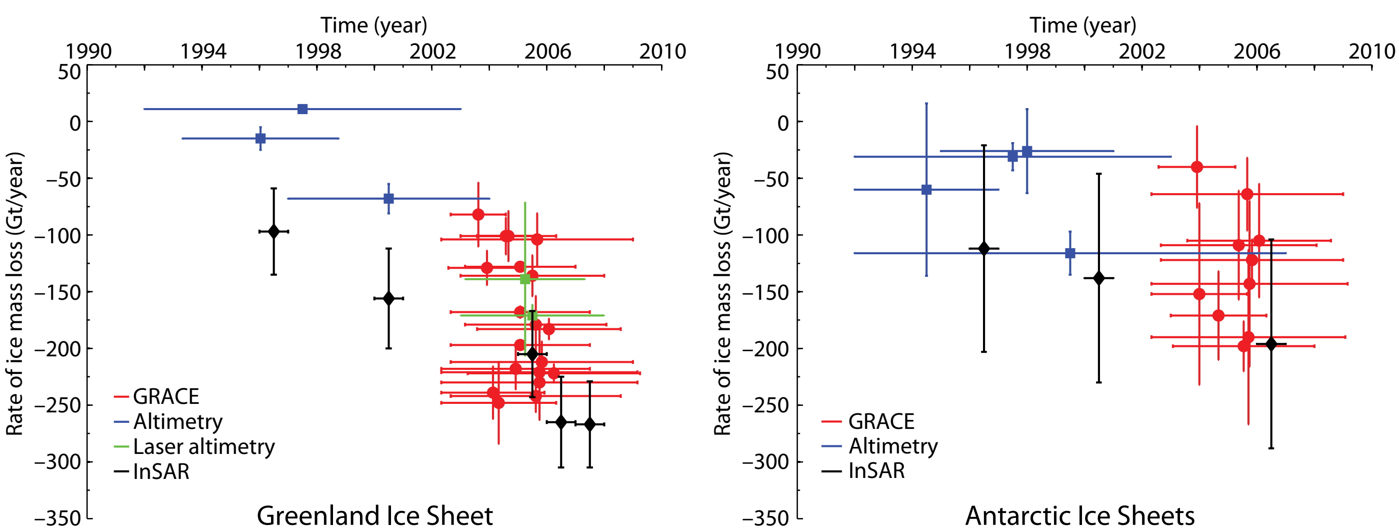


Figure 1. Mass loss from the Greenland Ice Sheet (left) and the Antarctic ice sheets (right) for 1992–2009, determined by various observers, summarized by A. Cazenave (LEGOS). *See Cazenave and Llovel (2010) for data sources*

react with quantitative analyses and ice sheet modeling responses that could be published in time for inclusion in the AR4. The AR4 authors were thus placed in the uncomfortable position of being obliged to report on dramatic new changes in the mass balance of the Greenland and Antarctic ice sheets, but had to continue to discuss future sea level projections based almost entirely on knowledge that preceded those new reports. The basic sea level projections for 2100 made by the AR4 were based on modeled mass balance changes and "conventional" dynamics (the redistribution of mass by flow in glacier and ice sheet systems). They did not include "rapid dynamics"—again, the modeling capability was simply absent, as had been the case in the Third Assessment and earlier. The AR4 group's actions were widely criticized—and widely misunderstood—in part because of confusion over the meaning and role of "rapid dynamics" (e.g., in an influential 2010 op-ed piece posted on Yale University's online publication *Environment 360*, authors Rob Young and Orrin Pilkey appear to believe that the AR4 authors left Greenland and Antarctica out of their sea level rise projections entirely [Young and Pilkey, 2010]).

One result of the exclusion of rapid dynamics from the 2007 AR4 sea level projections was a rush to investigate potential high-end sea level projections, inspired by continued growth in observed loss rates from the ice sheets. Paleoclimate analogs were clearly relevant, but problematic. Extraordinarily fast rates of sea level rise (~ 4 m/century) are known to have occurred during the decay of the Laurentide Ice Sheet some 12,000 to 14,000 years ago (Fairbanks, 1989), but the global distribution of ice at that time was very different than today, making the rates of sea level rise of that time poor analogs for the twenty-first century. Going back 125,000 years ago, to the last interglacial period, global ice conditions were more nearly a match to today's, and large sea level increases occurred then as well (Overpeck et al., 2006; Blanchon et al., 2009); however, for stratigraphic records extending that far into the past, the resolution of dating techniques diminishes, and "rapid" becomes a relative term. Whether the observed sea level rise occurred quickly or slowly on human time scales—did sea level rise 3 m in a century or 3 m in a millennium?—is very difficult to resolve.

