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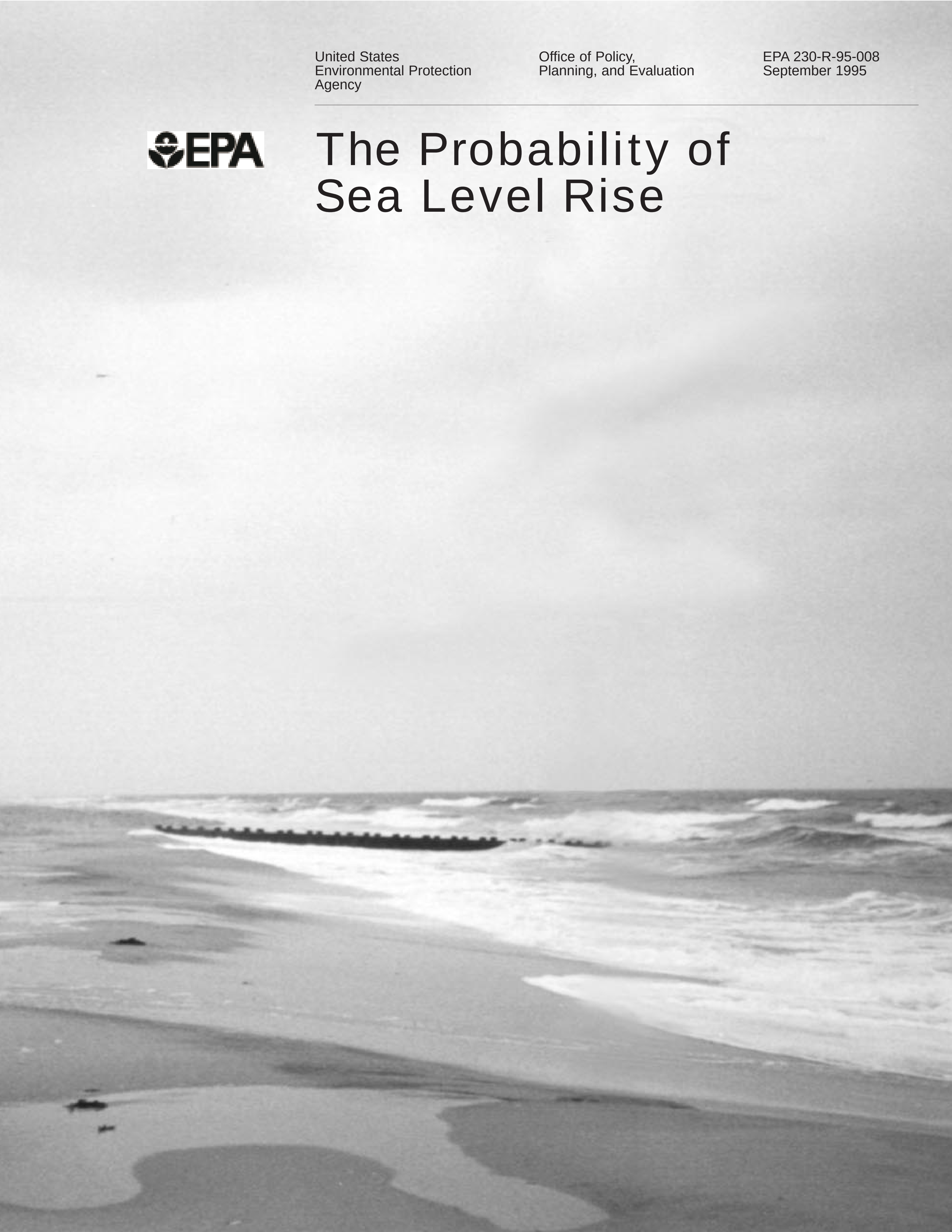
The Probability of Sea Level Rise



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THE PROBABILITY OF SEA LEVEL RISE

by

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This document has been reviewed in accordance with the U.S. Environmental Protection Agency peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Please send comments to James G. Titus, U.S. Environmental Protection Agency, Washington, D.C. 20460.

SUMMARY

The Earth's average surface temperature has risen approximately 0.6˚C (1˚F) in the last century, and the nine warmest years have all occurred since 1980. Many climatologists believe that increasing atmospheric concentrations of carbon dioxide and other gases released by human activities are warming the Earth by a mechanism commonly known as the "greenhouse effect." Nevertheless, this warming effect appears to be partly offset by the cooling effect of sulfate aerosols, which reflect sunlight back into space.

Climate modeling studies generally estimate that global temperatures will rise a few degrees (C) in the next century. Such a warming is likely to raise sea level by expanding ocean water, and melting glaciers and portions of the Greenland Ice Sheet. Warmer polar ocean temperatures could also melt portions of the Ross and other Antarctic ice shelves, which might increase the rate at which Antarctic ice streams convey ice into the oceans. Warmer polar air temperatures, however, would probably increase annual snowfall, which would partly offset the rise in sea level caused by warmer temperatures. Along much of the United States coast, sea level is already rising 2.5-3.0 mm/yr (10 to 12 inches per century).

By ratifying the United Nations Framework Convention on Climate Change, more than 120 countries have agreed to implement measures for adapting to rising sea level and other effects of changing climate. Because the design and location of coastal structures involve decisions that cannot be easily reversed, people responsible for these activities must either plan now or risk losing the opportunity for a meaningful response. Nevertheless, the value of planning for sea level rise depends upon the probability that the sea will rise by a given magnitude.

This report develops probability-based projections that can be added to local tide-gauge trends to estimate future sea level at particular locations. It uses the same models employed by previous assessments of sea level rise. The key coefficients in those models are based on subjective probability distributions supplied by a cross-section of climatologists, oceanographers, and glaciologists. The experts who assisted this effort were mostly authors of previous assessments by the National Academy of Sciences and the Intergovernmental Panel on Climate Change (IPCC).

The estimates of sea level rise are somewhat lower than those published by previous IPCC assessments, primarily because of lower temperature projections. This report estimates that global temperatures are most likely to rise 1˚C by the year 2050 and 2˚C by the year 2100, that there is a 10 percent chance that temperatures will rise more than 4˚C in the next century, and a 90 percent chance that they will rise by at least the 0.6˚C warming of the last century. By contrast, IPCC (1992) estimated that a warming of 2.8˚C was most likely. Our temperature estimates are lower because (a) we assume lower concentrations of carbon dioxide; (b) we include the cooling effects of sulfates and stratospheric ozone depletion; and (c) our panel of experts included a scientist who doubts that greenhouse gases will substantially increase global temperatures.

Based on the aforementioned assumptions, which this report explains in detail, our results can be summarized as follows:

1. *Global warming is most likely to raise sea level 15 cm by the year 2050 and 34 cm by the year 2100*. There is also a 10 percent chance that climate change will contribute 30 cm by 2050 and 65 cm by 2100. These estimates do not include sea level rise caused by factors other than greenhouse warming.

2. *There is a 1 percent chance that global warming will raise sea level 1 meter in the next 100 years and 4 meters in the next 200 years.* By the year 2200, there is also a 10 percent chance of a 2-meter contribution, and a 1-in-40 chance of a 3-meter contribution. Such a large rise in sea level could occur either if Antarctic ocean temperatures warm 5˚C *and* Antarctic ice streams respond more rapidly than most glaciologists expect, or if Greenland temperatures warm by more than 10˚C. Neither of these scenarios is likely.

3. *By the year 2100, climate change is likely to increase the rate of sea level rise by 4.2 mm/yr*. There is also a 1-in-10 chance that the contribution will be greater than 10 mm/yr, as well as a 1-in-10 chance that it will be less than 1 mm/yr.

4. *Stabilizing global emissions in the year 2050 would be likely to reduce the rate of sea level rise by 15 percent by the year 2100, compared with what it would be otherwise*. These calculations assume that we are uncertain about the future trajectory of greenhouse gas emissions.

5. *Stabilizing emissions by the year 2025 could cut the rate of sea level rise in half*. If a high global rate of emissions growth occurs in the next century, sea level is likely to rise 6.2 mm/yr by 2100; freezing emissions in 2025 would prevent the rate from exceeding 3.2 mm/yr. If less emissions growth were expected, freezing emissions in 2025 would cut the eventual rate of sea level rise by one-third.

6. *Along most coasts, factors other than anthropogenic climate change will cause the sea to rise more than the rise resulting from climate change alone*. These factors include compaction and subsidence of land, groundwater depletion, and natural climate variations. If these factors do not change, global sea level is likely to rise 45 cm by the year 2100, with a 1 percent chance of a 112 cm rise. Along the coast of New York, which typifies the United States, sea level is likely to rise 26 cm by 2050 and 55 cm by 2100. There is also a 1 percent chance of a 55 cm rise by 2050 and a 120 cm rise by 2100.

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CHAPTER 1

INTRODUCTION

Background and Organization

In the last several years, a steady stream of reports has estimated that the rate of sea level rise is likely to accelerate in the next century (EPA 1983; NRC 1983; NRC 1985; IPCC 1990; Wigley & Raper 1992). As a result, coastal decisionmakers around the world have gradually begun to consider how to respond. In many cases, no immediate response is necessary, because the time required to implement a response is less than the time likely to pass before the sea rises significantly (NRC 1987).

A number of important decisions, however, are sensitive to sea level rise on time scales of a century or so. In some cases, the cost of preparing for a large rise in sea level is small compared with the costs that would eventually be incurred if the sea rises more than assumed in a project's design. In such a case, it is rational to design for a relatively high scenario, even if that scenario is unlikely. For example, the Dutch flood-protection system is designed to endure the "ten thousand year storm," which has only a 1 percent chance of occurring in a given century (Goemans 1986). Thus, if a new dike is expected to last a century, maintaining the desired level of safety requires an explicit consideration of the probability distribution of sea level rise.

Similarly, if a state intends to protect its coastal wetlands or the public's legal right to access along the shore, the cost of anticipatory land use planning can be less than 1 percent of the eventual cost of remedial action (Titus 1991); thus, it can be rational to implement these land use policies even for areas with a low probability of inundation. A few states have added restrictions to the development of coastal property which essentially say that if sea level rises enough to erode or inundate it, the property owner must remove any structures that impede the landward migration of natural shorelines.[1] If other states consider this option for protecting their tidelands, they may wish to determine the resulting impact on coastal property values.[2] Doing so requires an explicit assessment of the timing and likelihood of the sea rising enough to inundate a particular property.

In spite of the need for this information, previous assessments of future sea level rise have not provided probabilities, for both computational and conceptual reasons. At the computational level, projections of sea level rise require complex nonlinear functions. Hence, even if we knew the distributions of the various uncertain processes, probability theory would offer us no direct "closed form" solution for estimating the probability distribution of future sea level rise. Instead, one must iteratively approximate the distribution by evaluating the models with alternate values for the various unknowns. But many models—particularly the "general circulation models" used to assess the impact of greenhouse gases on climate—cost too much to run for this to be possible.

Even where the computational problems can be solved, estimating probability distributions seems to involve more subjectivity.[3] Existing measurements may lead researchers to be confident that a particular set of low, medium, and high scenarios are reasonable. But ascribing probabilities requires an additional level of specification, and current knowledge does not permit this to be done with precision. For example, both Meier (1990) and IPCC (1990) report the results of committees that agreed to a high scenario in which the Antarctic contribution to sea level rise is zero. The committees did not, however, decide whether "no Antarctic contribution" represents a worst-case scenario or a scenario with some chance of being exceeded. Had they decided upon the latter interpretation, they would have faced the additional difficulty of estimating the probability of such an exceedence, which would have required more subjectivity.

The main reason to estimate probability distributions is that decisionmakers need this information. If the published literature does not provide a proba-

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[1] *E.g.*, South Carolina's Beachfront Management Act special permits; Texas' Open Beaches Act; and Maine's Dune Rule 355.

[2] In some states, the common law allows the government to prohibit bulkheads; hence, allowing a bulkhead to be built provides a windfall to a riparian owner, the value of which the state may wish to consider. In other states, property owners have a right to build a bulkhead; a rule prohibiting bulkheads would decrease property values. In either case, a measure of the probability distribution is necessary to determine the present discounted value of the property being lost at some future date. *See* J.G. Titus (draft), "Rising Seas, Coastal Erosion, and the Takings Clause."

[3] In reality, the subjectivity is no greater. Whether one picks low and high values or ascribes a probability distribution, one must subjectively interpret the literature.

bility distribution, then engineers, economists, and decisionmakers must implicitly or explicitly develop their own estimates, which are likely to be less accurate than the results of expert panels.[4]

This report presents the methods and results of a two-part effort to estimate the probability distribution of future sea level rise implied by the expectations of approximately twenty climate researchers. In the first phase, we developed a simplified model for estimating sea level rise as a function of thirty-five major uncertainties, derived probability distributions for each parameter from the existing literature, and conducted a Monte Carlo[5] experiment using 10,000 simulations. The first portions of Chapters 2 through 6 summarize the model, distributions, and results of that "draft" analysis:

> Chapter 2—emissions, concentrations, and atmospheric forcings of greenhouse gases;
>
> Chapter 3A—the use of a 1-D ocean model for estimating global temperatures and sea level rise due to thermal expansion of ocean water; and simple relationships describing the dynamics of polar air and water temperatures as functions of global temperatures;
>
> Chapter 3B—simple relationships describing changes in polar precipitation;
>
> Chapter 4—the impact of warmer polar temperatures and precipitation changes on the contribution to sea level from the Greenland ice sheet;
>
> Chapter 5—several alternative models relating polar warming to Antarctic ice discharges; and
>
> Chapter 6—our adaptation of the IPCC model of the contribution to sea level from small glaciers.

Figure 1-1 illustrates the relationships between the various models we used and developed to project sea level. Given the emissions projections, we used existing gas-cycle models to project atmospheric concentrations and the resulting radiative forcing (Chapter 2). We developed simple models of how upwelling may change, based on the results of three-dimensional models.[6] We used an existing model to project the resulting temperature and thermal expansion estimates (Chapter 3). We devised simple models for projecting changes in polar climate and Antarctic water temperatures (Chapter 3), as well as the impact of water temperatures on ice-shelf melting (Chapter 5). We developed a simple model of a possible fast-but-stable impact of ice-shelf melting on the Antarctic ice sheet contribution, while using existing models to simulate an unstable response and a stable-but-slow response (Chapter 5). We developed a simple model of how the runoff elevation in Greenland responds to climate change, but used existing models to project the actual contribution of the Greenland ice sheet to sea level (Chapter 4). We used an existing model to estimate the impact of small glaciers on sea level (Chapter 6). To estimate relative sea level at a specific location, one can combine tidal-gauge observations with the estimated glacial and thermal expansion contributions (Chapter 9).

In the second phase of this study, we circulated the draft report to a "Delphic" panel of experts[7]—approximately two dozen climatologists and glaciologists, listed in Table 1-1. In each case, we directed their attention to specific chapters, and asked them to review our assumptions, and suggest the assumptions that they would have used had they conducted the analysis. A few of the researchers provided comments without probability distributions; but twenty of the researchers did give us their best assessment of the values of the model coefficients most closely related to their own research. Moreover, five researchers even provided alternative model specifications. Given the probability distributions specified by our Delphic panel of experts, we reran the 10,000 simulations.

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[4] Focusing on probability distributions may also foster scientific cohesion by enabling scientific panels to avoid choosing sides in matters of scientific uncertainty, and instead lend partial credence to competing, contradictory viewpoints, until one or the other is disproved. For example, unlike previous EPA reports, this study does not reject out of hand the view of some "greenhouse skeptics" that greenhouse warming will be negligible. As discussed in Chapter 3, our simulations include the views of a representative skeptic.

[5] *See* Note 8, *infra*.

[6] Additional models were added in the second phase, based on the expert reviews.

[7] Broadly defined, a Delphic assessment is an analysis based in part on the opinions of experts. The origin of the term stems from the oracles at Delphi in Greek mythology, who, among other things, warned Oedipus that he would kill his father; they were also known as oracles of Apollo, the god of prophesy. The expert opinions of a Delphic assessment, like the pronouncements of the oracles at Delphi, are presumed valid regardless of whether there is an explanation supporting them. Nevertheless, in this report, the reviewers generally do provide explanations.

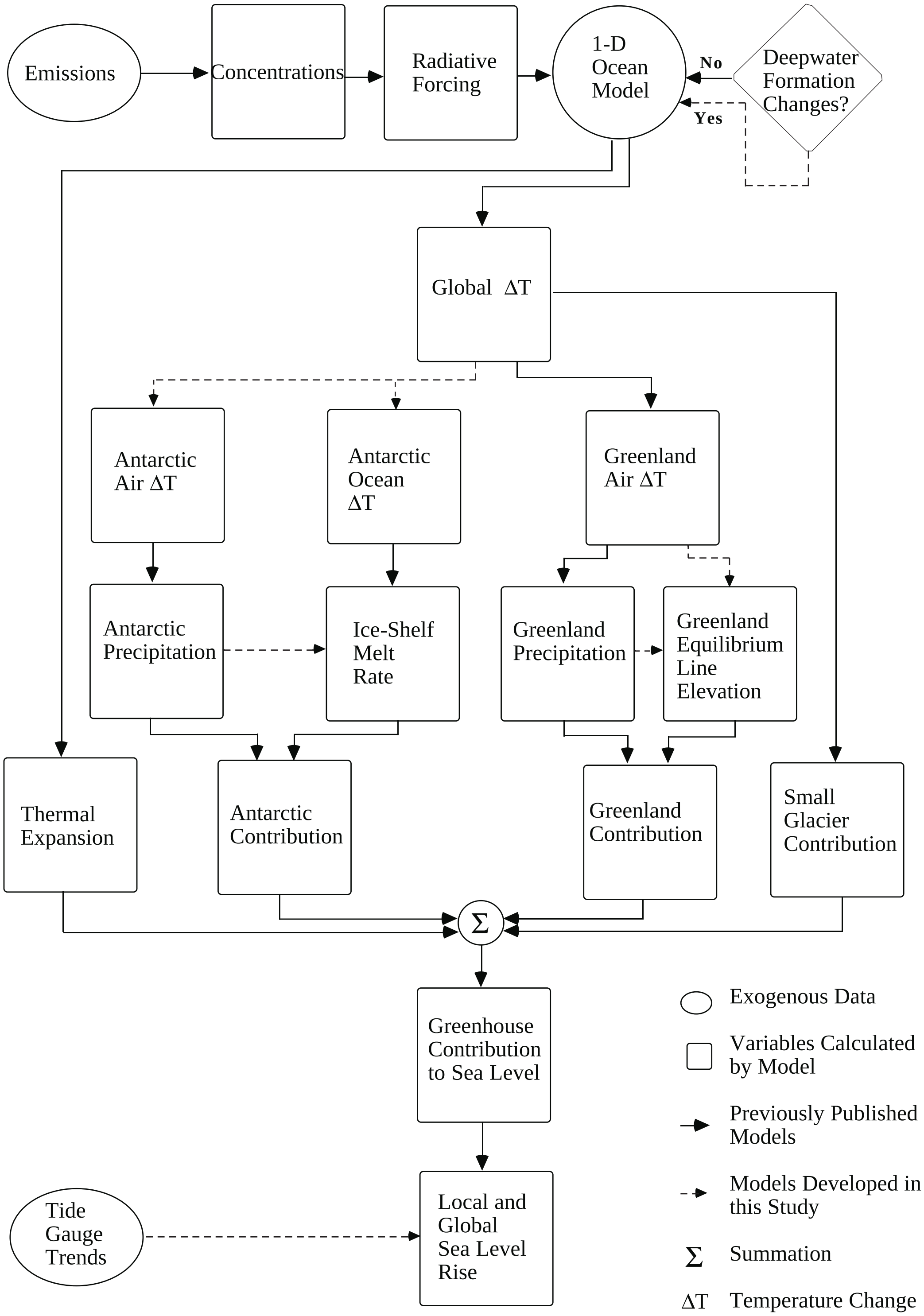

Figure 1-1. Relationship Between the Various Models We Used to Project Sea Level.