Nevertheless, for a period of a year or so following the release of the IPCC Fourth Assessment, newer projections, mostly informal, in the sense that they were not derived from a modeling study or other quantitative geophysical analysis, were put forth from a variety of sources that placed sea level by 2100 as high as 5 m above present (Hansen, 2007). These new sea level estimates had two effects. One was to create a widespread impression in the planning and policymaking community, as well as within political circles, that the scientific community had settled on a much higher estimate of future sea level rise—one approaching 5 m—than the very modest 0.2–0.8-m AR4 projection. (That these projections were "informal" did little to decrease their influence. Presidential Science Advisor John Holdren was called before House Committee on Science and Technology Chair Ralph Hall on February 17, 2011, to explain his statements in 2006 when, as president of AAAS, he had warned that a 4-m rise within this century was "within the realm of possibility;" for a Webcast of the hearing, go to: http://science.house.gov/hearing/full-committee-hearing). Another effect was to focus attention even more exclusively on the very problems that the glaciological research community was least equipped to solve: those dynamic changes particularly dependent on the poorly known processes of basal sliding and calving. By focusing so exclusively on the goal of developing a deterministic numerical modeling strategy, the glaciological community had backed itself into a corner. As the dynamic aspects of Greenland and Antarctica became progressively more dominant in the overall mass balance of the ice sheets (whether the glaciers and ice caps were experiencing a similar change was simply unknown), scientists could do little but measure the change and experiment with some simple ideas, including another stopgap (harkening back to the simple expedients of the 1980s): extrapolation.

MODERN OBSERVATIONS AND EXTRAPOLATION

Among the reactions to the absence of reliable model simulations of future glacier and ice sheet changes, a variety of simple experiments sought to project present-day rates of mass loss forward into the future, or in some other way to make quantitative projections of sea level rates (or components of sea level rise) that were empirical or conceptual in nature rather than process-based. Meier et al. (2007) compiled mass loss rates for Greenland, Antarctica, and glaciers and ice caps, all estimated for the common date of 2006, as well as the rate of change of mass loss. They then integrated, or extrapolated, the loss rates forward to 2050 and 2100 under two scenarios, one assuming no further acceleration (no further warming) and another assuming continued acceleration at the same rate as at present. Their results for 2050 showed a land ice sea level contribution of approximately 8 cm if no further acceleration occurred and 16 cm if the current acceleration were held constant. Of these amounts, the contribution from the Greenland and Antarctic ice sheets was 9 cm (no further acceleration) and 31 cm (constant acceleration). The corresponding values for 2100 were, for total sea level rise, 17 and 56 cm, and from the ice sheets, 9 and 31 cm.

The calculations also showed that all three land ice categories—Greenland and Antarctic ice sheets, and the glaciers and ice caps—were significant contributors. That calculation was simple enough, but what did it mean? More-sophisticated approaches could be taken to the details of how the rates, and especially acceleration, were calculated, and the uncertainties of the extrapolation could thus be refined; but the larger question is what the extrapolation means. Extrapolation in this case implies that the processes that operated during the period of observation will continue to operate in the same fashion during the extrapolation. Extrapolation of the recent Greenland mass loss record, for example, would imply that the observed accelerations (e.g., the doubling of mass loss between 1996 and 2006) will continue for the duration of the extrapolation. Critical questions immediately arise: what curve should be used to fit to the mass loss observations, and how far into the future should the extrapolations go? Both are questions of time scales, and both are questions whose answers lie in an understanding of dynamics. Meier et al. (2007) avoided the assumption that acceleration would continue without limit by considering two scenarios: continued acceleration to 2100, which was almost surely an overestimate, and no further acceleration past 2006, almost surely an underestimate. They then proposed that the actual event would lie somewhere between the two computed outcomes.

More recently, Rignot et al. (2011) calculated a detailed time series of loss rates for both Greenland and Antarctica using modeled surface mass balance and measured and estimated outlet glacier discharge, supplemented after 2002 by GRACE gravity data. The Rignot et al. (2011) compilation is at present the most detailed and longest record of mass loss yet done for the ice sheets (no data were presented for glaciers and ice caps). Like Meier et al. (2007), Rignot et al. (2011) extrapolated the observed loss rate, using a linear fit to the 1992–2009 trend and extrapolating only 40 years to 2050. Their results suggested that the Greenland and Antarctic ice sheets produce a combined sea level rise of ca. 15 cm by 2050 and 56 cm by 2100—slightly less than double the Meier et al. (2007) accelerating projection. It is unclear how much of the difference in these results lies in the analyses and how much in the data. The Rignot group had several more years of data at their disposal (the data available to Meier et al. extended only though 2005), and the recent acceleration of the discharge from both Greenland and Antarctica would have more influence on the trend for Rignot et al.'s analysis than for Meier et al.'s. How best to handle this influence in the extrapolation is again a question of time scales and a question of dynamics.

Many of the goals proposed by the early working groups have been achieved, or at least substantial efforts have been made. Oceanic circulation patterns around portions of the Antarctic and Greenland coasts have been studied. Heat transport beneath floating ice has been found to be a major component of the energy budget of certain marine margins (Jacobs et al., 1992; Holland et al., 2008). Surface mass balance has been determined by a combination of remote sensing, direct measurement, and modeling over large regions of the ice sheets (Box et al., 2006; Ettema et al., 2009). Ice motion, calving rates, and the forces and dynamics of flow in transition from grounded to floating ice have been studied extensively in Greenland and Antarctica by many methods (van der Veen and Whillans, 1989, 1993; MacAyeal et al., 2003; O'Neel et al., 2005; Joughin et al., 2003, 2008; Howat et al., 2008; Winberry et al., 2009; Motyka et al., 2011). A picture of ice sheet motion, growth, and decay is emerging, becoming progressively more detailed and finely sliced in time, and analyses appear in rapid succession, reporting overlapping (and, at times, conflicting) results (Velicogna, 2009; van den Broeke et al., 2009).

WEAKNESSES

For all the success of air- and spaceborne observations, certain longstanding theoretical and measurement objectives have consistently eluded researchers. Among the earliest stated goals for research were observations of basal sliding and calving, and improved understanding of subglacial processes, especially those operating at marine margins. The basis of englacial (within the ice) and subglacial hydrology and basal sliding was mostly established on mountain glaciers in the 1970s and 1980s (e.g., Röthlisberger, 1972; Iken and Bindschadler, 1986). Extensions to the fundamental theory were made in Europe, North America, and elsewhere in subsequent years (Hanson and Hooke, 1994; Iken and Truffer, 1997; Meier et al., 1994; Kamb et al., 1994), but progress was incremental, in part because of the extreme difficulty of obtaining measurements at the bed of a glacier. Substantial progress was made in Antarctica on the Siple Coast Ice Streams in the late 1980s using seismic methods (Alley et al., 1987; Engelhardt et al., 1990; Kamb, 1991), but after the mid 1990s, progress on subglacial processes became incremental. The situation in the case of iceberg calving is, if anything, even more bleak, with the most significant progress being limited to simple empirical work in the 1980s (Brown et al., 1982) and minor modifications of fundamental mechanics investigations made in the 1960s and 1970s (Reeh, 1968; Weertman, 1973). At present, the foundations of our theoretical knowledge of subglacial sliding and iceberg calving are not very different than what was available at the time of the First IPCC Assessment (Houghton et al, 1990). This limitation is particularly problematic given the emphasis placed on the development of deterministic models, which require functional components for all processes. Efforts have been made to substitute heuristic, or descriptive, rules in place of true process-driven models (e.g., Parizek and Alley, 2004), but the simplifications involved severely compromised processes known to exert significant control on glacier motion. As was the case nearly three decades ago, basal sliding and calving remain obscure but exert critical controls on glacier and ice sheet dynamics. The lack of detailed observations of basal topography, temperature, and other boundary conditions in critical regions further complicates modeling efforts. This is not to say that no progress has been made. Computational power and skill have increased tremendously; knowledge of the constitutive properties of ice as a nonlinear fluid has also greatly improved in recent years. Similarly, there have been some significant observational and theoretical gains in the intervening years concerning subglacial processes (e.g., Harper et al., 2007; Bartholomaus et al., 2008), but these advances have still not closed the gaps in our knowledge to a degree that "sliding laws" can be reliably and broadly implemented in numerical models. No clear solution to this problem is in sight.