TABLE 1-1
REVIEWERS WHO CONTRIBUTED TO THIS ANALYSIS

Global Climate and Polar Temperature Assumptions		
Robert Balling	Arizona State University	Tempe, AZ
Francis Bretherton	University of Wisconsin	Madison, WI
Martin Hoffert	New York University	New York, NY
Michael MacCracken	Lawrence Livermore National Laboratory	Livermore, CA
Syukuro Manabe	NOAA/Princeton Geophysical Fluid Dynamics Laboratory	Princeton, NJ
David Rind	NASA/Goddard Institute for Space Studies	New York, NY
Stephen Schneider	Stanford University	Stanford, CA
Sarah Raper[a]	University of East Anglia	Norwich, UK
Tom Wigley[a]	University Corporation for Atmospheric Research	Boulder, CO
Polar Precipitation Assumptions		
Richard Alley	Pennsylvania State University	Univ. Park, PA
Michael Kuhn	Innsbruck University	Innsbruck, Austria
Michael MacCracken	Lawrence Livermore Nat. Laboratory	Livermore, CA
David Rind	NASA/Goddard Institute for Space Studies	New York, NY
Stephen Schneider	Stanford University	Stanford, CA
Jay Zwally	NASA/Goddard Space Flight Center	Greenbelt, MD
Antarctic Assumptions		
Richard Alley	Pennsylvania State University	Univ. Park, PA
Anonymous	University Professor	United States
Charles Bentley	University of Wisconsin	Madison, WI
Robert Bindschadler	NASA/Goddard Space Flight Center	Greenbelt, MD
Stan Jacobs	Lamont Doherty/Columbia University	Palisades, NY
Craig Lingle	University of Alaska	Fairbanks, AK
Robert Thomas	NASA/Greenland Ice Core Project	Washington, DC
C.J. van der Veen	Ohio State University	Columbus, OH
T. Wigley and S. Raper[a]	University of East Anglia	Norwich, UK
Jay Zwally	NASA/Goddard Space Flight Center	Greenbelt, MD
Greenland Reviewers[b]		
Walter Ambach	University of Innsbruck	Innsbruck, Austria
Robert Bindschadler	NASA/Goddard Space Flight Center	Greenbelt, MD
Roger Braithwaite	Geological Survey of Greenland	Copenhagen, Dmk
Mark Meier	University of Colorado	Boulder, CO
Robert Thomas	NASA/Greenland Ice Core Project	Washington, DC
T. Wigley and S. Raper[a]	University of East Anglia	Norwich, UK
Jay Zwally	NASA/Goddard Space Flight Center	Greenbelt, MD

[a] Wigley and Raper provided a joint review based on their revisions to an unpublished analysis initiated by Richard Warrick. The Wigley & Raper study is summarized in Wigley, T.M.L., and P.D. Jones. 1992. "Detection of Greenhouse Gas Induced Climatic Change." Research Proposal to U.S. Department of Energy. During the study, Wigley moved from East Anglia to University Corporation for Atmospheric Research.

[b] The Greenland reviewers offered modeling suggestions but did not suggest independent parameter values, except for Wigley & Raper.

In the latter part of each of the following chapters, we summarize the reviewer changes and present the results of the Delphic Monte Carlo experiment. We discuss the draft and Delphic assumptions separately for two reasons. First, the separate discussion helps to avoid ambiguity with regard to which assumptions were developed by us and which were provided by the reviewers. Second, and perhaps more importantly, in many cases particular reviewers decided that the parameters from the draft were reasonable enough. For example, based on the commonly accepted 1.5 to 4.5˚C warming from a CO_2 doubling, we assumed that the most likely value is 2.6˚C, which is the geometric mean of this range. All but one of the researchers accepted this characterization. Had we used the arithmetic mean of 3.0˚C, most of the reviewers may well have accepted that formulation as well. Here and elsewhere, our initial specifications almost certainly had a lingering effect on the results of the analysis. By discussing the draft and the Delphic analysis separately, we enable readers to (a) examine how the reviewers changed our assumptions and (b) thereby evaluate the extent to which our initial assumptions may have biased the analysis.

The last three chapters present our final results. Chapter 7 summarizes the results of our analysis, focusing on the likely impact of greenhouse gases on temperatures and global sea level, and examining the sensitivity of the results to alternative emissions scenarios and other assumptions. Chapter 8 places the results in context, examining both the reasons that sea level projections have been revised downward and the practical uses to which sea level projections have been put. Finally, Chapter 9 explains how to use our estimates to project local sea level at specific locations.

How Much of This Report Is Worth Reading?

We warn the reader at the outset that, for all but a limited audience, most of this report is exceedingly dry—particularly Chapters 3, 4, and 5. The typical coastal engineer, geologist, lawyer, or policy analyst may prefer to read only Chapters 7, 8, and 9. For the more technical reader who is already familiar with the assumptions underlying the IPCC and other sea level rise assessments, it may be sufficient to read the sections entitled "**Expert Judgment**," particularly in Chapters 3A, 3B, and 5, along with the results reported in Chapter 7. Those trying to understand how this analysis differs from previous assessments should focus on the remainder of this Chapter and the "**Expert Judgment**" section in Chapter 3.

The remainder of this chapter summarizes methodological issues that are relevant to all of the chapters.

Approach

Our overall approach is to assume that

$$SL = M(a,b,c,...),$$

where SL is sea level,
M is the model, and
a, b, c,... are unknown coefficients.

We assume that the model would be true if we knew the actual values of the coefficients. But because no one knows their precise values, we must rely on estimates, each of which is uncertain. Based on available estimates and reasonable assumptions about the shapes of the distributions, one can estimate a probability density function for each coefficient.

In the simple case, where $SL=aX+bY$ and we have data on X and Y, probability theory provides us with a simple formula for estimating the distribution of SL. Projections of sea level rise, however, are nonlinear: Even simple models must multiply uncertain temperatures by uncertain melting-sensitivity parameters, and most models are far more complex. Under these circumstances, solving for the distribution is too complicated to be practical.

Statisticians have shown, however, that one can eventually converge on the distribution by randomly selecting values of the coefficients, running the model repeatedly, and treating the resulting estimates as a sample. This procedure is known as "Monte Carlo."[8] Because we wanted to estimate the rise with

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[8] The meaning of the term "Monte Carlo analysis" has evolved. Originally, the term referred to the use of many trials to numerically approximate a probability distribution—as opposed to analytically solving the equations. As the use of Monte Carlo techniques evolved, mathematicians have shown that the original approach of randomly selecting the input values is not as efficient as nonrandom sampling approaches such as Latin Hypercube. Although Latin Hypercube is a Monte Carlo technique in the original sense of the word, many authors use the term "Monte Carlo analysis" to refer only to exercises that employ totally random samples.

a 1 percent chance of being exceeded, 10,000 trials seemed to be sufficient.[9]

Table 1-2 lists thirty-five parameters used by the draft report. In most cases, we characterized probability distributions derived from the literature. In four cases, however, the draft used alternative models; in these cases, we specified n-nomial distributions based on our best guess about the combined opinion of the community.[10] For example, if we have two alternative models for estimating thermal expansion of ocean water, we assume that there is a chance of p that $SL=M_1(a,b,...)$ and a chance of (1–p) that $SL=M_2(a,b,...)$. Although this approach allows us to relax the assumption that a particular model is true, it still understates our uncertainty because there is a chance that none of the models we specify are either true or reasonably accurate summaries of the likely response of the relevant processes.

Combining Reviewer Opinions. Once the reviewers had reacted to our original draft by providing us with their subjective probability distributions, we had to decide (a) how to ensure that the insights of one reviewer would feed back onto the opinions of the other reviewers, and (b) how to combine the reviewer opinions to develop a probability distribution that fairly incorporates the combined wisdom of all the reviewers. Because of time and cost limitations, we followed the simplest approach that we could devise. Our feedback process primarily involved (1) circulating each of the reviewer assessments to all of the reviewers of a particular chapter; (2) notifying each reviewer if another reviewer questioned any aspect of his or her assessment; and (3) giving each reviewer an opportunity to change his or her subjective probability distributions based on the assessments of the other reviewers. We also played "Devil's Advocate" with each reviewer. For each parameter, we would discuss the potential implications of the reviewer's specified distribution to ensure that the reviewer was providing a well-considered opinion.

Our final estimates reported in Chapters 7 and 9 are based on weighting each opinion equally. We concede at the outset that there are more sophisticated ways for combining reviewer opinions. For example, we might have polled a second, independent group of experts regarding the validity of the opinions of the first group of experts, or we might have polled the original group regarding the credibility of other reviewers on specific parameters.[11] Because such iterations were not feasible,[12] however, weighting the opinions equally seemed justified under the circumstances.[13] The reviewers who participated represent a fair cross-section of scientific opinion regarding the key areas of climate sensitivity, polar temperature, polar precipitation, and glacier sensitivity.

Recognizing that other researchers may wish to weight the reviewer opinions differently,[14] we report all of the recommended probability distributions of every reviewer. So that the reader of this report can

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[9] The random Monte Carlo approach is not as efficient at estimating the extremes of a cumulative distribution as the Latin Hypercube method, but the complex weighting required by that algorithm would have required considerable time to implement. Moreover, Latin Hypercube might not have been very effective in our case unless we ran millions of trials. Unless the parameters are uncorrelated, Latin Hypercube requires many more trials than we conducted before its superiority emerges. As discussed below, there are thirty-five parameters, with complex functional relationships between many of them (*see* Correlations Between Parameters, *infra*). Even if there were only eight parameters, with distributions divided into four segments for sampling, the sample space would have 4^8 (*i.e.*, 65,536) different areas that had to be sampled; assuming that each required at least ten observations, one would require 650,000 simulations. *See* **Numerical Error of the Monte Carlo Algorithm**, Chapter 7, *infra*.

[10] This approach was extended in the final version, in two ways. First, several reviewers provided additional models from which to select. Second, our approach for incorporating the reviewer comments essentially treated each reviewer's opinion as a separate model from which to select.

[11] To call these more iterative methods a "Delphi" approach is somewhat of a misnomer: the oracles at Delphi did not provide commentary on the validity of the pronouncements of other oracles. Nevertheless, these iterative approaches are generally referred to as "Delphi."

[12] So that other researchers might use this report for other purposes, we wanted to keep this analysis "on the record," which would have been impossible if the reviewers had to rate the expertise of other scientists. A few reviewers had indicated at the outset that they would participate only if each opinion was counted equally. Moreover, as we interviewed most of the other researchers, we got the distinct impression that putting probabilities on scientific processes that they had studied was already a novelty, and that asking them to weight the opinions of other reviewers was beyond what they wanted to do. (Two reviewers did, however, indicate that they would have preferred to participate in a second iteration concerning the relative expertise of the various reviewers.)

[13] Additional iterations would probably have been more important were it not for the fact that obtaining the reviewer opinions was already a second iteration for this study, the initial iteration being the draft report we circulated, which was based on parameters obtained from the literature.

[14] Theoreticians of decision analysis generally disapprove of the practice of weighting all opinions equally. Nevertheless, Winkler (1971) and Seaver (1978) "have found little or no difference in the performance of various differential weighting schemes over equal weighting...." (Morgan & Henrion (1990) at 167).

A more complex weighting scheme is possible only if there is a group of experts ready and willing to assess the validity of the original set of subjective probability distributions. If the political or monetary cost of independently evaluating the experts is high relative to the cost of obtaining the opinions in the first place, there may not even be a theoretical justification for the more complex weighting schemes. *See e.g.*, Morgan & Henrion at 167 ("The administrator of EPA, or his surrogate, is likely to have difficulty publicly stating that he finds Dr. Jones's views six times more credible than Dr. Smith's views....").

TABLE 1-2
INITIAL ASSUMPTIONS IN DRAFT REPORT

(Also used to represent some runs in the final report, where reviewer did not suggest changes)

	Parameter Distribution		**Value of**	**Correlation with**
Parameter	**Name**	**Shape, Moments**	**Moments**	**Other Parameters**
CONCENTRATIONS OF GREENHOUSE GASES				
Emissions	**E**	Nordhaus & Yohe, scaled	IPCC92 scenarios for each gas	perfect correlation
OCEAN MODEL PARAMETERS				
Equilibrium ΔT_{2XCO2}	ΔT_{2X}	lognormal, σ limits	1.5, 4.5 ˚C	none
Diffusivity	**k**	lognormal, 2σ limits	1000, 3000 m^2/yr	**w** (1.0)
Probability of Case A	**C1**	binomial	Prob(C1 = 1) = 0.5	none
<u>Case A: Fixed Bottomwater Formation</u>				
Downwelling Ratio	π	lognormal, 2σ limits	0.2, 1.0	none
Upwelling Velocity	**w**	lognormal , 2σ limits	2.0, 6.0 m/yr	**k** (1.0)
<u>Case B: Bottomwater Formation Declines with Temperature</u>				
Downwelling Ratio	π	Fixed	0.2	none
Upwelling Velocity				
Initial	$\mathbf{w}_0$	lognormal, 2σ limits	2.0, 6.0 m/yr	**k** (1.0)
Transient	**w**	$\mathbf{w}(\Delta T)=\mathbf{w}_0\theta^{\Delta T}$		See function
Sensitivity of **w** to Temperature	θ	lognormal, 2σ limits	0.85^2, 1.0	none
POLAR CLIMATE				
<u>Equilibrium Polar Amplification</u>				
Antarctic Summer	P1	lognormal, σ limits	0.67, 1.5	P2 (0.5), P3
Antarctic Winter	P2	lognormal, σ limits	1.0, 3.0	P1 (0.5)
Greenland Annual	P7	lognormal, 2σ limits	1.0, 2.0	P1, P2 (0.5)
Circumpolar Ocean	P3	lognormal, σ limits	0.25, 1.0	P1 (0.75)
<u>Adjustment Times (in addition to the global lag)</u>				
Circumpolar Ocean	P4	lognormal, 2σ limits	20, 80 years	P5, P6 (0.5)
Antarctic Summer	P5	lognormal, σ limits	1, 20	P6, P4 (0.5)
Antarctic Winter	P6	lognormal, σ limits	1, 20	P4 (0.5)
Greenland	—	Fixed	No Additional Lag	

TABLE 1-2 (continued)

Polar Precipitation				
Antarctic	P8	lognormal, 2σ limits	See Table 3-3 (approx. 6%/˚C)	P8 (0.5)
Greenland	P9	lognormal, 2σ limits	V(t)/V(0), $(9\%\|\Delta T = 1)$ V'(t)/V'(0) (8.5%)	P7 (0.5)
Antarctic Precip. Adjustment for Area	P10	lognormal, 2σ limits	1/3, 2/3	none
ANTARCTIC ICE SHEET AND ICE SHELF ASSUMPTIONS				
Ice Shelf Melt				
Seaice Sensitivity to Global Temperature	P10	lognormal, 2σ limits	0.05, 0.2	$P10 = e_{w/T}$
Sensitivity of Ross Ice Shelf Warm Intrusions	1+A1	lognormal, 2σ limits	1, 36	none
Ross Melt Response to Warm Intrusion	A2	lognormal, 2σ limits	0.25, 1.0	none
Probability of Undiluted CDW Under Ross	C3	binomial	$\min(0.05\Delta T_{cdw}, 0.25)$	none
Sensitivity of Weddell Sea to T_{cdw}	A3	fixed	1.0	none
Ronne/Filchner Basal Melt from Weddel Warming	A4	lognormal 2σ limits	1.91, 3.33	none
Threshold for Melt Only Model	A7	Right Triangular	$p(x) = 2x$ $F(x) = x^2$	none
Ice Stream Model				
Initial Velocity of Ice Stream B	V0	lognormal, 2σ limits	100, 300 m/yr	none
Upstream Length, Shelf Backpressure	L	lognormal, 2σ limits	100, 300 km	none
Calving	C2	Trinomial		none
		Fixed Calving	P(C2 = 2) = 0.7	
		Reference Calving	P(C2 = 0) = 0.3	
		Enhanced Calving	P(C2 = 1) = 0.0	

NOTE: **V(t)** is the saturation vapor pressure at a particular time. **V'(t)** is *d*V/*d*T at a particular time. **e** is elasticity.

TABLE 1-2 (continued)

ANTARCTIC ICE SHEET MODEL SELECTION

Model	Probability (%)
AM1, IPCC No Ice Sheet Response, Precipitation Only	10
AM2, Basal Melt Only	20
Thomas Ice Stream—Extrapolation Options	
AM3, Continent Wide	5
AM4, Only to Streams that flow Through Shelves	10
AM5, Ratio of Ice Discharge to Melting	10
AM6, Ice Stream Specific Response	25
AM7, Oerlemans Model—Linearization	20

GREENLAND

Zero Ablation Line Response to ΔT	G1	lognormal, σ limits	111.1, 186.3 m/˚C	none
Calving Response to Ablation	G2	normal, 2σ limits	0, 1.14	none
Response Time Due to Refreezing	G3	lognormal, σ limits	12.5, 50 years	none

SMALL GLACIERS

Response Time	τ	lognormal, σ limits	10, 30 years	none
Historic Contribution				
Oerlemans	M1	normal, σ limits	0.515, 1.885 cm	none
Meier	M2	normal, σ limits	1.2, 4.4	none
Probability of the Meier Estimate	C4	binomial	P(C4=1) = 0.5	none

gain a rough understanding of the results implied by each reviewer's assessments, we also disaggregate results by reviewer, where feasible. For example, for each climate reviewer (Chapter 3A), we report global and Greenland temperature estimates, as well as the Greenland, Antarctic, and total sea level contribution.[15] *Because of the procedures we followed, our final results must be viewed as conditional probability estimates—conditional on the assumption that the participating reviewers adequately represent the cross-section of scientific knowledge on the parameters for which they provided probability distributions.*

Correlations Between Parameters. For a variety of reasons, our uncertainty regarding one parameter may be related to our uncertainty regarding another parameter. As discussed in Chapter 3, for example, the parameters **k** (diffusivity) and **w** (upwelling velocity) used in ocean models are often viewed as being perfectly correlated, because the pattern by which ocean water temperatures decline with increasing depth is consistent with the assumption that **k**/**w**=500 meters.[16]

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[15] The estimates of sea level contribution by climate reviewer, however, require assumptions regarding glacier parameters, for which the climate reviewers generally expressed no opinion. For these assumptions, we weight all nonclimatic reviewers equally. (The Wigley & Raper assessment was an exception to this procedure, as explained below.)

[16] See Chapter 3 for additional discussion of these parameters.

At least some of the factors that might lead Antarctic winter temperatures to warm could also cause summer temperatures to warm (*e.g.*, the latitudinal ocean circulation); so there is some correlation between summer and winter warming, albeit less than perfect. The draft accounted for some of these relationships by generating random values of the parameters with specified correlations.

The various reviewers of Chapter 3 suggested several additional correlations. For example, because reduced thermohaline circulation[17] might imply a weaker Gulf Stream with which to heat Greenland, one researcher had a correlation of 0.5 between possible changes in **w** and Greenland temperatures. Another reviewer assumed that the warming of the Antarctic circumpolar ocean will lag farther behind global temperatures in cases where emissions grow more rapidly or the climate sensitivity parameter ΔT_{2X} is larger; again a correlation of 0.5 was used.

The Delphic Monte Carlo analysis includes a second type of correlation, designed to preserve the internally consistent visions of the future implied by particular reviewers' assumptions. For example, although most reviewers of Chapter 3 did not specify a correlation between π and changes in **w**, there was a tendency for those who expected a low π to also expect a decline in **w**, and for those who used high values of π to consider **w** as less likely to decline. We preserve the "consistent visions" by generating separate probability distributions for each researcher, rather than by developing a single composite distribution for each parameter.

For the most part, these consistent visions apply only to a particular chapter. The joint review provided by Tom Wigley and Sarah Raper, however, provided assumptions sufficient to estimate all of the contributors to sea level. Therefore, we treat their consistent vision as applying to the entire analysis; simulations representing their suggestions on warming, for example, are not combined with anyone else's assumptions regarding Antarctica.

Our procedure for preserving these correlations is analogous to treating the reviews of each chapter as a deck of cards. Separate groups of reviewers provided comments on the nonprecipitation climate variables (Chapter 3A), precipitation (Chapter 3B), Greenland (Chapter 4), and Antarctica (Chapter 5). Our procedure was as follows:

1. We divided the assumptions into six decks:

    Deck 2: This deck has 10,000 cards, each of which has a random value for each parameter discussed in Chapter 2.

    Deck 6: Same as Deck 2, for Chapter 6.

    Deck 3A: This deck is composed of eight piles, each of which corresponds to one expert reviewer, with the first pile representing Wigley & Raper. Each pile has 1250 cards, each of which has a random value for each of the nonprecipitation climate parameters discussed in Chapter 3. Each pile uses different underlying distributions corresponding to the distributions suggested by the particular researcher.

    Deck 5: Same as Deck 3A, for Chapter 5.

    Deck 3B: Same as Deck 3A, except that only six researchers provided distributions, so there are only six piles.

    Deck 4: Same as Deck 3A, except that seven of the eight piles are drawn from the same underlying distribution. The first pile represents the distributions specified by Wigley & Raper. The remaining seven piles are drawn from the distributions accepted by the glaciologists who reviewed Chapter 4.

2. The top pile in each deck represents the suggestions of Wigley & Raper, because their joint review was the only review that suggested parameters for the whole array of sea level contributors. We remove the top pile from each stack and set it aside temporarily.

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[17] Thermohaline circulation refers to ocean currents driven by different densities, which in turn result from different temperatures and salinities. For example, evaporation over the Gulf Stream increases the salinity level and thereby the density of ocean water, enabling water to sink as it reaches the North Atlantic, forming deep water. This sinking helps propel the circulation that causes the Gulf Stream to flow north. Some climatologists expect warmer global temperatures to cause more rainfall over the North Atlantic, which would reduce salinity and deepwater formation, and thereby slow the Gulf Stream.