Since the earliest days of the organized pursuit of projections of future sea level rise (which essentially date from the 1970s and the outset of general circulation modeling of a CO_2-warmed future), glaciological projections have been built upon the assumption that a deterministic, process-driven numerical model of glacier dynamics (including ice-atmosphere and ice-ocean interaction) is feasible. To date, this modeling has not been possible, largely because of significant gaps in our knowledge of the basic physics driving crucial glaciological processes, with basal sliding and calving chief among them. Remarkable advances have been made in certain other areas, such as in the investigation of the constitutive properties of ice as a continuous deformable medium (e.g., Durand et al., 2006; Jacka and Li, 2000). But, a model is only as strong as its weakest parts, and wherever sliding and calving are significant phenomena, model-based efforts to analyze or project realistic glacier behavior have been unsuccessful.

Another notable result of assessments of contemporary loss rates and conceptual projections is the *relative* contribution of land ice sources: where is most of the water coming from and where is it likely to come from in the future? For all periods for which complete data are available for direct comparison, glacier and ice cap mass loss rates constitute the principal source of land ice mass loss (e.g., Houghton et al., 1990, 1996; Church et al., 2001; Lemke et al., 2007; Cazenave et al., 2008, 2009; Allison et al., 2009; Cazenave and Llovel, 2010). The recent rapid increase in ice sheet mass loss has led to speculation that ice sheet losses now dominate sea level contributions, but the data for direct comparison are unavailable. The most recent ice sheet assessment of Rignot et al. (2011) places the combined ice sheet loss rate in 2009 at ca. 900 GT yr^{-1}. The most recent formal global assessment of glacier and ice cap mass loss (Cogley, 2009a) placed global glacier and ice cap mass loss at ca. 510 GT yr^{-1} for 2001–2005, the most recent period for which global upscaled data are available. For a more direct comparison, the combined ice sheet mass loss rate from Rignot et al. (2011) for 2001–2005 is ca. 332 GT yr^{-1}. With no comprehensive, global upscaled compilation of glacier and ice cap loss rates after 2005, no better calculation can be made of the combined net land ice mass loss rate to compare to Rignot et al.'s 2009 value. Ice sheet loss rates may well have surpassed glacier and ice cap loss rates, or may soon pass them, but the fact remains that without any proper accounting of the aggregate glacier and ice cap loss rate, the net loss from land ice cannot be reliably calculated. Given the present magnitude of glacier and ice cap loss rates, fractional changes in that rate are significant. Speculation that the

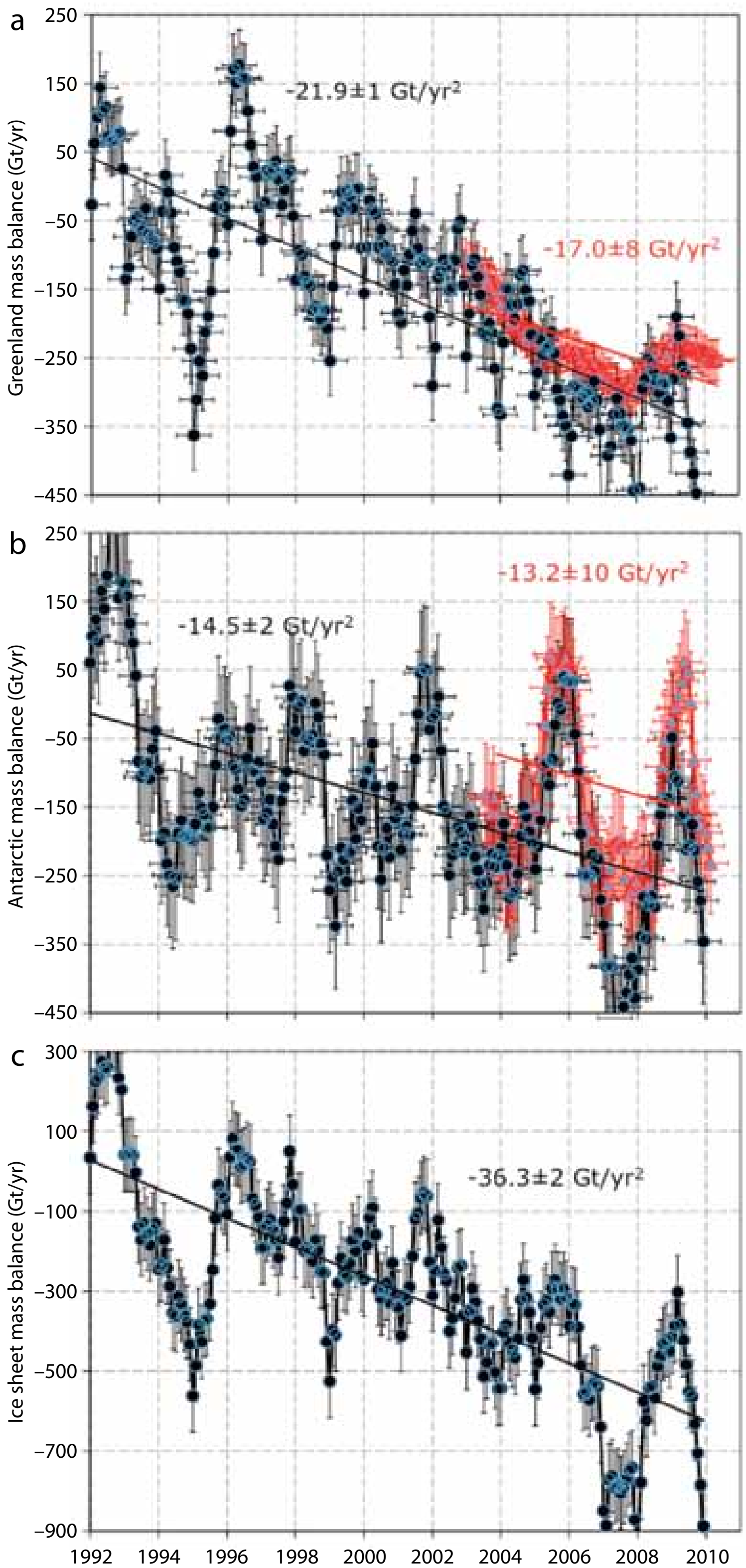


Figure 2. Mass loss from (a) the Greenland Ice Sheet, (b) the Antarctic ice sheets, and (c) combined loss from Greenland and Antarctic ice sheets, as determined by Rignot et al. (2011). The linear fits show the average rates of acceleration of loss during the period of observation, from 1992 to 2009. *Figure from Rignot et al. (2011)*

depletion of the glacier and ice cap reservoir may not accelerate at the same pace as the ice sheets, or may start to diminish as their aggregate area declines, may well be true. Better knowledge of this change, however, is crucial if the net land ice contribution is to be known.

Without observations, which continue but have not been compiled in more than six years, and without a completed inventory, which has yet to be accomplished, no reliable assessment of contemporary rates of sea level rise can be made. Without this knowledge, projections of sea level rise are blind to future contributions from glaciers and ice caps. Will these contributions be significant? The Rignot et al. (2011) projection included an estimate for total sea level rise, borrowing thermal expansion projections from the AR4 and glacier and ice cap projections from Meier et al. (2007). Even using the latest rates from Greenland and Antarctica and 2006 values for glaciers and ice caps, the projected sea level rise for 2050 breaks down into very nearly equal quarters: 25% each from Greenland, Antarctica, glaciers and ice caps, and thermal expansion. Extrapolation at least has the virtue of allowing investigation of *comparative* magnitudes, and nothing in the observations or our knowledge of projections suggests conclusively that, on the 50–100-year time scale, glaciers and ice caps will be negligible contributors, or, indeed, significantly smaller contributors than the ice sheets. However, our ability to project what glacier and ice discharge will actually be is grossly compromised, both by lack of basic inventory knowledge (where are the glaciers and how big are they?) and up-to-date observations of their rate of change. This absence of continued support for glacier