3. We shuffle the remaining piles of Decks 3B and 5. If we did not shuffle Deck 5, for example, the simulations that use the suggestions of the last reviewer of Chapter 3A would only use the parameters specified by the last reviewer of Chapter 5. By shuffling the deck, the simulations using this last climate reviewer use the assumptions of all the Antarctic (Chapter 5) reviewers in roughly equal proportions. There is no need to shuffle Deck 2 or 6, because they are already randomly mixed, as are the remaining seven piles of Chapter 4.

4. We put the Wigley & Raper piles back on the top of each deck.

5. We draw the top card from each deck and run a simulation using the parameter values. We then draw the next card from each deck and repeat the process for all 10,000 simulations.

Thus, the first 1250 simulations represent the consistent vision of Wigley & Raper across all chapters. The following 1250 simulations use the consistent vision of the second climate reviewer but include a random selection of parameters drawn from all other chapters.

Time Horizon. Like most previous assessments of sea level rise, we focus on the year 2100. However, we do not truncate our analysis at that date. We extend our analysis farther into the future for both technical and policy reasons.

On the technical side, several glacial modeling efforts have suggested that impacts from Antarctica will not be significant until after the year 2100 (*e.g.*, Huybrechts & Oerlemans 1990). Yet the potential impacts have long been discussed. To end our analysis before Antarctica is likely to have a significant impact, would lead our assessment to exclude consideration of some of the most important research on the issue of long-term sea level rise. If we could be certain that Antarctica will not make a contribution within the relevant time horizon, disregarding that research might be warranted; however, no such certainty exists. In a similar vein, examining longer time horizons helps to provide a better understanding of the implications of one's assumptions, and the impacts likely to occur over longer periods of time are similar to the worst-case scenarios of what could happen in the next century.

On the policy side, no one has demonstrated that impacts after the year 2100 are irrelevant. The remoteness of the twenty-second century, we suggest, can be better addressed by discounting the future than by ignoring it completely. Policymakers concerned with nuclear waste sites have considered potential consequences thousands of years into the future. The roads that are built today can determine the locations of development for centuries into the future, even if specific structures only last one-hundred years. Although local planning commissions generally focus on the next few decades, the civic groups that propose policies often include churches and historic preservation groups with perspectives stretching back several centuries. Finally, Cline (1992) argues that all climate impact assessments should extend two-hundred years into the future, and at least one chapter of a draft IPCC report has attempted to extend the analysis out several centuries (Pearce et al. 1994).

Most officials will be more concerned with "best-guess" estimates for the next few decades. But the importance or lack of importance of very-long-run and very-low-probability impacts can only be ascertained if impact analysts have scenarios of these remote contingencies.

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CHAPTER 2

CONCENTRATIONS OF GREENHOUSE GASES

Anthropogenic Emissions

This analysis is based on the IPCC assumptions for emissions and concentrations, as updated by Wigley & Raper (1992). That analysis considers seven greenhouse gases (CO_2, CH_4, N_2O, CFC-11, CFC-12, HCFC-22, and HFC-134a) as well as three gases with important indirect effects on climate (SO_2, carbon monoxide, and volatile organic compounds). For all gases other than CFC-11, CFC-12, and HCFC-22, we characterize (anthropogenic) emission rates through the year 2100 using lognormal distributions, with the geometric means and standard deviations calculated from the six emission scenarios from IPCC (1992). For the two CFCs, we used the IPCC scenarios directly.[1]

Figure 2-1 compares our probability density function for CO_2 emissions with that of Nordhaus & Yohe (1983). For the year 2100, Nordhaus & Yohe have a median of about 14 gigatons (Gt) per year of carbon and a geometric mean of 19 Gt/yr, while both our median and geometric means are 16 Gt/yr. Our 68 percent confidence interval (σ range) extends from 8 to 34 Gt/yr, while the 68 percent limits for Nordhaus & Yohe are 7 and 31 Gt/yr. Our 1, 5, and 10%-high scenarios are 88.5, 53.6, and 41.3 Gt/yr, respectively. Nordhaus & Yohe found similar uncertainty. Although the highest 7 percent of their simulations are reported at around 52 Gt/yr, this estimate presumably reflects a truncation of the distribution; their 10th percentile is approximately 43 Gt/yr. Edmonds et al. (1985) found even more uncertainty: Their 5%-high scenario is 80 Gt/yr, roughly equal to our 2%-high scenario; and their 25%-high scenario of 28 Gt/yr is almost as great as our 16% (σ-high) limit. Figure 2-2 compares our projections of CO_2 emissions with the six IPCC emissions scenarios for the years 1990 to 2100.

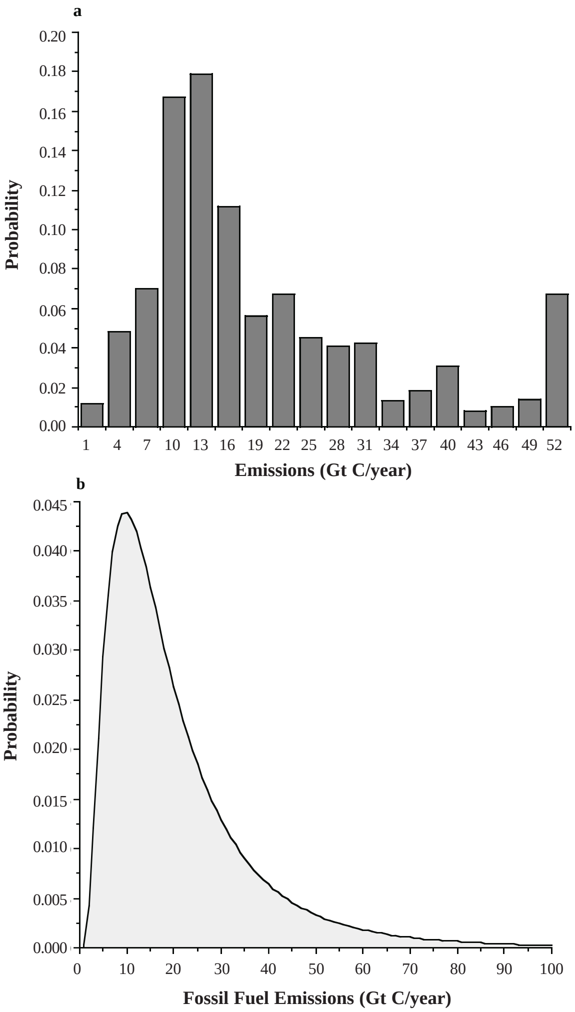

Figure 2-1. **Probability Density of CO_2 Emissions in the Year 2100.** (a) Nordhaus & Yohe (1983); (b) this analysis.

For simplicity, we assume that emissions for the various gases are perfectly correlated. This assumption allowed us to draw from only one distribution to calculate all emissions, rather than from one distribution for each gas. In effect, we assume that the IPCC scenarios were already designed to convey the combined uncertainty of future emission rates.[2] Moreover, because economic growth and policies on emissions reduction are the primary factors driving changes in emission rates, emissions are highly correlated.

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[1] For CFC-11 and CFC-12, three of the IPCC scenarios assume that emissions decline to zero. As a result, the geometric standard deviation cannot be calculated. Therefore, we follow the procedure outlined above for the three nonzero scenarios and draw from this distribution one-half of the time. The other half of the time we draw from one of the three zero-tending emissions scenarios. For HCFC-22, two of the IPCC scenarios assume that emissions decline to zero. Here again we follow a similar procedure, drawing from a distribution 2/3 of the time and from one of the two zero-tending scenarios 1/3 of the time.

[2] This assumption is not as unreasonable as it might seem at first glance. IPCC Scenario E, for example, which has the highest CO_2 emission rate, assumes less emissions of HCFCs and methane than assumed by Scenario F. Thus, assuming perfect correlation among the scenarios is unlikely to overstate total uncertainty of radiative forcing.

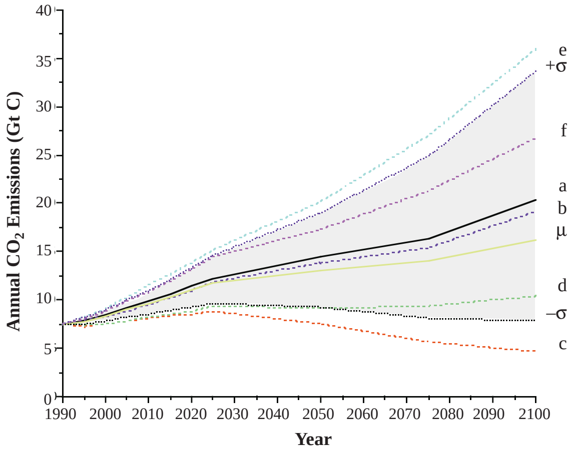

Figure 2-2. IPCC (1992) CO_2 Emissions Scenarios. a=IS92a,...f=IS92f. The shaded area shows the emissions rates bounded by our σ-low and σ-high scenarios. The scenario μ represents the geometric mean from our analysis.

The IPCC projections did not extend beyond the year 2100. While we would have liked to consider subsequent changes in emission rates, the available analyses after that year are rather sparse.[3] Therefore, our simulations assume that emissions are constant after the year 2100. Temperatures and sea level will continue to change, however, because the processes determining atmospheric concentrations, climate, thermal expansion, and glacial contributions each take several decades to reach equilibrium.

Concentrations and Radiative Forcing

Given the emission rates, we calculate concentrations using the same models as IPCC (1992), as modified by Wigley & Raper. For greenhouse gases other than CO_2, we explicitly consider uncertainties in atmospheric lifetimes (unlike IPCC and Wigley & Raper). Table 2-1 lists the atmospheric lifetimes employed by Wigley & Raper, along with the uncertainty as estimated by various studies. In each case, we treat the ratio of the high to the low value as representing the ratio between the σ-high and σ-low scenarios.

The fate of CO_2 is generally modeled as being more complex than the fates of other greenhouse gases. Wigley & Raper, for example, assume that there are four independent sinks, with lifetimes of 1.6, 30, 80, and 330 years, and that, even in equilibrium, about 13 percent of the CO_2 emitted remains in the atmosphere.[4] After one hundred years, only 1/e (37 percent) of the carbon emitted in a particular year remains, which is consistent with an atmospheric lifetime of one hundred years (*i.e.*, an annual decay rate of 1 percent). But after ten years, 25 percent of the carbon has been removed, implying a much more rapid adjustment at first; while after two hundred years, 27 percent still remains, implying a slower adjustment. Thus, the term “lifetime” when applied to CO_2 cannot be viewed as a shorthand for the entire atmospheric decay function, but only as an estimate of how long it takes for various sinks to absorb all but 1/e of the carbon emitted in a given year.

Table 2-1 suggests that the lifetime for CO_2 is less certain than the lifetime for the other greenhouse gases. Nevertheless, we omit any consideration of this uncertainty and simply adopt the set of parameters used by Wigley & Raper. The complexities that we would have to address are beyond the scope of this analysis for two reasons: (1) there are many ways to alter the carbon cycle model to convey the fourfold uncertainty regarding the “lifetime” of CO_2, and none could be readily justified[5]; and (2) changes in temperatures, oceanic circulation, and ecosystems are likely to alter the underlying carbon cycle in ways that are not adequately captured by any carbon cycle model that could be readily adapted for our purposes.

The uncertainty surrounding future radiative forcing is less than the uncertainty surrounding emissions, for two reasons. First, concentrations represent the cumulative impact of all past emission rates; thus, they respond with a long lag to emission rates. For example, the impact of a doubling or a halving of emission rates after ten years would increase or decrease concentrations of CO_2 by less than 10 percent; thus, our uncertainty about what emissions will

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[3] Cline (1992b) discusses results from the Nordhaus model. He reports that the model projects about a 25 percent increase in emissions during the 22nd century, but this scenario is based on the assumption that per capita economic growth is only 0.1 percent per year. When Cline modifies the model to allow for a 1 percent annual economic growth, he finds that emissions could approximately double during that time period.

[4] Concentrations respond to emissions of a unit of CO_2 as follows: $\text{Mass}(t) = 0.13 + 0.22e^{-t/330} + 0.26e^{-t/80} + 0.29e^{-t/20} + 0.01e^{-t/1.6}$.

[5] The most obvious way would have been to assume fourfold uncertainty in all of the lifetimes, but such a result would imply fourfold uncertainty for the initial response (*e.g.*, first decade) when, in fact, the short-term uncertainty is much smaller. We considered arbitrarily assuming that the two slower reservoirs of 80 and 330 years have fourfold uncertainty, but Tom Wigley convinced us that such an assumption would probably be worse than ignoring carbon cycle uncertainty.

TABLE 2-1
PROBABILITY DISTRIBUTIONS OF ATMOSPHERIC LIFETIMES
OF GREENHOUSE GASES USED IN THIS REPORT
(years)

Gas	Wigley Point Estimate	Range	Source	Uncertainty ($\sigma_{high}/\sigma_{low}$) in simulations[a]
N_2O	132	110–168	WMO	1.53
CFC-11	55	42–66	WMO	1.57
CFC-12	116	104–113	WMO	1.09
HCFC-22	15.8	13.5–17.7	WMO	1.31
HFC-134a	15.6	N.A.	WMO	1.31[b]
CH_4	11.8	10–14	Vaghjiani (1991)	1.4
CO_2	100	50–200	IPCC (1990)	1.0

[a] Calculated as the ratio of the high to low estimate under “Range.”

[b] Lacking a published estimate of uncertainty, we assume that the uncertainty for HCFC-134a is the same as that of HCFC-22.

NOTE: In all cases other than CH_4 and CO_2, the simulations use the Wigley & Raper point estimate for the median and “Uncertainty” for the geometric standard deviation. In the case of CH_4, the Vaghjiani & Ravishankara estimates of 10 and 14 years are treated as σ limits; *i.e.*, the Wigley & Raper value is not used. In the case of CO_2, we ignore uncertainties in the adjustment period.

do in the next decade has little impact on our uncertainty regarding concentrations ten years hence. Second, radiative forcing is proportional to the *logarithm* of CO_2 concentration, a functional specification that inherently reduces uncertainty.

Figure 2-3 illustrates our draft estimates of the increase in radiative forcing by the years 2030 and 2100. Our median estimate of 6.2 watts per square meter (W/m^2) by the year 2100 was similar to the IPCC (1992) estimate for radiative forcing under Scenario A, but much less than the 7.5 W/m^2 estimated by IPCC (1990).

Expert Judgment

Because of the extensive review of the IPCC scenarios, we did not develop reviewer-based probability distributions for this chapter in the manner undertaken for the next three chapters. Nevertheless, we did make some changes due to the reviewer comments.[6]

The draft, like the IPCC (1990) and (1992) reports, ignored the negative effects of sulfates and ozone depletion. Several reviewers told us to include those offsetting effects and we have done so, based on the Wigley & Raper (1992) sulfate scenarios. CFC emissions cause a long-term depletion of stratospheric ozone, a greenhouse gas; this delayed effect eventually offsets the warming from CFC emissions.[7]

Figure 2-4 illustrates the resulting estimates of radiative forcing. Part (a) compares our uncertainty for radiative forcing with the IPCC scenarios. Ignoring the uncertainty in atmospheric lifetimes, our σ limits for the year 2100 are 3.9 and 7.1 W/m^2, slightly above the range implied by IPCC (1992) scenarios C and E. Figure 2-4b shows that including the uncertainty surrounding non-CO_2 atmospheric lifetimes expands this range to 3.6 to 7.5 W/m^2 in the unlikely event that high and low lifetimes correspond with high and low emission rates. The figure also shows that the sulfates reduce radiative forcing by about 8 percent in the median scenario.

The results also include the biological feedback suggested by Wigley & Raper (1992). The draft had used the same version of the carbon cycle model as used by IPCC (1992), which resulted in a CO_2 con-

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[6] Subsequent chapters present the model as originally presented by the reviewers, followed by the reviewer changes. Because the reviewer changes are straightforward, this chapter only presents the postreview version of our assumptions.

[7] On the other hand, CO and VOC emissions can result in reduced atmospheric OH, which could in turn slow the rate at which methane leaves the atmosphere.

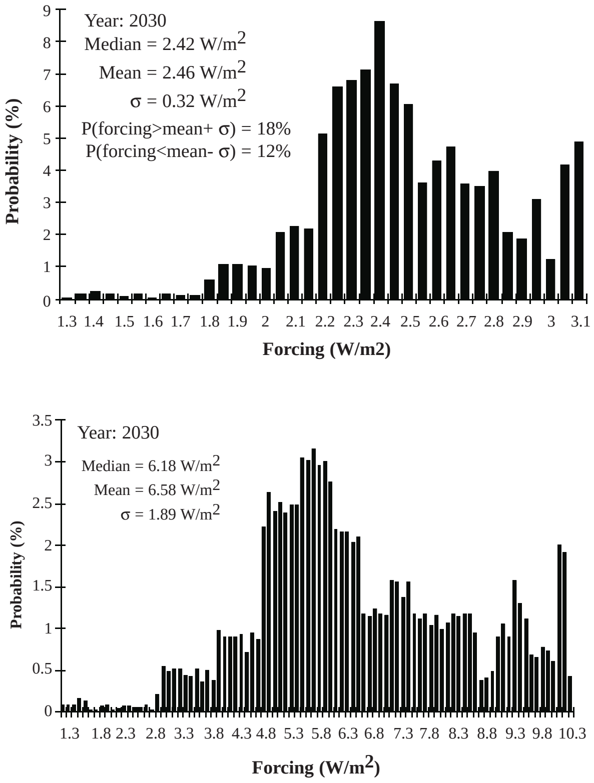

Figure 2-3. Increase in Radiative Forcing: Draft Report. Probability density function for the years 2030 and 2100. Note that the 6.2 W/m^2 median is well below the 7.5 W/m^2 from the IPCC 1990 Business-as-Usual Scenario.

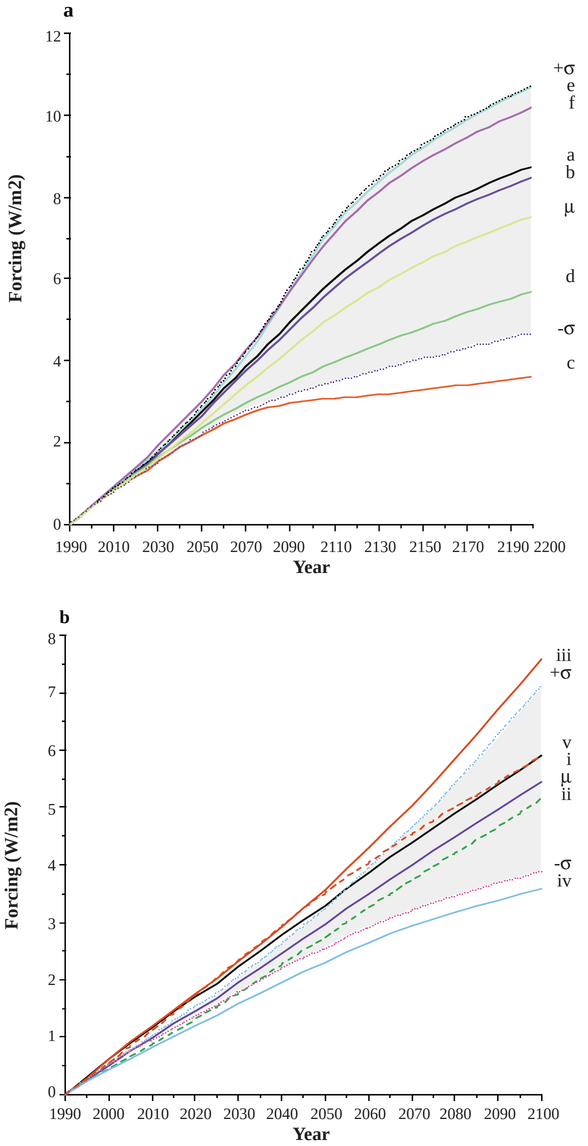

Figure 2-4. Increase in Radiative Forcing: Final Report. (a) Scenarios based on the median atmospheric lifetimes from our analysis, with median (μ) and σ limits (shaded) for emissions, are compared with (a) the six IPCC scenarios and (b) scenarios with (i) high atmospheric lifetime and median emissions; (ii) low atmospheric lifetime and median emissions; (iii) high lifetimes and high emissions; (iv) low lifetimes and low emissions; and (v) median emissions and median lifetimes with the negative impact of sulfates removed.

centration of 800 ppm by the year 2100. The “feedback” version of the model, by contrast, results in a CO_2 concentration of about 730 ppm.

The reviewer comments also led us to change the shape of the emission distribution. The draft had used the shape of the distribution implied by the Nordhaus & Yohe (1983) results. The reviewers suggested that a lognormal distribution would be more appropriate; so we adopted that functional specification.