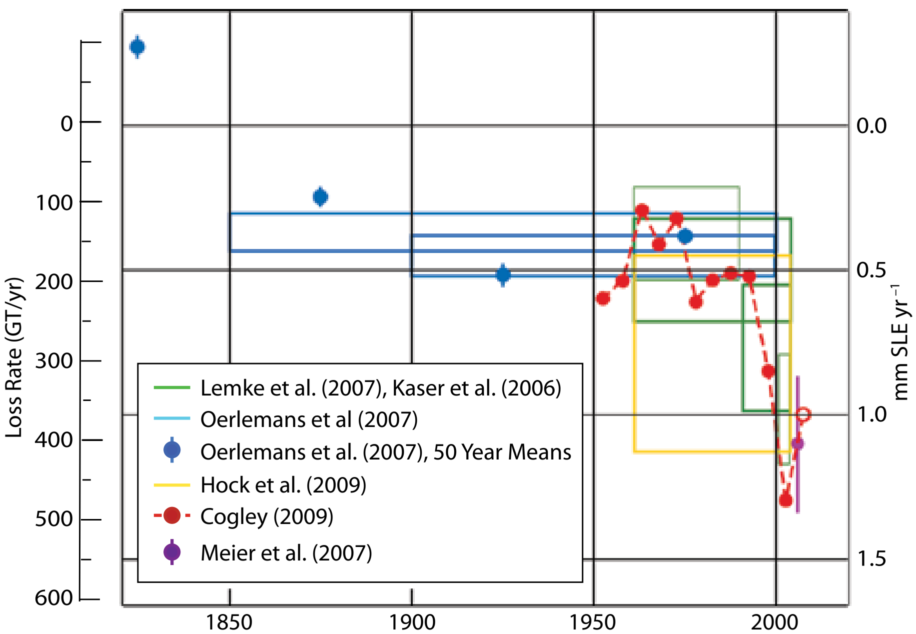


Figure 3. Mass loss from all glaciers and ice gaps exclusive of the Greenland and Antarctic ice sheets, for ca. late nineteenth century to 2006, determined by various observers. *Figure courtesy G. Kaser*

and ice cap observations points to one last question: what is our purpose in studying sea level?

THE FUTURE

A half-century ago, when geophysicists worldwide embarked on the International Geophysical Year, glaciers and ice sheets were objects of mystery, and could be studied for their own sake, for the sake of knowledge, for the sake of discovery, for the sake of satisfying an urge to understand the nature of a complex process. Those motivations have carried us far, and have prepared generations of scientists for the present day when, in addition to the satisfaction of intellectual urges, scientists are called upon to answer particular problems of societal relevance, such as the height to which sea level might rise by a certain date. Practical problems of this type differ from purely intellectual problems in that they frequently involve difficult, uncertain, or truly intractable aspects, such as determining the mass balance of hundreds of thousands of small glaciers scattered across the globe or the physical properties of the ice-bedrock interface buried beneath several kilometers of ice. Nevertheless, a solution has to be found, and posed in a form useful to the groups and individuals best positioned to put the information to good use for the benefit of society. In the case of sea level rise, the immediate consumers of scientific information (in addition to other scientists) are planners, policy-makers, coastal engineers, and similar decision makers who need the best available information on future sea level. The preferred form for sea level projections is as a probability distribution function (PDF), by which, for a certain future date, a range of possible values is given for sea level, with probabilities indicating a mean value and tails of lower probability indicating low-end and high-end possibilities. As discussed here, much of the focus of the glaciological research community has been on the dynamics of marine-based ice—that is, on the possibility of "rapid dynamic changes" that would transfer ice quickly from land to ocean and raise sea level far faster than by melt alone. Such events appear in the PDF as a "Fat Tail": events of high consequence, and low but not a vanishing probability, hence, the "fat" tail of the distribution. Such events are both spectacular and important, but they are not the entire story, nor are they the entire PDF.

The peak of the PDF, the lower-impact, higher-probability event—the event that is, in fact, most likely to occur—is composed of more mundane stuff. It is, simply, the sum of all land ice contributions, the discharge, evaluated to the best of our ability, coming from Greenland, from Antarctica, and from the 300,000 or more glaciers and ice caps scattered across the globe. The "Fat Tail," as important as it may be, cannot tell the entire story. Neither can the deterministic model solve all glaciological problems, until and unless the missing physics is discovered. We have gaps not only in our knowledge but in our plans. We need a broader view of observations: what are *all* the land ice loss rates? We need a broader view of potential solutions: what lies between a fully deterministic model and blind extrapolation? And, finally, we need to view our particular role as scientists in the service of society: what questions are we called upon to answer, and how do we address those questions optimally?

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