Several reviewers commented on our assumptions for the post-2100 period. David Rind felt that emissions are likely to keep changing. Tom Wigley also disagreed with the assumption that emissions would stay constant, believing that such a continuation could not be sustained by the available *reserves*; moreover, the effects of global warming would probably lead nations to limit emissions even if reserves were sufficient. Jae Edmonds, by contrast, stated that available coal and shale oil *resources* are sufficient to sustain the Edmonds et al. (1985) 5th percentile estimate (80 Gt/yr) for at least a few centuries.

William Cline suggests that the few available studies imply that emissions could continue to rise after the year 2100. Cline (1992a) reports that Alan S. Manne believes that a linear extrapolation of emission rates is reasonable, which implies that the Manne & Richel (1990) estimates of CO_2 emissions would increase by about 0.6 percent per year from 27 Gt/yr in 2100 to 712 Gt/yr in 2275. Cline (1992b) shows that the Nordhaus (1992) model implies that emissions would increase from 20 Gt/yr in 2100 to more than 50 Gt/yr by 2275.

Both of those estimates focus on median scenarios; it seems less likely that the 88 Gt/yr implied by our 1%-high scenario would also continue at such a growth rate. Yet, to assume that high emission rates are more likely to stabilize or decline than the median scenario implies that there is less uncertainty surrounding emissions for the year 2200 than for the year 2100. This counterintuitive assumption should be used, in our view, only if there is a physical or economic constraint in the available supply of fossil fuels.

For purposes of our high scenario, such a constraint does not seem likely. Edmonds et al. (1985) estimate that there is 5000 to 18,000 Gt of coal that can be mined at $85/ton. If 70 percent is emitted as carbon, this estimate implies that our 1%-high scenario could be sustained for 40 to 150 years at a price of $85/ton. Because we are focusing on the high end of the range of possible emission rates, the high end of the available reserves is more relevant than the low end. Given the lower emission rates likely to prevail during the twenty-first century, the high scenario could be sustained until at least the year 2200. Prices greater than $85/ton, moreover, would increase the available coal and could also make oil shale economical. Finally, new discoveries and better technologies would increase the amount of fuels available at a given price. Therefore, we conclude that there is no physical constraint rendering it impossible to sustain the high scenario for the period of this analysis.

In light of the lack of knowledge regarding future emission rates, it still seems most reasonable to keep emissions fixed at the year 2100 level. Arguments can be made for increasing or decreasing the median scenario and for expanding or narrowing the range of uncertainty for subsequent years. The assumption of fixed emissions after the year 2100 is easier to understand, allows us to avoid manipulating the IPCC (1992) emissions scenarios, and at least in the narrow sense enables us to avoid additional speculation.[8]

Final Results

Table 2-2 illustrates our results for the increase in radiative forcing for the period 1990 to 2100. Largely because we included sulfates and the biological CO_2 feedback, our final estimates of radiative forcing are lower than reflected in previous IPCC assessments, as well as our draft report. IPCC's (1992) scenario A was about 6.2 W/m^2 and IPCC's (1990) business-as-usual scenario was 7.5 W/m^2, whereas our median is only 4.9 W/m^2.[9] About 1 percent of our simulations have higher forcing than the 8.5 W/m^2 that IPCC (1992) estimated for Scenario E,[10] while about 20 percent have a forcing less than the 3.5 W/m^2 projected for Scenario C. The table also shows our estimates for the year by which radiative forcing will increase by 4.4 W/m^2—the equivalent of a CO_2 doubling—over the 1990 level; the median estimate is the year 2089, with a 10 percent chance that the doubling equivalent will occur before 2068.

Our scenarios for radiative forcing are broadly consistent with recent assessments. Our *mean* estimate of radiative forcing (5 W/m^2) is only slightly less than the forcing estimate reported by Wigley & Raper (1992). Although IPCC (1992) had a higher forcing, the recent IPCC (1994) report on radiative forcing has adopted scenarios that are much closer to the Wigley & Raper estimates. Most importantly, the IPCC has lowered the projected CO_2 concentration from 800 ppm to about 730 ppm by the year 2100. *See also* Wigley (1993). Although IPCC (1994) did not endorse a specific estimate of the average global forcing effect of sulfates, it did acknowledge that sulfates have been offsetting global warming.[11]

We also show a selected set of 61 scenarios, which we follow throughout the course of this report.

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[8] In the broader and more realistic sense of the word, to assume no change in a changing world is highly speculative. Nevertheless, the convention of deeming such an assumption as not speculative is well established. *See e.g.*, IPCC (1990) (assuming that the contribution of groundwater and Antarctic ice sheet changes to sea level will be zero because the process is too difficult to model).

[9] Even though our analysis is based on Wigley & Raper (1992), our median is less than their estimate for Scenario A (5.3 W/m^2), because Scenario A's emissions are greater than the geometric mean of the six emission scenarios.

[10] About 20 percent of our simulations, however, have more forcing than the 6.6 W/m^2 estimated by Wigley & Raper for Scenario E.

[11] As this report went to press, the IPCC was considering whether and how the effect of sulfates should be incorporated into global temperature projections for the comprehensive assessment due to be published at the end of 1995.

TABLE 2-2
CUMULATIVE PROBABILITY DISTRIBUTION FOR THE CHANGE IN CARBON DIOXIDE AND RADIATIVE FORCING

Cumulative Probability (%)	Forcing 1990–2100 (W/m^2)	CO_2 by 2100 (ppmv)	Year by Which CO_2 Exceeds 600 ppmv	Year by Which Doubling Equivalent for all Gases[a]
0.1[b]	1.3	405	>2200	>2200
0.5[b]	1.8	427	>2200	>2200
1.0[b]	2.0	439	>2200	>2200
2.5[b]	2.3	462	>2200	>2200
5.0[b]	2.6	482	>2200	>2200
10	3.0	511	>2200	>2200
20	3.6	554	2131	2151
30	4.0	591	2103	2117
40	4.4	633	2088	2099
50	4.9	680	2078	2089
60	5.4	729	2070	2081
70	5.8	792	2064	2077
80	6.4	878	2059	2073
90	7.2	1047	2052	2068
95	7.8	1204	2048	2066
97.5	8.2	1363	2045	2064
99	8.7	1614	2042	2062
99.5[b]	9.0	1775	2040	2061
99.9[b]	9.4	2364	2037	2059
Mean	5.0	738	N.A.	N.A.
σ	1.6	242	N.A.	N.A.

N.A. = Not applicable.

[a] "Doubling equivalent" refers to the year by which radiative forcing increases by 4.4 W/m^2 over 1990 levels, which is the radiative forcing from a doubling of CO_2.

[b] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

Figure 2-5 shows a "spaghetti diagram" of radiative forcing for these scenarios for the years 1990 to 2300. We selected these scenarios by ranking all the scenarios according to the amount of sea level rise for the year 2200. Figure 2-5 and all other spaghetti diagrams in this report illustrate (from highest to lowest) the following simulations: 1, 2, 5, 10, 50, 100, 200, 400, 600...9400, 9600, 9800, 9901, 9951, 9991, 9996, 9999, 10000. Thus, the top and bottom seven simulations should be viewed as extreme (1 percent) scenarios; otherwise, the simulations shown represent equal levels of probability. We show a disproportionate amount of extreme scenarios because (a) if unintended model calculations are taking place, they are most likely to occur and/or become noticeable in the extreme scenarios; (b) risk assessments inherently must focus on extreme scenarios; and (c) as a practical matter, extreme scenarios tend to be more widely spaced than the more typical scenarios, which makes them more legible.

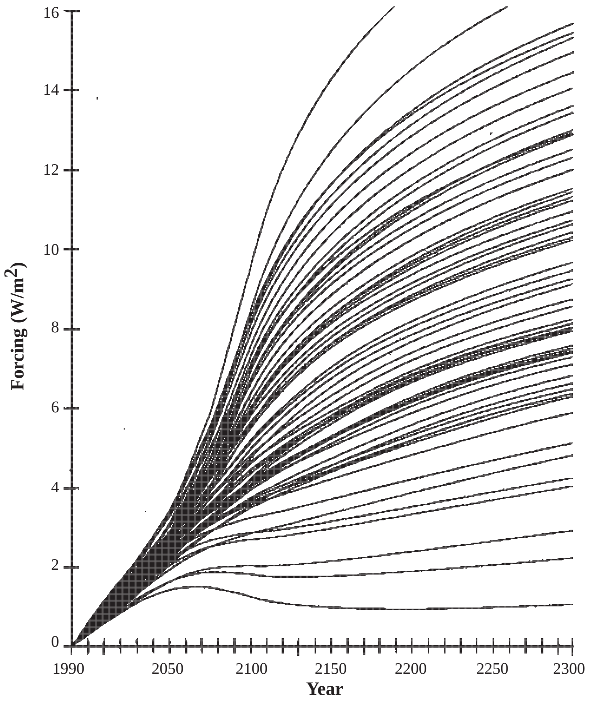

Figure 2-5. Projections of Greenhouse Forcing: Selected Simulations. This and all other spaghetti diagrams illustrate simulations 1, 2, 5, 10, 20, 50, 100, 200, 400, 600,..., 9400, 9600, 9800, 9901, 9951, 9981, 9991, 9996, 9999, 10000, where 1 and 10000 represent the simulations with the highest and lowest estimates of sea level rise for the year 2200.

The uncertainty in radiative forcing is fairly small for the next 50 years, with virtually all scenarios showing an increase between 2 and 3 W/m^2. After the year 2050, however, IPCC scenarios C and D assume that CO_2 emissions decline or remain constant, while other scenarios assume a continuing increase. As a result, the range increases to about 2.5 to 8.0 W/m^2 by 2100 and 2.6 to 13 W/m^2 by 2200. The effect of Scenario C's declining emissions can be seen in the bottom two curves, which decline after around 2070. Even though emissions are assumed to remain constant after the year 2100, radiative forcing continues to increase during the following two centuries for all but a few of the scenarios, due to the long atmospheric lifetime of CO_2.

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Chapter 2

CHAPTER 3

CLIMATE CHANGE

Given the concentrations of greenhouse gases and resulting radiative forcings during particular years, projections of sea level rise require two types of climatic information: (1) estimates of the downward penetration of heat for calculating the thermal expansion of ocean water; and (2) estimates of polar air temperatures, water temperatures, sea ice, and precipitation changes for calculating the glacial contribution to sea level.[1]

Following the general convention, we use a one-dimensional ocean model to simultaneously calculate transient air temperatures and thermal expansion of ocean water. We then employ subsidiary equations to estimate changes in sea ice and polar temperatures. After summarizing the results from our initial draft assumptions, we present the assumptions suggested by the expert reviewers and the resulting estimates. Because a different set of reviewers commented on our equations for polar precipitation, we present those assumptions and results separately at the end of this chapter.

PART A: TEMPERATURE AND THERMAL EXPANSION

The Use of 1-D Ocean Models to Estimate Global Temperature and Thermal Expansion

Although three-dimensional models are generally used to estimate equilibrium responses to greenhouse gases, their cost is too great for undertaking analyses that require many runs of a given model. Hoffert et al. (1980) first proposed a one-dimensional upwelling-diffusion model for analyzing global warming during specific years; numerous studies have employed that model and its descendants. The most widely used of these descendants is the model by Wigley & Raper (1987, 1992), which has been used to produce the official temperature and sea level scenarios of the Intergovernmental Panel on Climate Change. *See e.g.*, IPCC (1990, 1992). To be consistent with IPCC, we used the Wigley & Raper model as well.[2] The model requires us to supply coefficients for (1) the equilibrium average surface warming[3] for a CO_2 doubling (ΔT_{2X}); (2) vertical mixing/diffusion (**k**); (3) upwelling velocity (**w**); and (4) the ratio of the warming of newly formed (polar) bottom water to warming of surface water (π).

Like IPCC and Wigley & Raper, we ran the model using historic concentrations of greenhouse gases from a representative preindustrial starting point (*i.e.*, 1765) to the present. This procedure ensures that when we project the model into the future, the resulting estimates of thermal expansion and warmer temperatures reflect the delayed impact of past emissions as well as the impact of future emissions. While a single historic simulation might be preferable,[4] we follow the convention of IPCC and Wigley & Raper by simulating the model over the historic data for each of our simulations. Figure 3-1 compares actual temperatures with the projected temperatures using the Wigley & Raper model under various scenarios. The model projects a flattening out of the warming over the years 1955–70 because of the negative forcings associated with sulfates and CFC-related ozone depletion (*see* Chapter 2).

Unlike the original version by Hoffert et al. (1980), this model treats the two hemispheres sepa-

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[1] Ideally, we would also like to know whether the precipitation in polar areas is in the form of rain or snow. Because the models we use for Greenland and Antarctica assume that all precipitation is snowfall, this chapter does not address that question.

[2] Tom Wigley and Sarah Raper helped us adapt their model for our purposes.

[3] Since at least 1979, studies of the greenhouse effect have focused on the equilibrium impacts of a CO_2 doubling, that is, an estimate of how much the Earth's average temperature would rise if the concentration of atmospheric CO_2 doubled and then remained at the higher level indefinitely. *See e.g.,* NAS (1979).

[4] For the reader familiar with one-dimensional modeling, we note that this procedure may be analytically and computationally inferior to simply running the historical simulation to 1990 once and starting each of the 10,000 simulations at that point. For example, if we assume that temperature sensitivity is 4.5˚C, the model estimates much more historical warming than what actually occurred, which in turn implies a greater temperature difference between the mixed layer and the thermocline than actually exists. As a result, the model will overstate the downward penetration of heat and thermal expansion that ought to result from future greenhouse forcing. Conversely, for low values of ΔT_{2X}, the model understates thermal expansion.

A decline in upwelling also reduces the temperature difference between the surface and the thermocline. As a result, the net effect of simulating history each time is functionally similar to imposing a correlation between low values of ΔT_{2X} and declines in upwelling. *But see* Chapter 9, Notes 6 and 7.

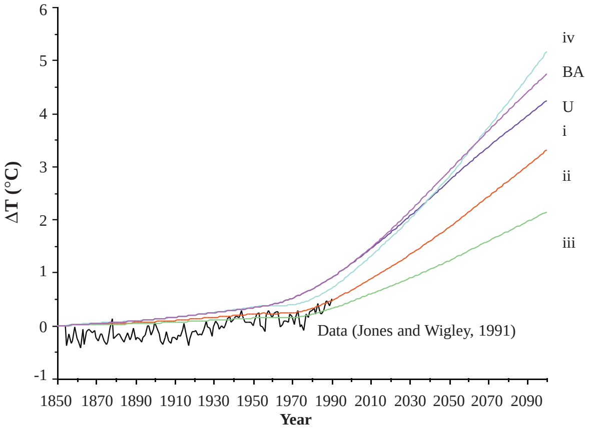

Figure 3-1. Comparison of Historic Temperatures and Projections of the Wigley & Raper Model. Curves (i) and (ii) use the medium assumptions and IPCC scenario IS92a emissions of greenhouse gases; (ii) also includes the offsetting forcings from sulfates and CFC-induced ozone depletion. Curves (iii) and (iv) are the same as (ii), except for ΔT_{2X} values of 1.5 and 4.5˚C. Curve BAU is the same as (i), except that it uses the IPCC (1990) "Business-as-Usual" emission scenario. The jagged curve that stops in the 1990s represents historic temperatures.

rately. Thus, it would be possible to supply the model with Northern and Southern Hemisphere values for **k**, π, and **w**. Nevertheless, we follow the convention of previous studies and run the ocean model based on the assumption that these parameters have the same values for both hemispheres.[5]

Previous assessments of sea level rise have assumed that the values of these parameters are fixed. In reality, however, the three-dimensional processes that π, **k**, and **w** approximate are all likely to change. The importance of allowing for such changes depends on the purpose to which the model is likely to be put, *e.g.*, whether the principal goal is to project transient surface temperatures or sea level. Regardless of the values of π, **k**, and **w**, the transient air temperature will eventually approach ΔT_{2X} if CO_2 is held fixed at twice its preindustrial concentration; those parameters merely determine how rapidly temperatures adjust to their equilibrium. IPCC (1990) showed that temperature is not extremely sensitive to these parameters, especially after the first few decades of a model run.

Sea level rise, by contrast, is very sensitive to these parameters, particularly in the long run. For a given rise in global surface temperatures, the oceanic expansion depends on the resulting rise in water temperatures at every depth. The upper (mixed) layer warms almost as much as the Earth's average surface temperature, but the bottom water only warms by π times that amount. Intermediate waters initially warm *less* than the bottom water, but eventually warm more than the bottom and less than the surface.[6]

Figure 3-2 illustrates the sensitivities of the Wigley & Raper model to a CO_2 doubling, holding **k** and **w** constant at the median values described below, for π=0, 0.2, and 1.0, and ΔT_{2X}=2.5˚C.[7] Surface temperature change is about 18 percent less for π=1 than for π=0 after the first 100 years, and 16 percent less after 500 years. Thermal expansion, however, is 40 percent *greater* after 100 years, 90 percent greater after 200 years, and over three times as great after 500 years. This difference occurs because even after 500 years, the deep ocean (*e.g.*, depth of 2 km) warms only 0.05˚C for π=0, while for π=1 it warms by approximately 1˚C. During the first century, most of the thermal expansion takes place in the mixed layer and upper thermocline, which warm by about the same amount for π=0 and π=1. During later centuries, however, the majority of expansion comes from the thermocline and deep ocean. Even though both the warming and the coefficient of expansion are much greater for the mixed layer than for the thermocline and deep ocean, there is far more water to expand in those lower layers; hence they ultimately contribute the majority of thermal expansion.

Figure 3-2 also illustrates the impact of an instantaneous 50 percent decline in deepwater formation (**w**) with no change in greenhouse gas concentrations (the relevance of which is discussed below).[8] Such a change in ocean circulation would warm the thermocline (Figure 3-2b) substantially. Assuming that π=0.2, a 50 percent decline in deepwater formation would

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[5] We occasionally refer to hemisphere-specific values for these parameters as part of the conceptual justification for the global values that we use, but all model runs use the same values for both hemispheres.

[6] This model artifact probably does not correspond to reality. *See* Figure 3-5 and accompanying text, *infra*.

[7] The significance of these parameter values is described below. We remind the reader that the assumption π=1 implies that the water that sinks toward the bottom in polar regions warms as much as the global average warming; π=0 implies that the water sinks at the same temperatures as today. For a given amount of heat, warmer sinking water means that the water remaining at the surface is colder.

[8] The paramater literally represents the average rate of upwelling throughout all portions of the ocean other than those where downwelling occurs. Because the amount of deepwater formation is proportional to the upwelling velocity, we mean both "deepwater

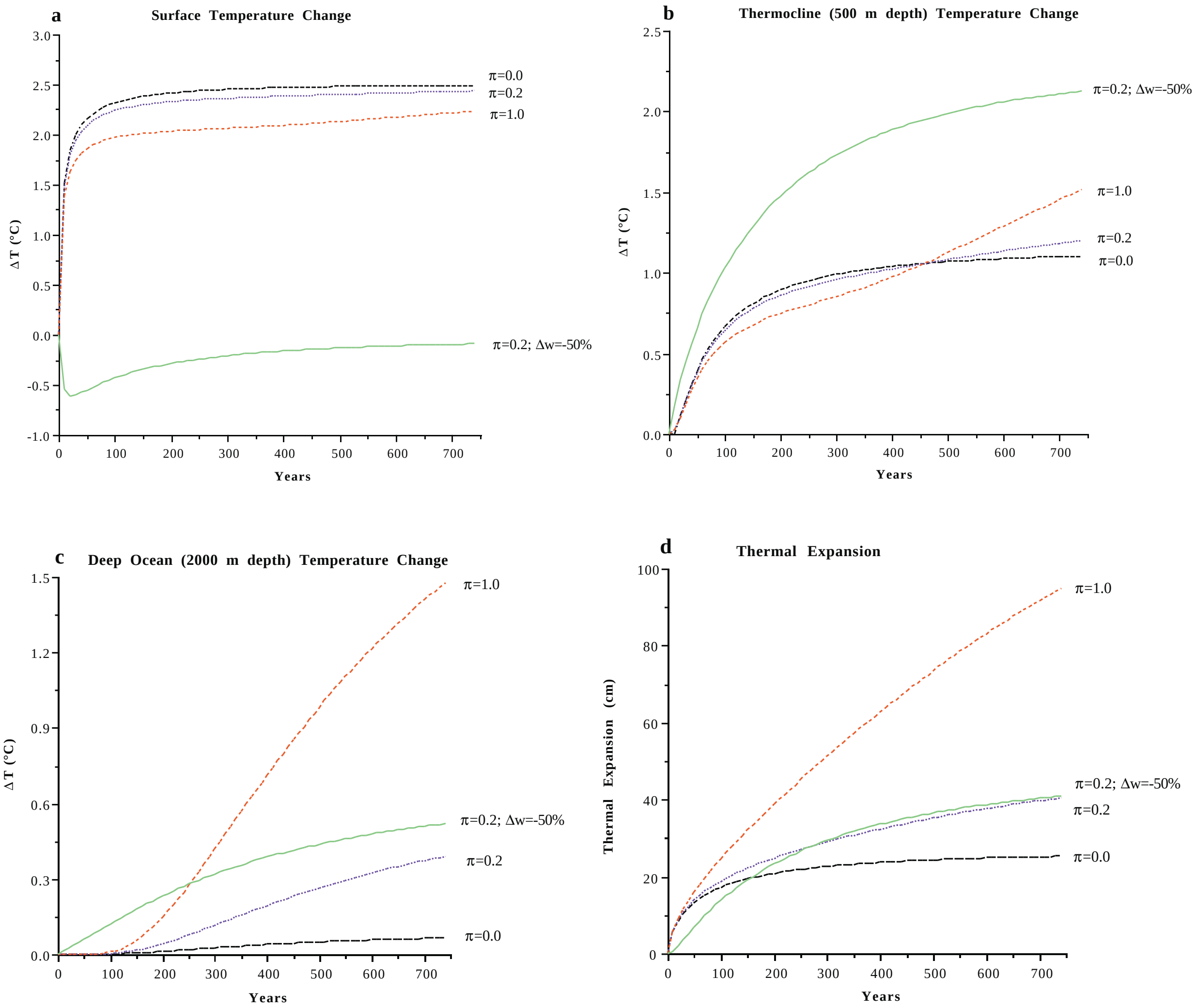

Figure 3-2. Impact of CO_2 Doubling or 50 Percent Reduction in Deepwater Formation: Evolution Over Time. Impacts on (a) surface temperature; (b) thermocline temperature at 520 m depth; (c) deep ocean temperature at 2020 m depth; and (d) ocean expansion, resulting from one-time doubling of CO_2 or halving of deepwater formation, with ΔT_{2X}=2.5˚C, as projected by the Wigley & Raper model. The first three curves assume a CO_2 doubling with climate sensitivity of 2.5˚C, with π equal to (i) 0, (ii) 0.2, and (iii) 1.0. The fourth curve (iv) holds greenhouse gases constant but cuts the upwelling velocity from 4 m/yr to 2 m/yr, with π=0.2.

raise sea level about as much as a CO_2 doubling (Figure 3-2d).

When using an upwelling/diffusion model to estimate thermal expansion, the sinking water amplification parameter π serves two purposes, which tend to suggest vastly different values. The direct function of the parameter is to indicate the rise in the temperature of *newly formed* deep water as a fraction of the warming of globally averaged surface temperature. For a given value of the upwelling velocity parameter **w**, however, π represents the equilibrium ratio of the warming of *all* deep water to the warming of the surface temperatures. Because the Earth will not warm enough to measure π for several decades, this parameter must be picked based on theory and judgment, not measurement. This judgment would be substantially helped, however, if three-dimensional modeling studies would report the temporal evolution of π—preferably for both hemispheres.

Previous assessments have generally picked **w** and **k** based on direct measurements and the fact that the existing temperature-depth profile is determined by a given ratio of **k**/**w**. By contrast, π cannot be measured directly; thus, it is picked so that the one-dimensional model has desirable properties. A value of π=1 allows the model to assume that, in equilibrium, the shape of the temperature-depth profile does not change; this assumption is a reasonable default because no one knows whether the difference between temperatures of deep and surface water will increase or decrease. A value of π=0 allows the model to reflect the fact that most deep water is formed by the creation of sea ice, which will always occur at the same temperature, unless sea ice changes substantially.[9]

The initial simulations we distributed to the reviewers were split evenly between runs in which we employed (a) fixed values of the three parameters and (b) those in which we allowed **w** to change in response to global temperatures.

Fixed Parameters (OM1)

One can pick π based on either (1) a reasonable assessment of the warming of polar sinking water or (2) on desired equilibrium properties of the model. Most deep water is formed by the freezing of surface sea water: The salt is separated from the ice, leaving a brine that is denser than surrounding sea water due to its higher salinity and perhaps its colder temperature as well. Because global warming will not change the temperature at which saltwater freezes, the deep water that is formed would logically be no warmer than it is today, implying that π=0. The assumption of π=1 is more reasonable for areas where deep (or intermediate) water is formed as a result of evaporation-driven salinity increases, as in the North Atlantic and Mediterranean regions. If one assumes that π_{SH}=0 for the 80 percent of bottom water formed through salt rejection in the Antarctic, but that π_{NH}=1 for the 20 percent that is formed from evaporation in the Northern Hemisphere, the average global value of π is 0.2.

One consequence of using a low value of π in thermal expansion calculations is that most of the ocean is assumed to warm much less than the surface, even in equilibrium. As a result, total thermal expansion estimates are lower than would be the case if all of the ocean warmed uniformly, especially in the long run.[10] In the absence of a strong theoretical explanation for how the shape of the temperature profile might change, a reasonable default assumption might be to assume no change. Thus, for example, IPCC (1990) assumes that π=1; as Figure 3-3 shows, the temperature-depth profile flattens if π=0, while largely retaining its current shape if π=1.

A possible problem with π=1 is that such an assumption, at least superficially, implies that the newly formed polar bottom water warms 1:1 with the global average surface temperature. Many researchers find this assumption unlikely because of the role of sea ice; *see e.g.*, Wigley & Raper (1991). Others believe that, in the long run, the downwelling water could warm as much (and perhaps more) than the global average warming, but that initially the warming will be less because Antarctic warming will lag behind global warming. As a result, the initial value of π_{SH} is close to 0, but it gradually increases to (and perhaps even beyond) a value of 1.0.[11]

Schlesinger & Jiang (1991), for example, ran their coupled ocean/atmosphere model for twenty years, after which time polar ocean temperatures are projected to warm between 0.004 and 0.57 times the global average warming, with a depth-averaged value of 0.14. They suggested that with a longer run, the depth-averaged value would probably be closer to 0.4; accordingly, they suggested that it would be appropriate for analyses employing simpler models to assume that π=0.4.

The analogy between three-dimensional and one-dimensional models is less than perfect. Most importantly, π does not literally represent polar warming; a 1-D model does not even have latitude. Instead, π represents the amount of additional heat conveyed by downwelling to the deep ocean, expressed as a fraction of the amount of heat that would be conveyed if greenhouse forcing warmed the downwelling water by as much as it warms the average surface temperature. Therefore, $\pi=\Delta T_{polar}/\Delta T_{global}$ only if ΔT_{polar} is averaged only over the regions and seasons in which downwelling takes place. Because the Schlesinger & Jiang calculations do not refer directly to the warming of the downwelling region, their suggestion that π=0.4 is somewhat *ad hoc*, but it is probably as reasonable as other procedures for picking the value of π.

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[9] The relationship between π and seaice formation is described further, below.

[10] In the very long run, it is even theoretically possible for the bottom water to warm more than the surface—especially if bottom-water creation due to seaice formation were to decline.

[11] *See* **Expert Judgment**, *infra* for a discussion of the wide divergence of opinion on the value of π.

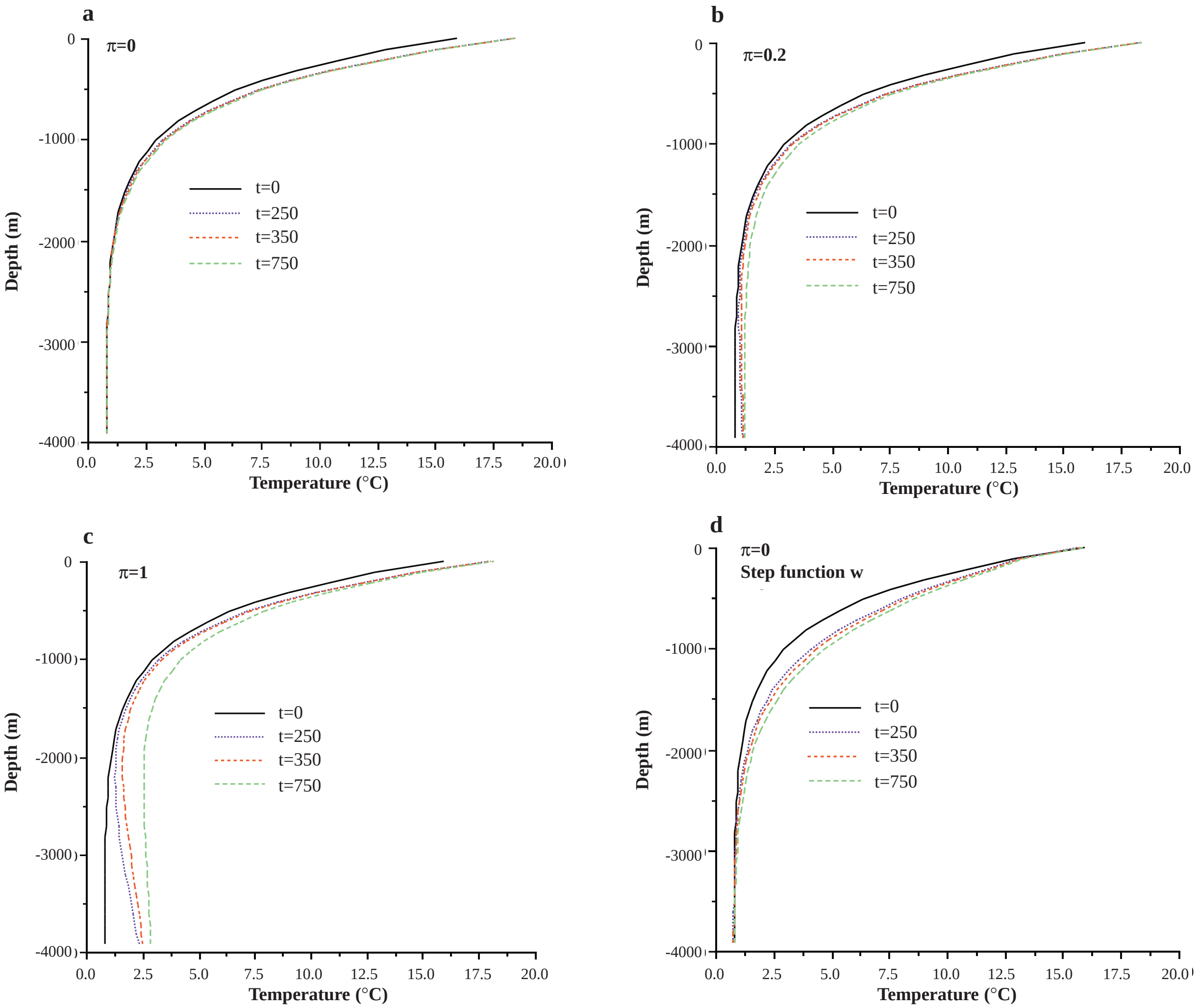

Figure 3-3. Impact of CO_2 Doubling or 50 Percent Reduction in Deepwater Formation: Depth-Temperature Profiles. These profiles correspond to Figure 3-2; *i.e.*, instantaneous CO_2 doubling in 1990 with (a) $\pi=0$, (b) $\pi=0.2$, and (c) $\pi=1.0$; and (d) no change in CO_2 but 50 percent reduction in upwelling velocity. Each box shows profiles for years 0, 250, 350, and 750.

An alternative approach is to pick the value of π that comes closest to duplicating temperature or thermal expansion estimates from a 3-D coupled ocean model. As we discuss below, for example, Figure 3-6 shows that a value of $\pi=0.6$ approximates the 25 cm of thermal expansion projected over a 95-year period by the GFDL model; a value of 0.13 approximates the Southern Hemisphere surface warming.

Allowing **w** to Vary (OM2)[12]

As long as the three parameters are fixed, the value of π determines the amount of heat reaching the deep ocean. Thus, other than by sheer coincidence, it is impossible to pick a specific value of π that both (1) conforms to the narrow definition $\pi=\Delta T_{\text{polar sinking}}/\Delta T_{\text{global}}$ and (2) functionally represents a desired assumption regarding the long-term evolution of $\Delta T_{\text{surface}} - \Delta T_{\text{deep}}$. The approach endorsed by Wigley & Raper and Schlesinger & Jiang (1991) focuses on the former—which is at least arguably "measurable" from 3-D transient experiments—and accepts whatever result is

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[12] We remind the reader that by "fixed **w**," we mean that $\mathbf{w}=\mathbf{w}_0$ throughout a given simulation, not that all simulations use the same value for **w**.

implied regarding equilibrium deep ocean temperatures (and thus thermal expansion). The approach followed by IPCC (1990), by contrast, (a) constrains the calculations to a reasonable default assumption that in the long run the middle and deep oceans warm as much as the surface, and (b) accepts the implied assumption that the bottomwater-formation temperature rises by ΔT_{global}, even though the freezing point of water stays relatively constant.[13]

If one allows **w** to vary over time, by contrast, one can assume that sea water will continue to freeze at the same temperature, without having to assume that, in equilibrium, there will be a large increase in the temperature difference between bottom and surface waters; by contrast, when π=0 and **w** is fixed, this assumption is unavoidable. Thus, our second approach is to assume that in the Southern Hemisphere, π=0, but that $\mathbf{w}_{SH}$ declines in proportion to the decline in annual Antarctic seaice formation that accompanies warmer temperatures. Because Northern Hemisphere deep water is generally not formed by freezing, we assume that π_{NH}=1. This case also assumes that w_{NH} declines, albeit for a different reason: increased precipitation prevents salinity in the Gulf Stream from rising as much as today, thereby reducing downwelling in the North Atlantic. *See* Manabe & Stouffer (1993).

Figure 3-4 compares the (OM2) case where π=0.2 and w declines geometrically by 15 percent per degree Celsius (C) of surface warming, with three OM1 cases (fixed **w**) where π is set to 0, 0.2, and 1.0. The figure illustrates warming at (a) the surface and depths of (b) 520 m and (c) 2000 m, as well as (d) thermal expansion. Radiative forcing is based on the IPCC (1990) "Business-as-Usual" scenario through the year 2100, and constant thereafter, with ΔT_{2X}=2.5. For the first century, the surface temperature of the OM2 (variable-**w**) case is within 1 percent of the OM1 (π=1) case, while thermal expansion is somewhat less. During subsequent centuries, thermal expansion diverges markedly.

The rough equivalence in thermal expansion estimates is largely coincidence. Given the similarity of surface temperatures, both cases have about the same amount of expansion in the mixed layer. In the variable **w** case, however, the thermocline (Figure 3-4b) warms more rapidly due to the declining rate at which colder bottom water upwells to this depth. The deeper layers of the ocean warm much more rapidly in the π=1.0 case because, by definition, the very bottom warms as much as the surface. With **w**=4 m/yr, a depth 200 m above the bottom receives water that downwelled fifty years previously. Warming at this depth by the year 2100 is equal to the 2050 surface warming, ignoring any diffusion from the surface (which is negligible at this depth). Thus, the cases differ in that the declining **w** allows more downward diffusion over time, while the π=1 allows for a gradual warming of the deep ocean by directly replacing the coldest remaining layer in each time step with water that has warmed as much as the surface.

The variable-**w** case is more realistic than π=1 in many ways. As Figure 3-5 shows, the one-dimensional model with π=1 yields an odd depth pattern of temperature changes: Not only do deep layers warm more than the surface and intermediate layers (Figure 3-5g), but a fairly substantial inversion also results (Figure 3-5c). This odd result stems from the fact that the model assumes that all downwelling conveys water to the very bottom (as opposed to distributing this water to various layers). By 2100, the bottom (4000 m) reaches a temperature of 2.8˚C, compared with the 1.2˚C that prevails at 3000 m; by 2500, the bottom reaches 5.0˚C, compared with 3.1˚C at 2000 m. By contrast, in the variable-**w** case, the inversion is trivial even after 500 years: 1.36˚C at 4000 m and 1.33˚C at 3000 m. This anomaly should not lead one to automatically disregard the relatively high thermal expansion estimates of π=1; the inversion probably *diminishes* the thermal expansion estimates. A more sophisticated 1-D model might avoid the inversion by distributing the additional heat due to downwelling at various depths. Because these warmer depths are accompanied by higher expansion coefficients, the resulting sea level rise would be somewhat greater.

Nevertheless, the variable-**w** assumption creates a number of risks. Like setting π_{SH} at zero in the fixed-**w** case, allowing **w** to decrease may satisfy a narrow criteria: the parameter in the one-dimensional model corresponds to reasonable expectations of how the 3-D variable would change. But it may do so at the expense of causing unintended dynamic model properties. Furthermore, intended reasonable "default" properties may not in reality be correct, or they may be overwhelmed by other changes that we cannot foresee. For example, a decrease in seaice formation would seem to imply less bottom water and hence a decline in **w**. Yet the 1-D models were

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[13] At prevailing salinities, the freezing point is typically about –1.9˚C. Although lower salinity would raise the freezing point somewhat, it cannot warm by more than 1.9˚C, and even that would require an unrealistic 99.9% decline in ocean salinity. Thus, for any significant value of ΔT, $\Delta T_{polar\ sinking}$ will be well below ΔT, unless the deep water is formed by a process other than seaice creation.

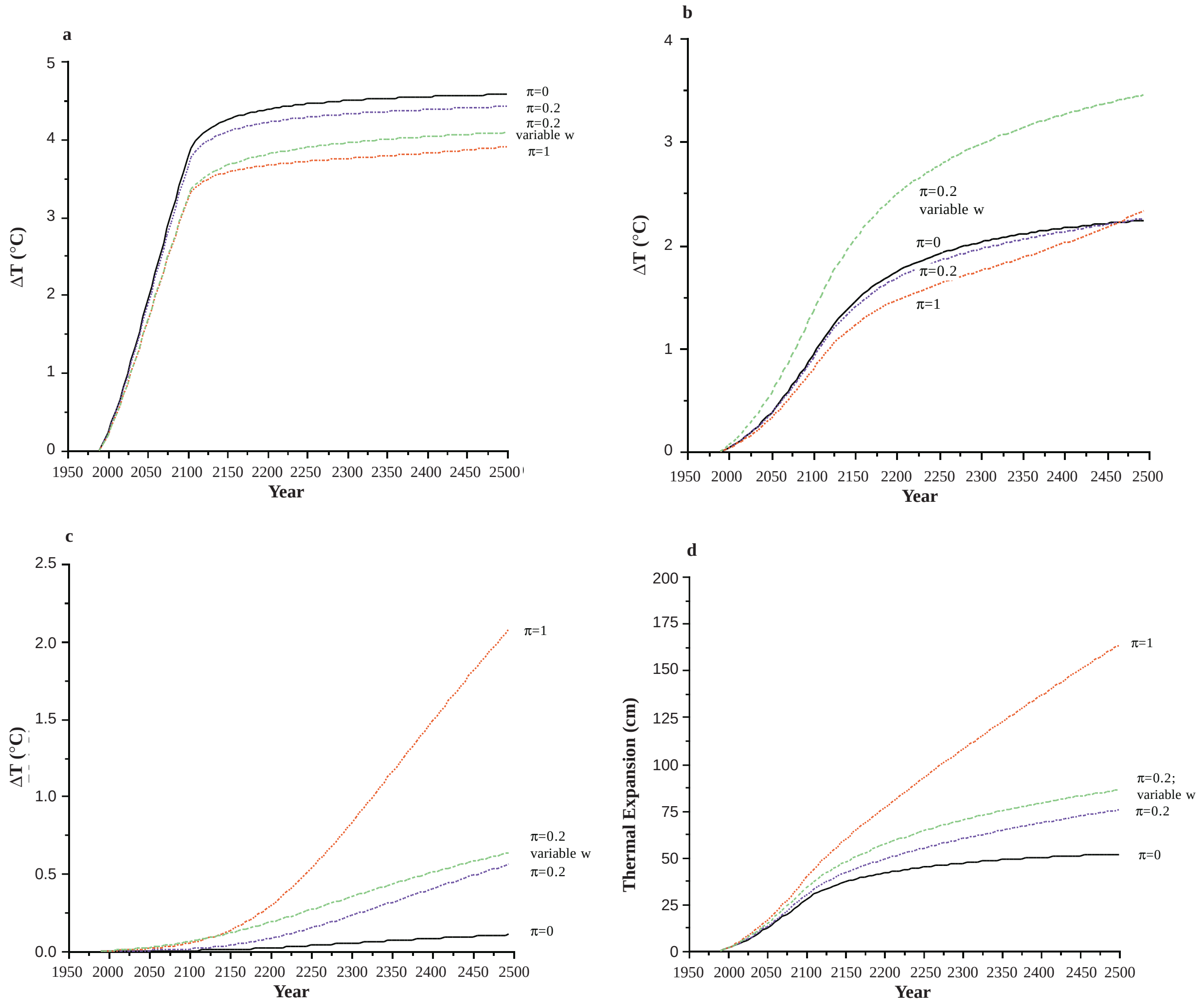


Figure 3-4. Impact of IPCC Business-as-Usual Scenario Over Time. Impacts on (a) surface temperature; (b) thermocline temperature at 520 m depth; (c) deep ocean temperature at 2020 m depth; and (d) ocean expansion, assuming that greenhouse gas concentrations increase through 2100 as projected by the IPCC (1990) Business-as-Usual scenario, and remain constant thereafter. The first three graphs assume that climate sensitivity is 2.5˚C for a CO_2 doubling, and that π equals (a) 0, (b) 0.2, and (c) 1.0; (d) also assumes that π=0.2, but that upwelling velocity (**w**) declines 15 percent per degree (C) of surface warming. In all cases, the initial 1990 conditions are derived by running the model from 1765 to 1990 using historic concentrations.

designed and calibrated to deal with the way the ocean circulates today; there is no guarantee that either (1) Antarctic bottomwater formation will change in proportion with the reduction in seaice formation or (2) that a decline in bottomwater formation will change thermocline temperatures in the same fashion as a 1-D model would suggest.

Although these uncertainties caution us against taking any of the results too seriously, they do not necessarily imply that the resulting thermal expansion estimates are less reliable than for the (OM1) case where $\mathbf{w}=\mathbf{w}_0$ and π=0.2 (π_{SH}=0). For example, if sea ice declines and deepwater formation does not decline or declines less than proportionately, it seems reasonable to assume that the downwelling water must be significantly warmer, which would imply a relatively high value for π. Presumably in this case, deep water formed by processes *other* than salt rejection must (at least partly) offset the reduction in bottom water formed by sea ice, and such downwelling

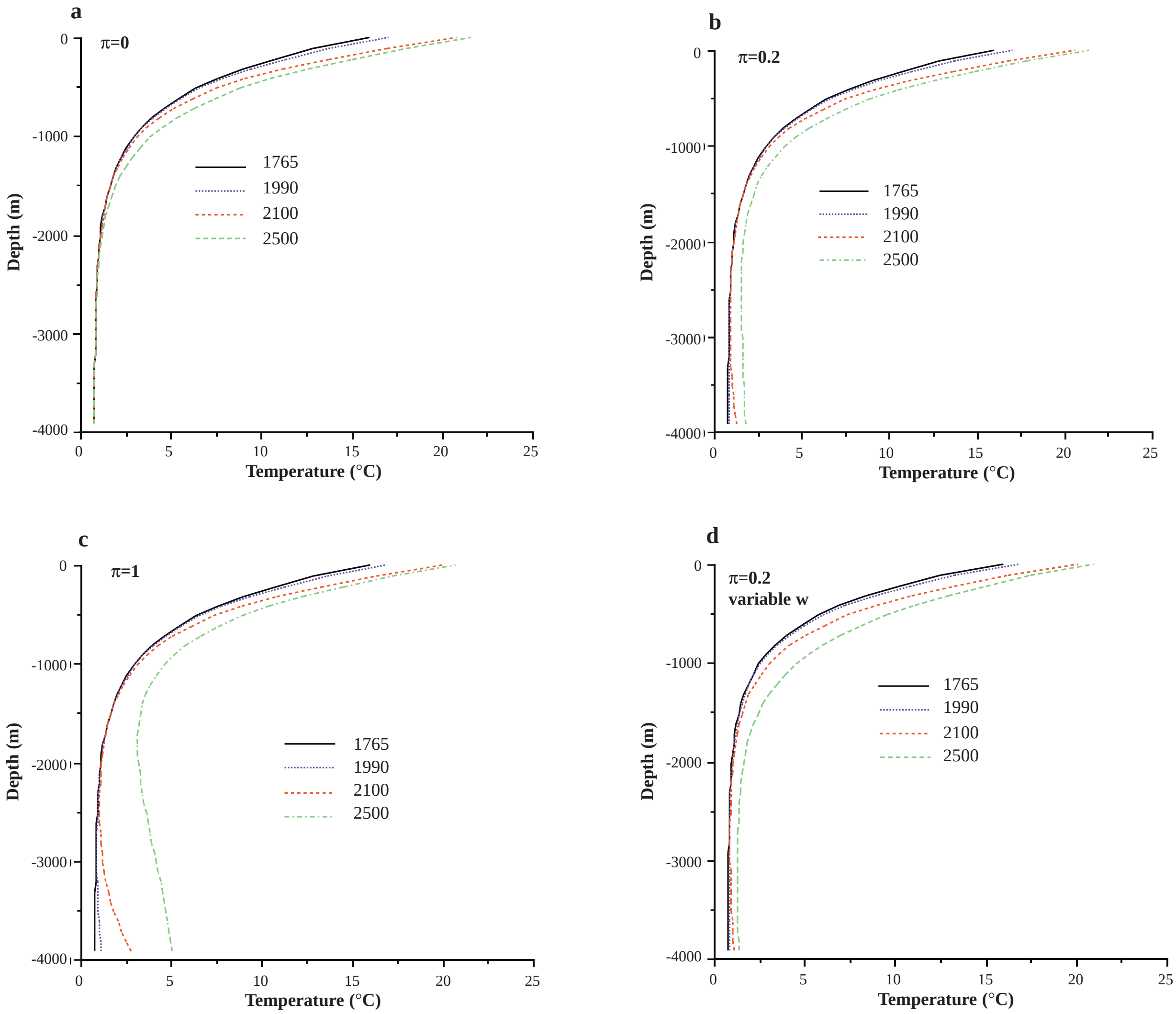


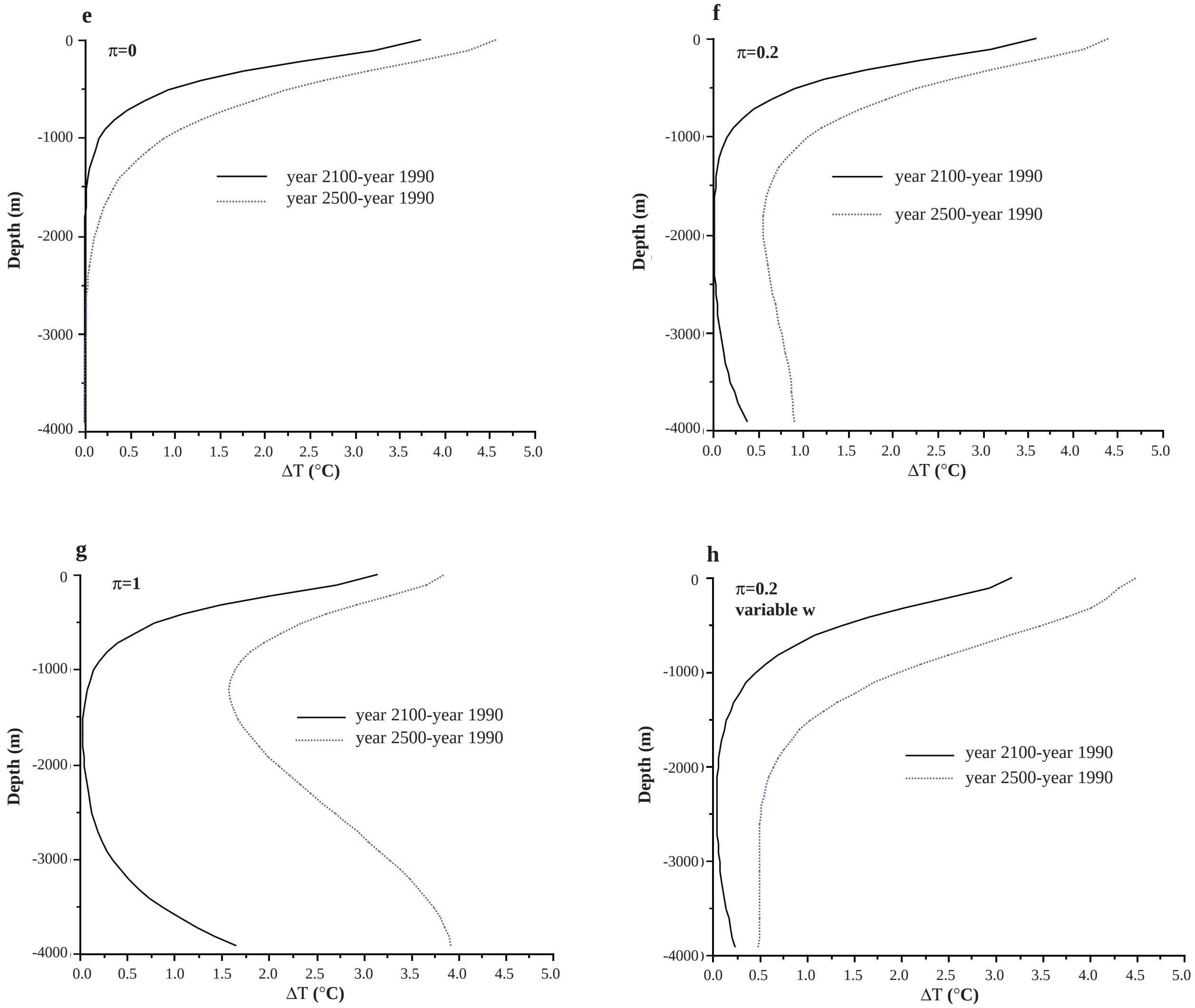
Figure 3-5. Impact of IPCC Business-as-Usual Scenario on Temperature-Depth Profile. These profiles correspond to Figure 3-4; *i.e.*, IPCC (1990) increases in greenhouse gas concentrations with (a) $\pi=0$, (b) $\pi=0.2$, (c) $\pi=1.0$; and (d) $\pi=0.2$ along with upwelling velocity declining 10 percent per degree (C) of surface warming. Absolute tem-

continued on page 9

generally would take place at a higher temperature.

One theory for expecting downwelling not to decline as sea ice declines is that thermohaline circulation is driven by equatorial upwelling, as well as polar downwelling. To this extent, elimination of seaice formation need not lead to a proportional reduction in the forces that cause water to downwell. Moreover, increased evaporation in the tropics might further increase the tropical force contributing to downwelling. Because the circumpolar ocean is 3˚C warmer than the *in situ* freezing point of sea water and may be warmer in the future, the replacement downwelling water would presumably be at least 3˚C warmer than the bottomwater formed by sea ice. Thus, if the assumption that **w** declines in proportion with the decline in sea ice is an overestimate of the actual decline in **w**, we also are underestimating π_{SH} by assuming it to be zero—it could be much higher, implying that π could be closer to one.

How should we pick the rate at which **w** changes? Just as π can be picked either to satisfy expected changes in polar water temperatures or to satisfy desirable long-term dynamic properties, so can **w** be picked based either on estimates of circulation changes or to satisfy



peratures are shown for the years 1765, 1990, 2100, and 2500. Note that the inversions in box c for 1990 and 2100 are unreported results from IPCC (1990). The post-1990 *changes* in temperatures corresponding to boxes a-d are shown in boxes e-h, respectively, for the years 2100 and 2500.

dynamic properties. In the case of **w**, the literature offers both (a) estimates of how seaice formation might respond and (b) 3-D model estimates of total changes in circulation. The most obvious dynamic property to watch is the ability of the model to duplicate thermal expansion estimates from 3-D models.

Figure 3-6a compares projected thermal expansion over a 95-year period using the 1-D model for various sensitivities of π and **w**, with the results from the Geophysical Fluid Dynamics Laboratory (GFDL) model reported by Manabe et al. (1991). For a value of π=0, **w** must decline by slightly more than 25 percent per degree (C) to duplicate the 25 cm of thermal expansion; if π=0.2, **w** declines 15%/˚C; if π=0.4, **w** declines about 5%/˚C; and if π=0.6, a fixed **w** slightly overpredicts the GFDL estimate of thermal expansion. Figure 3-6b shows the surface warming for the same combinations of π and **w**. All of the combinations that provide good fits for thermal expansion underestimate the 2.7˚C Southern Hemisphere warming projected by the GFDL model, with the high values of π (which are accompanied by low sensitivities of **w**) coming closer. As Figure 3-6c shows, the GFDL coupled ocean model

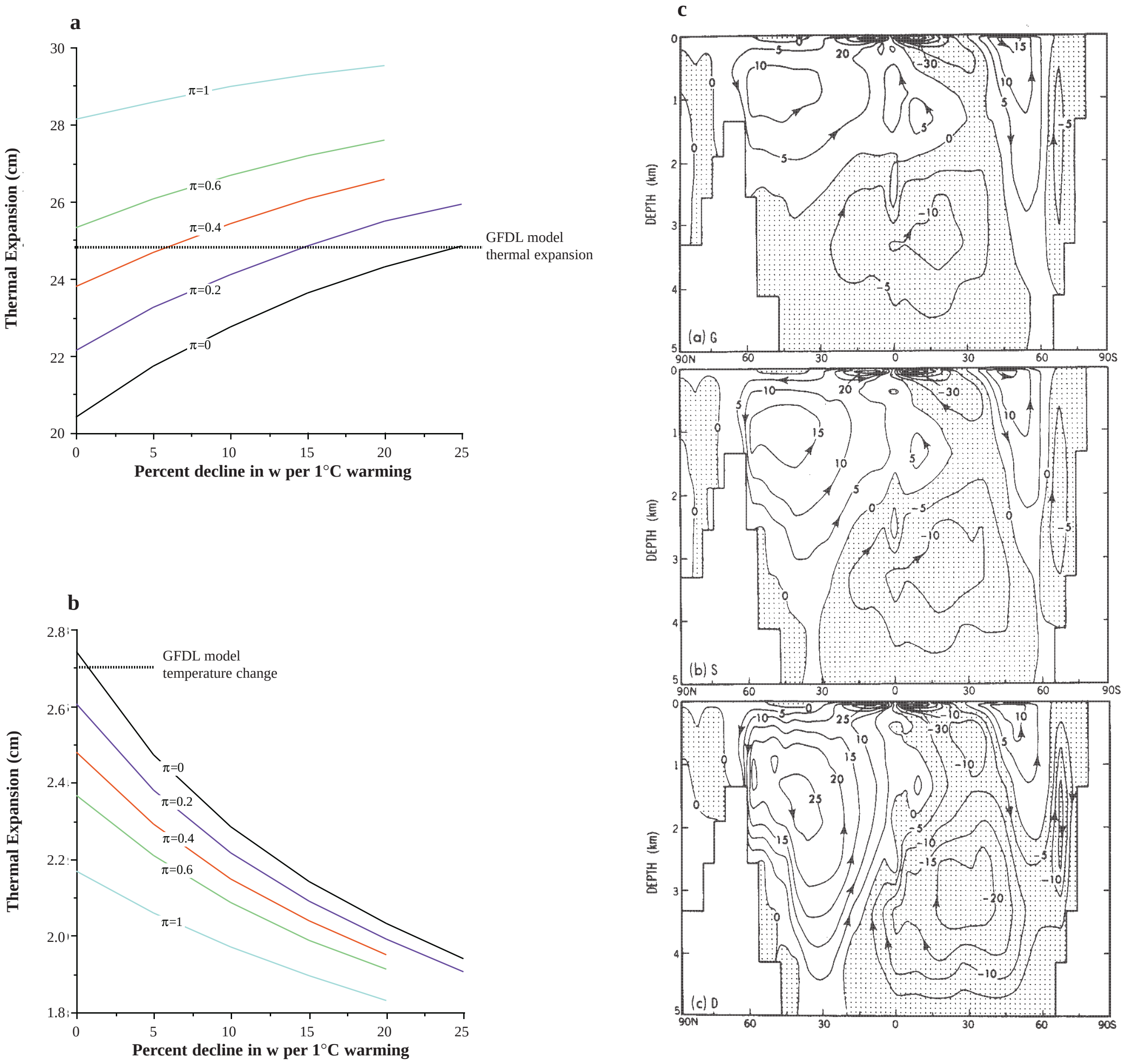


Figure 3-6. Using the GFDL Coupled Atmosphere-Ocean Model to Derive a Reasonable Value of How Upwelling Velocity Responds to Global Warming. Given various values of π, (a) shows thermal expansion as a function of the upwelling sensitivity. The GFDL estimates of thermal expansion can be duplicated by combinations in which upwelling sensitivity is approximately equal to 0.25–π/2, at least for 0<π<0.6. Unfortunately, these combinations do not duplicate Southern Hemisphere temperatures, as shown in (b). Nevertheless, the derived value of **w**-sensitivity is further supported by (c) GFDL's estimate of the change in stream functions over a seventy-year period: A one-third decline in circulation is evident between the S (baseline) and G (CO_2 doubling) simulations; similarly, a 50 percent reduction in CO_2 would increase mixing by about 1/2, as shown in the D-simulation.

SOURCES: Manabe et al. (1991) for three-dimensional results; see text for 1-D results.

suggests approximately a one-third reduction in overall upwelling after seventy years (by which time global temperatures rise 3˚C).

The impact of warming on annual seaice formation also is an indicator of changes in downwelling. Parkinson & Bindschadler (1982) estimated a 50 percent reduction in Antarctic seaice formation for a 5˚C warming in Antarctic air temperatures, which corresponds to a decline of 14.8%/˚C. Although the sensitivity in that analysis referred to Antarctic (rather than global) temperatures, the implied sensitivity is broadly consistent with that suggested by comparing 1-D with 3-D models.

Parameter Distributions for the 1-D Model in the Draft Report

We now present our reasoning behind the initial set of parameter distributions employed in the draft Monte Carlo analysis that was circulated to the reviewers. As discussed below, the reviewers used these initial distributions as a starting point in selecting the distributions used in the simulations.

Climate Sensitivity (ΔT_{2X})

Since the 1979 National Academy of Sciences report *CO_2 and Climate: A Scientific Assessment*, the consensus estimate has been that a CO_2 doubling will warm the Earth's average surface temperature 1.5 to 4.5˚C in equilibrium. That report and a second panel (NAS 1982) stated that 3˚C was the most likely value. Subsequent reports such as NAS (1983) and IPCC (1990) concluded that the most likely value is 2.5˚C. Wigley & Raper (1991) employed their one-dimensional model to estimate that historic warming is consistent with a value of about 3.3˚C. They have subsequently concluded that they may have overestimated the impact of historic aerosols, which would imply a sensitivity closer to 2.5˚C. On the other hand, their analysis assumed that π=0.2 and that **w** remains constant; allowing **w** to decline or a higher value of π would result in a higher sensitivity estimate. Overall, their analysis does suggest that the historic record thus far is consistent with the consensus estimate of ΔT_{2X}.

Nevertheless, this range has not met with universal acceptance. Patrick Michaels, the State of Virginia's climatologist, estimated that the warming is likely to be about 1˚C (Michaels et al. 1992); and Sherwood Idso of the U.S. Agricultural Research Service in Tempe, Arizona, has long argued that the warming is likely to be much less than the consensus assumes. Idso & Balling (1991), for example, estimated a sensitivity of only 0.35˚C. At the other end of the spectrum, Lashof (1989) estimated that the warming could be as high as 8 to 10˚C, particularly if the anthropogenic doubling induces biological feedbacks to release additional greenhouse gases.[14]

The combined picture that these studies paint is that our uncertainty is a skewed distribution that can be roughly described as lognormal. The draft report assumed that ΔT_{2X} is lognormally distributed with a geometric mean of 2.6˚C and σ limits of 1.5 and 4.5˚C. This distribution has a mean of 3.0˚C and a 2 percent chance of exceeding Lashof's 8˚C estimate, as well as a 5 percent chance of falling below Michael's 1˚C.

Diffusivity (**k**) and Initial Upwelling Velocity ($\mathbf{w}_0$)

The parameters **k** and **w** determine how rapidly the ocean reaches its new equilibrium. Diffusivity (**k**) represents the rate at which heat is transported from the relatively warm surface layers of the ocean downward to the colder thermocline and deep ocean. The parameter represents conduction and local-scale mixing, as well as the diffusion that its name suggests. Sarmiento et al. (1976) used measurements of the distribution of radium and radon isotopes to estimate upper and lower bounds for **k** as a function of depth. IPCC (1990) accepted the Hoffert et al. (1980) calculations that the depth-averaged value of **k** implied by Sarmiento et al. is between 1000 and 3000 m^2/yr, and used the intermediate value of 2000 m^2/yr.

The upwelling velocity parameter **w** can be literally interpreted as the speed at which ocean water flows upward, averaged over the entire ocean except for those areas where ocean water is sinking. Because the total water that sinks must equal the total water flowing upward, and because the region over which ocean water sinks is relatively small, this parameter is estimated as the ratio of global deepwater formation divided by the area of the ocean.

In picking the current upwelling velocity $\mathbf{w}_0$, a primary consideration is to ensure that when combined with the value for **k**, the ocean model duplicates

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[14] Both Michaels et al. and Lashof included nonclimatic factors in their estimates. Michaels et al. included the expected correlative increase in aerosol concentrations; Lashof included possible biological feedbacks that might increase natural greenhouse gas emissions.

today's temperature-depth profile. IPCC assumed that $\mathbf{k}/\mathbf{w}$=500 m, implying that $\mathbf{w}$=4 m/yr. This value is consistent with existing literature: Perry & Walker (1977) estimated the total bottomwater formation to be 35 to 55 million cubic meters per second. Averaged over the entire (nonbottomwater-forming) area of the ocean, this range implies an average upwelling velocity of 3.3 to 5.2 m/yr.

We used a lognormal distribution for $\mathbf{k}$ and $\mathbf{w}_0$ to avoid negative values. As a result, we had to choose between using the IPCC values as the medians of our distribution and using the ranges derived from previous studies; we opted for the former.[15] Thus, the draft assumed that $\mathbf{k}$ has a median of 2000 m^2/yr with 2σ limits of 1333 and 3000. Given the assumption for $\mathbf{k}/\mathbf{w}$, $\mathbf{w}_0$ had a median of 4 m/yr with 2σ limits of 2.67 and 6.0; the σ limits of 3.3 and 4.9 m/yr were thus consistent with the Perry & Walker estimates.[16]

Probability that Upwelling Velocity Changes

Under OM1, the ocean model treats $\mathbf{w}$ as fixed and draws π from a distribution described below. For OM2, by contrast, the ocean model allows $\mathbf{w}$ to change over time. Lacking analysis favoring one model over the other, the draft assumed that each of these cases were equally likely; that is,

$$\text{Prob(OM1)} = \text{Prob(OM2)} = 0.5.$$

Thus, half of the simulations assumed that $\mathbf{w}=\mathbf{w}_0$ and half assume that $\mathbf{w}$ changes.

Values of π in the Fixed-$\mathbf{w}$ Case

Under OM1, the draft used a lognormal distribution for both hemispheres, with 2σ limits of 0.2 and 1. The high end is justified by its use in IPCC (1990) and by the fact that, without additional information, the simplest assumption is that in equilibrium the various layers of the ocean warm by the same amount. The low end is justified by its use in Wigley (1992) and the fact that without additional information it might be reasonable to assume that the temperature at which the nonfreezing bottom water (20 percent) forms would rise by the global average, while the water forming due to freezing (80 percent) would continue to occur at the same temperature.

Values of π and $\mathbf{w}$ in the Variable-$\mathbf{w}$ Case

Ideally, we would treat the two major sources of deepwater formation differently: (a) in the North Atlantic, where bottom water is caused by evaporation, we would assume that π=1 and allow $\mathbf{w}$ to change as indicated in various studies reporting declines in North Atlantic bottomwater formation[17]; (b) in the Southern Hemisphere, where bottom water is created by freezing, we would assume that freezing still occurs at the same temperature (*i.e.*, π_{SH}=0), but that it (and thus $\mathbf{w}_{SH}$) declines as described below.

Because the Wigley & Raper one-dimensional model does not fully account for heat transfer between the hemispheres, we must run the model using global values for $\mathbf{w}$ and π. Thus, we set π=0.2, which is consistent with the assumption that π_{NH}=1.0 and π_{SH}=0.0.

The literature provides two possible ways to estimate how $\mathbf{w}$ might change as temperatures rise: (1) assume a direct relationship between global (or Antarctic) temperatures based on coupled-ocean models; and/or (2) estimate the decline in seaice formation resulting from warmer temperatures and assume that $\mathbf{w}_{SH}$ declines proportionately. The GFDL coupled-ocean model run reported by Manabe et al. (1991) projects about a 30 percent decline in deepwater formation by the time global temperatures rise 3˚C. As described above, the Wigley & Raper model most closely approximates the thermal expansion estimates generated by GFDL when $\mathbf{w}$ declines 5 and 15 percent per degree (C) of surface warming, for π=0.4 and 0.2, respectively. Parkinson & Bindschadler (1985) estimated that a 5˚C uniform Antarctic warming would cause a 50 percent decline in sea ice, which would decrease $\mathbf{w}$ by 40 percent (because 80 percent of deep water is formed in Antarctica).

At first glance, the estimates from seaice reduction and 3-D modeling results are fairly consistent. However, the Manabe et al. projections coincide with a warming of only about 1˚C in Antarctica, implying a sensitivity three times greater than that implied by Parkinson & Bindschadler.

The draft assumed that both $\mathbf{w}$ and sea ice decline as temperatures warm. We define the parameter θ to describe how w changes:

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[15] With 2σ limits of 1000 and 3000, a normal distribution implies a median (mean) of 2000, but a lognormal distribution implies a median (geometric mean) of 1732.

[16] We remind the reader that $\mathbf{k}/\mathbf{w}$=500 m refers to the current situation. Thus, in the cases where w declines as temperatures rise, we have to pick an initial value for $\mathbf{w}_{1765}$ such that when the simulation reaches the year 1990, $\mathbf{w}=\mathbf{w}_0$.

[17] Seaice formation in the North Atlantic is relatively minor. Although seaice formation in the Arctic Ocean is significant, the mixing between the Arctic and the other oceans is sufficiently small for it to be safely ignored in a one-dimensional model.

$$\mathbf{w} = \mathbf{w}_0 \, \theta^{\Delta T}.$$

The draft assumed that θ has a lognormal distribution with a median of 0.85, consistent with the results shown in Figure 3-6. To allow for some possibility of increased upwelling, the draft assumed that the σ limits for θ are 0.85^2 (*i.e.*, 0.72) and 1.0.

Polar Climate: Subsidiary Equations

The one-dimensional model estimates only one of the components of sea level rise directly: thermal expansion. As we discuss in Chapter 6, the models for projecting the alpine contribution to sea level rise are simple enough to require only a projection of global temperature change, which is also provided by the 1-D model. But 99 percent of the world's land-based ice rests on the polar ice sheets of Antarctica and Greenland. Thus, for estimating future sea level rise, the impact of greenhouse gases on polar climate could be as important as its impact on the worldwide average change in temperatures.

Early climatic assessments (*e.g.*, NAS 1979) suggested that polar temperatures were likely to warm two to three times as much as the global average. This result was based on both paleoclimatic evidence and the results of mixed general circulation models. Because of these projections, the relationship between global and polar temperatures is commonly known as the "polar amplification parameter." As Table 3-1 shows, many general circulation model studies with mixed-layer oceans suggest a considerable polar amplification. On the other hand, more recent studies (with deep-ocean models coupled to atmospheric models) suggest that the polar amplification may be less than 1.0.

Moreover, the annual average change in temperatures is not the best indicator for the impact of climate change on these ice sheets. Greenland is tens of degrees below freezing during winter, so a winter warming would not induce melting; the impact on summer temperatures is far more important. Antarctica is so cold that surface melting is trivial throughout the year. Ice flows gradually toward the oceans in the form of ice streams that are buttressed in part by floating ice shelves, most of whose bases are melting. If warmer climate is going to induce a significant contribution of Antarctic ice, it may do so through warmer water intruding beneath the ice shelves. Such warm intrusions could be enhanced either by warming the circumpolar ocean or by reducing the amount of sea ice. Finally, warmer temperatures could increase precipitation in polar areas, offsetting the potential contribution to sea level. Because most polar precipitation occurs during the warmer months, summer temperatures are more important than winter temperatures.[18]

TABLE 3-1
GREENLAND WARMING ESTIMATED BY VARIOUS CLIMATE MODELS

Model	Year	Season	Warming (°C) Greenland	Global
Coupled Ocean				
GFDL	60–80	winter	3–5	2.3
GFDL	60–80	summer	1.0–1.5	2.3
GFDL	60–80	annual	3–4	2.3
MPI	56–65	annual	2–5	1.3
NCAR	31–60	annual	1	0.5
UKMO	65–75	annual	1–2	1.7
Equilibrium Mixed-Layer Ocean				
GFDL	$2XCO_2$	winter	8–18	4.0
GFDL	$2XCO_2$	summer	2–6	4.0
CCC	$2XCO_2$	winter	4–8	3.5
CCC	$2XCO_2$	summer	2–6	3.5
UKMO	$2XCO_2$	winter	0–4	5.2
UKMO	$2XCO_2$	summer	2–4	5.2

SOURCE: IPCC 1990, 1992.

Although several studies have reported the likely equilibrium impact of a CO_2 doubling on polar air temperature changes, relatively few have reported time-dependent projections. Fewer still have examined the likely changes in polar ocean temperature changes. Therefore, the draft used the simplest procedure: assume that (1) in equilibrium the temperature change is a constant times the global change, but that (2) at least in the Southern Hemisphere, the polar temperature change lags behind the global change.

This section describes the draft report's assumptions for polar temperature and seaice changes. Because different reviewers were involved, we defer discussion of precipitation changes until the final section of this chapter. Conceptually, our projections require two tasks: (1) estimating the relationship between global warming and equilibrium polar temperatures; and (2) specifying the dynamics and adjustment times by which polar temperatures respond

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[18] See Chapters 4 and 5 for more details on Greenland and Antarctica.

to global warming.

Equilibrium Polar Warming

Our projections of the equilibrium conditions toward which polar temperatures would tend required us to specify parameters for Antarctic air temperatures, Antarctic water temperatures, and Greenland air temperatures.

Antarctic Air Temperatures. The draft report assumed that, in equilibrium, the summer surface air warms P_1 times the global average surface warming. P_1 was lognormally distributed with a median of 1.0 and 2σ limits of 0.67 and 1.5, based on IPCC (1992).

The draft assumed that winter temperatures would be more sensitive. (As Table 3-1 shows, most modeling studies have reached this result as well.) Sea ice would decline as a result of the increased radiative forcing from greenhouse gases, even if temperatures did not warm; summer warming also reduces sea ice. Where sea ice is removed, air temperatures will be much warmer during winter because the exposed ocean can keep the air at around the freezing point, rather than tens of degrees below freezing. Because seaice retreat will allow these warmer areas to advance inland, temperatures over the coastal portions of the continent will be warmer as well. We assumed that, in equilibrium, the winter surface air warms P_2 times the global average. The draft report assumed that P_2 is lognormal with 2σ limits of 1.0 and 3.0. *See* IPCC (1992).

We also considered the correlation between winter and summer Antarctic warming. Uncertainties regarding polar amplification in summer and winter must be correlated, because changes in ocean circulation and sea ice would affect both. The correlation must be less than 1, however, because it is unlikely that all the processes that affect summer and winter temperatures would affect them in the same proportions.[19]

Because the correlation must be greater than zero but less than one, the draft assumes that $\rho_{P1,P2}=0.5$.

Southern Hemisphere Circumpolar Ocean Warming. The draft expresses the equilibrium change in circumpolar ocean temperatures as P_3 times the average equilibrium surface warming of the Earth.

As mentioned above, climate modeling studies suggest that the winter warming of Antarctic air temperatures does not result from warmer ocean temperatures as much as from the decline in sea ice, which enables oceanic heat to escape and warm the cold Antarctic air. By contrast, during summer, the surface air and the surface water should warm by about the same amount (although the change in water temperatures at ice-shelf depths may be different). This reasoning suggests that the summer Antarctic air temperature increase would be a better indicator of Antarctic ocean warming than the average annual warming of Antarctic surface temperatures, which would imply a warming of 0.67 to 1.5 times the global warming.

Coupled ocean-atmosphere models suggest that ocean waters will warm by less than the global average warming, at least for the first century. As discussed below, Manabe et al. (1991) estimated that the polar ocean may warm by only about 25 percent as much as global temperatures after one hundred years. Fitting a simple differential equation to those results suggests that the long-run warming would be only about 1/2 the global warming.[20]

The draft report assumed that P_3 is lognormal with a median of 0.5. As discussed below, such an assumption yields results that are consistent with the Manabe et al. (1991) results. Moreover, if extrapolated backwards in time, this assumption implies that during the last ice age, the circumpolar ocean temperature would have been hovering at about the freezing point.[21] Somewhat arbitrarily, we assumed a fourfold uncertainty (*i.e.*, σ limits of 0.25 and 1.0) and a 0.75 correlation with summer equilibrium warming. Thus, in only about

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[19] Note that the radiative effect of seaice retreat is positive in the summer but zero during the polar night. On the other hand, convection of heat from ocean to air is much more enhanced during winter, when the air is much colder than the water, than during summer, when they are both at approximately the same temperature.

[20] More recently, Manabe & Stouffer (1993) report that after 500 years, the circumpolar ocean warms as much as the global average temperature; *i.e.*, $\Delta T_{cdw}=\Delta T$. Manabe himself suggests that the Antarctic ocean temperatures should warm as much as the global average, but with a 100 to 300 year lag. *See* **Expert Judgment**, *infra*.

[21] The current circumpolar ocean temperature is about 1.9˚C above the *in situ* freezing point. A more realistic approach might have been to assume that dT_{cdw}/dT is low, as long as there is permanent sea ice, but that it increases as the area of sea ice, ice shelves, and icebergs decline. Such an assumption would resolve the inconsistency between the positive polar amplification that climatologists have long expected for a CO_2 doubling equilibrium and the fact that such an amplification cannot be extrapolated backwards without freezing much of the southern ocean. Lacking an objective basis for describing how this marginal rate of polar amplification might increase, we retained the proportional assumption. *But see* Hoffert's suggested distributions under **Expert Judgment**, *Circumpolar Ocean Warming, infra*.

15 percent of the simulations would the circumpolar deep water (CDW) warm by more than the global average—even in equilibrium. For the most part this would happen along with scenarios in which summer Antarctic warming is also greater than the global average warming (and thus where precipitation increases are significant as well).

Greenland Temperatures. IPCC (1990) assumed that Greenland warms 1.5 times the global average. As Table 3-1 shows, coupled ocean-atmosphere models suggest that Greenland warming will be between one and two times the global average warming. As with Antarctica, GFDL suggests that the summer warming will be less than the winter warming, as does the equilibrium mixed-layer run by the Canadian Climate Center (CCC). Although the United Kingdom Meteorological Office (UKMO) mixed-layer run suggests that summer warming will be greater than winter warming, the summer warming is still less than global average equilibrium warming. The draft report assumed that annual temperatures in southern Greenland rise P_7 times the global average, with P_7 being lognormal with two σ limits of 1 and 2. Because existing models for the Greenland contribution to sea level rise only consider annual temperatures, we follow suit.

Adjustment Times for Polar Temperatures

Manabe et al. (1991) employed a coupled ocean-atmosphere model with a linear time trend in forcing. They estimated that average global temperatures eventually follow a linear trend, after an initial "startup" of a few decades; such a temporal pattern could be approximately described by the first-order differential equation:

$$\frac{dT}{dt} = a\,(T_{eq} - T),$$

where $\mathbf{T}_{eq}$ is the equilibrium temperature implied by atmospheric forcing at a given time, and $1/\mathbf{a}$ is the e-folding time. Because $\mathbf{T}_{eq}$ follows a linear time trend, the trajectory for transient temperatures would be approximately:

$$\frac{dT}{dt} = a\,(Bt - T),$$

where **B** represents the annual trend of equilibrium (also called "committed") warming (*i.e.*, climate sensitivity expressed as the sensitivity to a CO_2 doubling, divided by the number of years CO_2 takes to double). If b=aB,

$$\frac{dT}{dt} = a\,(Bt - T),$$

and the only solution through the origin is:

$$T = \frac{b}{a^2}\,e^{-at} + \frac{b}{a}\,(t - \frac{1}{a}).$$

The GFDL results seem to suggest that the adjustment time for Antarctic temperatures may be much longer than for average surface warming, as shown in Table 3-2. Solving for **a** and **B** suggests that the e-folding times for global surface temperature, Antarctic air, and circumpolar water are nine, twenty-nine, and fifty years, respectively. Even so, the long-term warming trend for water temperatures is only about half that of air temperatures.

The simple linear first-order differential equation is only a rough summary of the dynamics.[22] A possible alternative approach for summarizing the dynamics would be to use higher order differential equations, and estimate the coefficients by fitting a nonlinear regression of their solutions through the annual (or at least decadal) time series. At least for surface air temperatures, a second-order equation seems likely to more accurately describe the dynamics: The first-order equation assumes that the difference between the equilibrium and the actual value declines exponentially; second-order equations, by contrast, can capture a response that declines as the sum of two declining exponentials. Given the evidence that the mixed layer adjusts in a matter of decades while the deep ocean takes centuries, such a functional form would seem applicable. On the other hand, the simplified version may be preferable for purposes of a Monte Carlo analysis, since each parameter clearly represents a particular issue.

A further problem remains with the simple differential equation: We are already using a one-dimensional upwelling-diffusion model to capture the dynamics of the global surface temperature adjustments. Different values of π, **k**, and **w** lead to different adjustment times and "shapes" of the adjustment function. Therefore, to use the lag functions derived from GFDL results for Antarctic air and water temperatures would leave us with the risk that for some combinations the temporal pattern of adjustment for the polar temperatures would be inconsistent with that of the

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[22] Consider transient surface air temperatures: the fit we obtain implies an equilibrium warming (for $2XCO_2$) of only 2.6, while the $2XCO_2$ equilibrium run by Manabe et al. with a mixed-layer ocean suggests 4.2. If we fit the simple differential equation using the equilibrium values, we obtain much longer e-folding times of 38 and 300 years for average and Antarctic air temperatures, respectively.

TABLE 3-2
LINEAR FIRST-ORDER DIFFERENTIAL EQUATIONS FIT TO GFDL TRANSIENT ESTIMATE OF GLOBAL AND POLAR TEMPERATURES

Change in Temperatures

Year	Global Surface	75˚S Air	500 m-deep Circumpolar	South Greenland
15	0.3[a]	0.1	—	—
25	0.7	0.2	—	—
35	1.1	0.3	—	—
45	1.4	0.5[a]	—	—
50	1.5	0.5	—	2.0
55	1.6	0.5	—	—
65	2.0	0.4	—	—
70	2.3[b]	—	—	3.15–3.8[b]
75	2.5	1.0	0.75[a]	—
85	2.9	1.5	—	—
90	3.1	1.5	1.0[a]	4.6
95	3.3[a]	2.0[a,b]	—	—

Fitting equation to (**a**) years

	Global Surface	75˚S Air	500 m-deep Circumpolar	South Greenland
a	0.1147	0.0356	0.0202	—
B	0.0382	0.0221	0.0206	—
e-fold	8.7	28.1	49.5	—
ΔT_{2X}	2.66	1.54	1.44	—

Fixing B based on equilibrium run and fitting to year **b**

	Global Surface	75˚S Air	500 m-deep Circumpolar	South Greenland
a	0.02646	0.005	—	0.022–0.031
B	0.0603	0.115	—	0.0912
e-fold	38.7	200	—	31–44
ΔT_{2X}	4.2	8.0	—	6.1

[a] Years employed in solving for **a** and **B** in the equation $dT/dt=a\,(Bt-T)$. In each case, we used the first year that could be estimated from the graph along with the last year of the time series. To avoid arbitrariness of picking particular years, subsequent drafts might try nonlinear regression of the solution $Y=b/a^2\, e^{-aX}+b/a\,(X-1/a)$, especially if more years are available for ocean temperatures. Moreover, with a regression it would be possible to test whether higher order differential equations yield significantly better fits.

[b] Greenland calculations are based on GFDL graphs, which indicate that by year 70 Greenland temperatures rise 0.5 to 0.6 times the equilibrium warming expected from a CO_2 doubling.

global temperatures.

To prevent such an inconsistency, we assume:

$$\frac{dT_{polar}}{dt} = \frac{P_1\, \Delta T_{global} - \Delta T_{polar}}{P_5}.$$

That is, polar temperatures tend toward an equilibrium that is functionally dependent on the calculated *transient* global temperature.

Based on the results from GFDL, the draft assumed that the median value of the e-folding time for Antarctic water at ice-shelf depths (P_4) is 40 years; we employed arbitrary 2σ limits of 20 and 80 years in a lognormal distribution.

For Antarctic surface air summer and winter temperatures (P_5 and P_6), the draft assumed that the lag is less certain. Unlike deep ocean temperatures, Antarctic air temperatures have been estimated by mixed-layer transient models, which do not show as much of a lag. Even though there is a consensus that mixed-layer ocean models are inferior, the draft assumed that they cannot be totally discounted. Therefore, the σ limit on the low end is one year, which implies that 16 percent of the time, the lag will be negligible. On the high end, we assumed a σ limit of 20 years, derived from the GFDL results. The correlation (of the logarithms) between P_4 and each of these parameters was assumed to be 0.5.

For Arctic temperatures, by contrast, the GFDL results suggest that the lag is not appreciably different from the lag for global temperatures. Therefore, the draft assumed that the one-dimensional model's estimate of the lag between forcing and global temperatures completely captures that lag for Greenland temperatures. This assumption is consistent with IPCC (1990).

Changes in Antarctic Sea Ice

The draft report used the same functional form for seaice changes as we use for the change in **w** in the variable-**w** case (*i.e.*, sea ice declines as temperatures rise). We define the parameter P_{10} to describe how sea ice changes:

$$\text{seaice} = \text{seaice}_0\, P_{10}^{\Delta T}$$

The draft assumed that P_{10} has a lognormal distribution with the same median and 2σ limits as θ in the variable-**w** case. These estimates were justified primarily by the Parkinson & Bindschadler (1982) study.

TABLE 3-3
CUMULATIVE PROBABILITY DISTRIBUTION OF GLOBAL WARMING BASED ON ASSUMPTIONS FROM THE DRAFT REPORT (˚C)

Cumulative Probability (%)	2030	2100	2200
1	0.35	0.85	1.05
5	0.51	1.2	1.9
10	0.6	1.5	2.24
20	0.75	2.0	3.1
30	0.88	2.3	3.6
40	0.97	2.7	4.2
50	1.1	3.1	4.8
60	1.2	3.5	5.6
70	1.3	3.9	6.3
80	1.5	4.6	7.5
90	1.75	5.6	9.3
95	1.95	6.5	10.9
97.5	2.1	7.3	12.6
99	2.4	8.3	14.7
99.5	2.5	9.1	16.4
Mean	1.1	3.3	5.4
σ	0.45	1.6	2.9

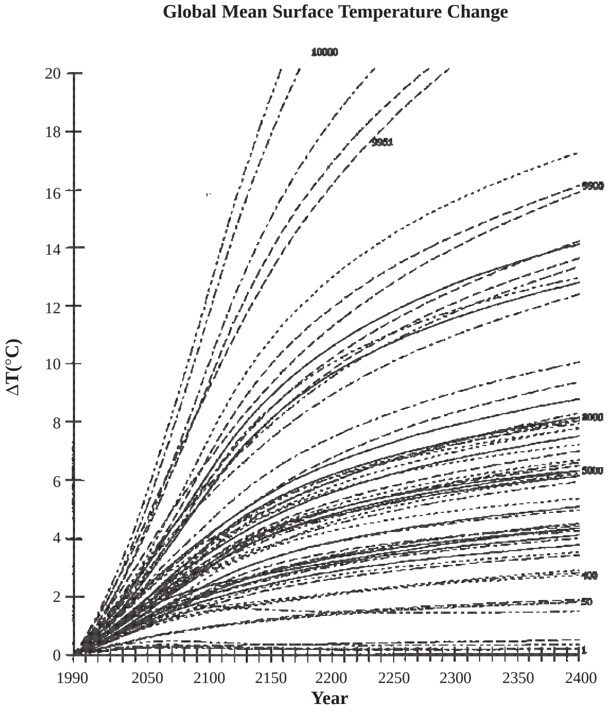

Figure 3-7. Selected Scenarios of Global Warming: Draft Report. See Figure 2-5 and accompanying text for explanation.

The draft also assumed that P_{10} and θ are perfectly correlated, implying that $P_{10}=\theta$.

Results for Initial Draft Assumptions: Temperature and Thermal Expansion

Table 3-3 illustrates the probability distribution of global warming for selected years given the initial draft assumptions for concentrations (see Chapter 2) and the climate variables described above. As the table shows, our median estimate for the year 2100 was 3.1˚C, 10 percent higher than IPCC's 2.8˚C best estimate for the IS92a scenario. Our 90 percent confidence interval was also somewhat higher than the IPCC range: IPCC's low estimate for the IS92a scenario of 1.8˚C is 20 percent greater than our 5%-low estimate of 1.5˚C, while IPCC's high IS92 estimate of 4.2˚C is 35 percent less than our 5%-high estimate of 6.5˚C. The draft report's estimates for the year 2100 are somewhat higher than the IPCC projections principally because our lower values of π allow for a more rapid adjustment of surface temperatures.

Figure 3-7 illustrates temperature estimates for selected simulations through the year 2400.[23] Although temperatures increase throughout the simulation period for most runs, a few runs show a peak around the year 2075; that result stems from the declining emission rates assumed in IPCC scenario IS92c. Figure 3-8 shows the corresponding probability densities for 2100 and 2200.

The importance of the lower values of π is further affirmed when one compares our thermal expansion estimates (Figure 3-9 and Table 3-4) with those of IPCC (1990). For the year 2100, our median draft estimate of 30 cm was about 25 percent less than IPCC's "best estimate," even though our estimated temperature was about the same (the IPCC 1990 report had slightly higher temperatures than the 1992 report). Similarly, our 60 percent confidence interval (20 to 44 cm) was about 25 percent lower than the range spanned by the IPCC low-to-high range of 26 to 58 cm. Only 5 percent of our simulations exceed the IPCC high estimate, while

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[23] See Figure 2-5 and accompanying text for a discussion of the selection criteria for this and other spaghetti diagrams.

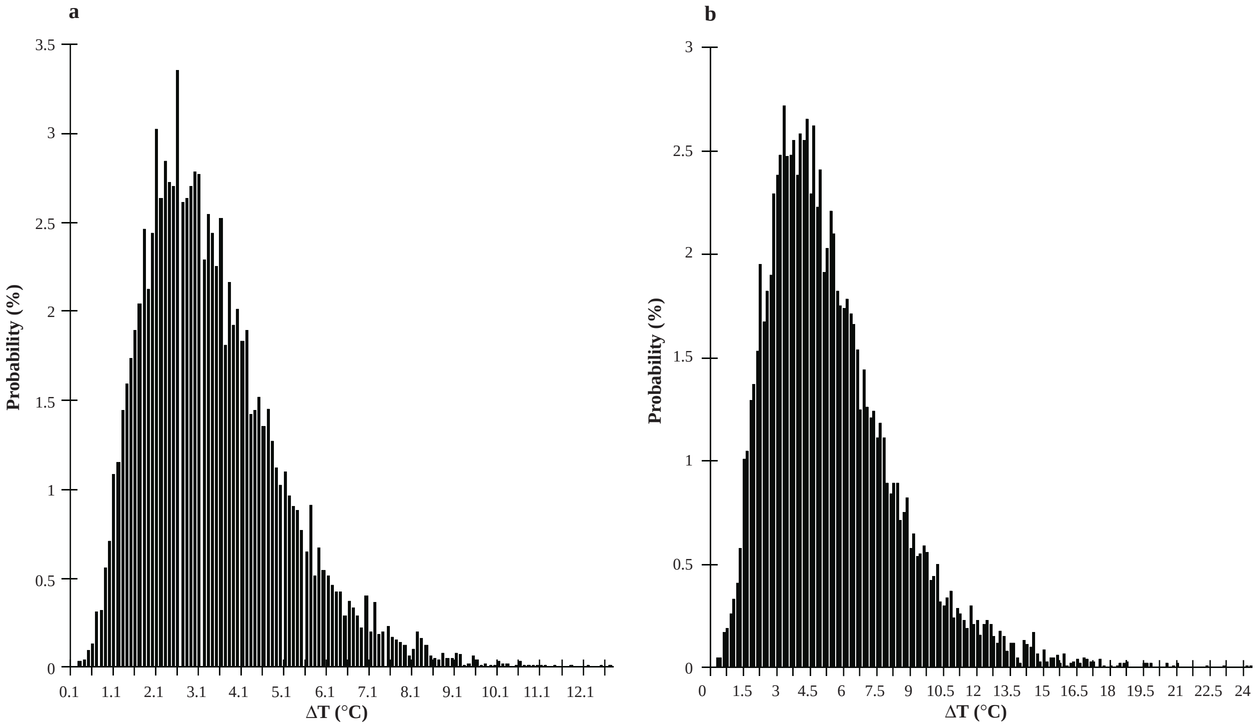


Figure 3-8. **Probability Density for Surface Warming: Draft Report.** Estimated probability density of surface temperature warming between 1990 and (a) 2100 and (b) 2200.

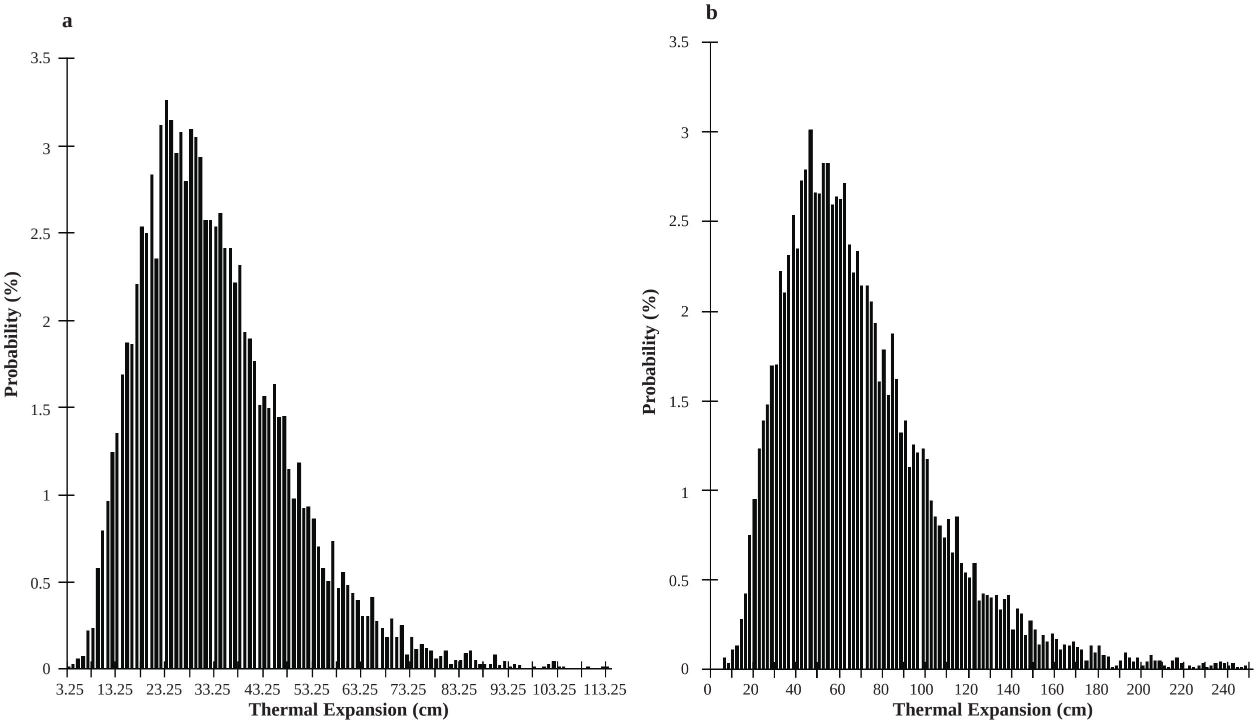


Figure 3-9. Probability Density for Thermal Expansion: Draft Report. Estimated probability density for sea level rise due to thermal expansion between 1990 and (a) 2100 and (b) 2200.

TABLE 3-4
CUMULATIVE PROBABILITY DISTRIBUTION OF THERMAL EXPANSION BASED ON ASSUMPTIONS FROM THE DRAFT REPORT (cm)

Cumulative Probability (%)	2030	2100	2200
1	2.8	8.7	16
5	4.0	13	23
10	4.8	16	30
20	5.8	20	39
30	6.8	23	46
40	7.5	27	53
50	8.4	34	61
60	9.3	38	71
70	10	44	79
80	11	52	93
90	13	60	115
95	15	78	137
97.5	—	—	161
99	18	113	193
99.5	—	—	215
Mean	8.8	32	68
σ	3.3	15	36

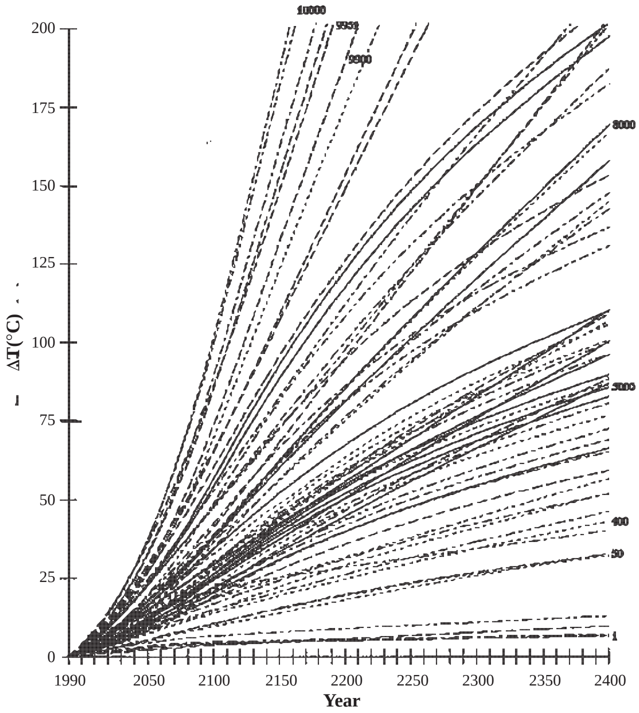


Figure 3-10. Thermal Expansion for Selected Simulations for the Period 1990–2400: Draft Report. See Figure 2-5 and accompanying text for additional explanation.

35 percent of them fell below the IPCC low estimate.

Figure 3-10 provides a spaghetti diagram of thermal expansion for the period 1990–2400. All scenarios show increasing expansion, including the few scenarios for which temperatures decline after 2075. The slight drop in temperatures would result in thermal contraction of the mixed layer; but because temperatures would still be about 1.5˚C warmer than today, the deep layers of the ocean would continue to warm and expand, more than offsetting contraction at the surface.

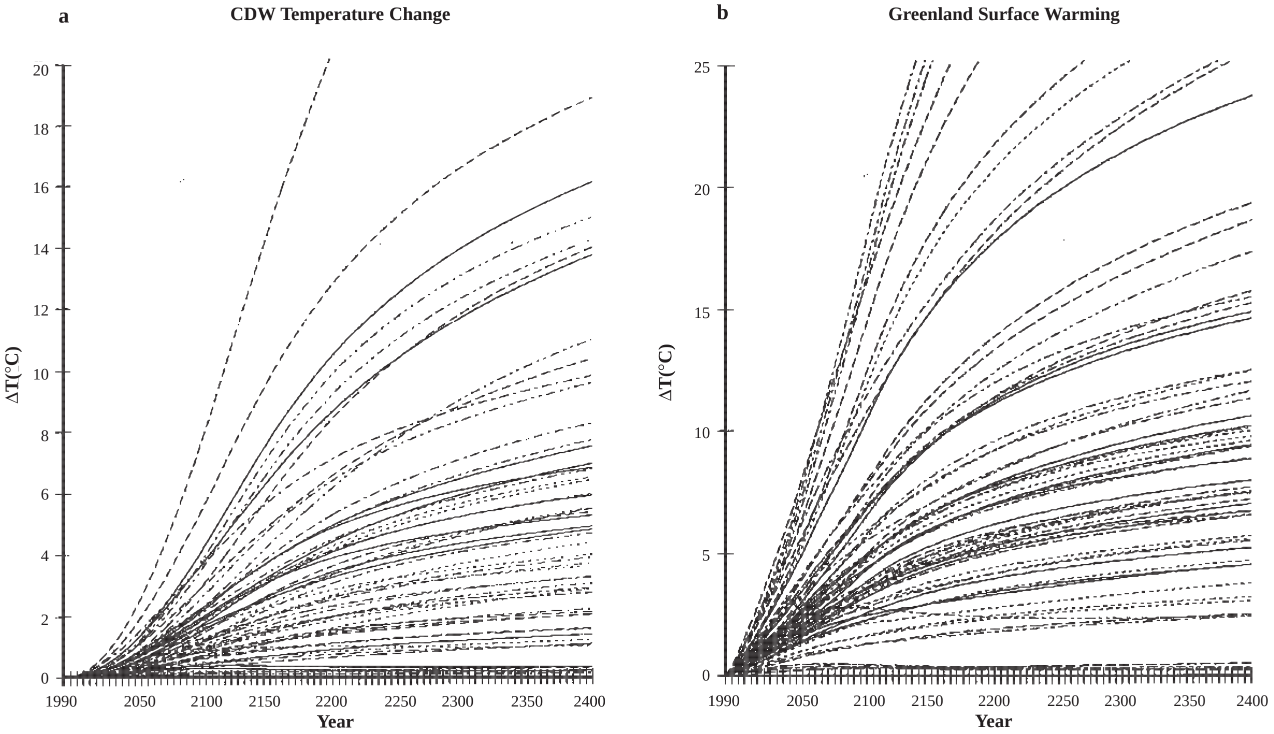
Figure 3-11 shows the warming of Greenland, Antarctic air temperatures, and circumpolar deep water for selected simulations. Please note that seven of the curves shown are from the upper 1 percent of all simulations. In spite of the occasional extreme simulation, for example, the 1%-high scenario resulted in a circumpolar ocean warming of about 6.5˚C during the next 200 years, less than half the 1%-high for global warming.

Expert Judgment

Our final results are based on the subjective distributions provided by expert reviewers for the various parameters; Table 3-5 lists the eight expert reviewers who examined the draft report and provided distributions for the climate assumptions other than precipitation.

Even though this final report is based on reviewer-specified distributions, we have focused on the initial distributions of the draft report for two reasons. First, the reviewers were reacting to an initial draft; so those desiring to scrutinize the methods and results of this report can only do so by considering the initial specifications to which the reviewers were reacting. Second, the initial distributions retain a residual relevance. In several cases, a given reviewer would find that, for a given parameter, our specifications were adequate: that is, while the reviewer would not have selected precisely the same values that we specified, she did not believe that her specifications would have been sufficiently different for alternative specifications to be worthwhile.

All but one of the reviewers were participants in the IPCC (1990) Science Assessment. Our reasons for selecting these reviewers were that we wanted (a) repre-



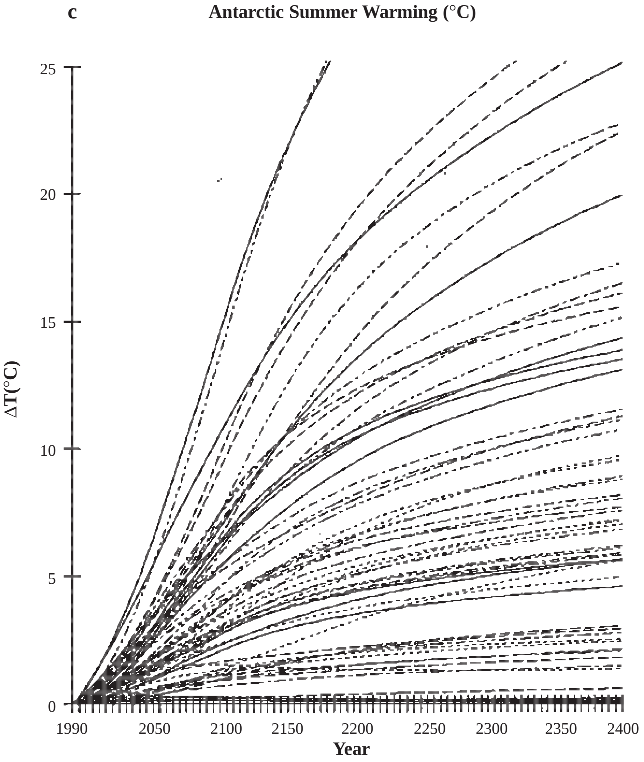


Figure 3-11. Polar Warming for Selected Simulations for the Period 1990–2400: Draft Report. These spaghetti diagrams illustrate warming of (a) circumpolar deep water, (b) Greenland air temperatures, and (c) Antarctic air temperatures. (See Figure 2-5 and accompanying text for explanation.)

TABLE 3-5
EXPERT REVIEWERS OF CHAPTER 3 (excluding precipitation)

Robert Balling	Arizona State University	Tempe, AZ
Francis Bretherton	University of Wisconsin	Madison, WI
Martin Hoffert	New York University	New York, NY
Michael MacCracken	Lawrence Livermore National Laboratories	Livermore, CA
Syukuro Manabe	NOAA/Princeton Geophysical Fluid Dynamics Laboratory	Princeton, NJ
David Rind	NASA/Goddard Institute for Space Studies	New York, NY
Stephen Schneider	National Center for Atmospheric Research	Boulder, CO
Sarah Raper	Climate Research Unit, University of East Anglia	Norwich, UK
Tom Wigley	University Center for Atmospheric Research	Boulder, CO

sentatives from the major general circulation models and (b) those with experience using one-dimensional models to project transient climate change. All of the major modeling groups were invited to participate, as were all of the authors of the IPCC chapter on time-dependent climate change. Almost all of the U.S. scientists contacted agreed to participate. We were less successful in securing the reviews of foreign modeling experts, with two notable exceptions: Tom Wigley and Sarah Raper from the University of East Anglia[24] provided a set of probability distributions based on a probability analysis that they had performed but not published. John Church from CSIRO in Australia offered to provide simulations from his model of thermal expansion, an offer that our time and budget constraints unfortunately prevented us from implementing.

There is an important difference between the ways that scientific assessments (*e.g.*, NAS 1979; IPCC 1990) and Delphic probability analyses choose models and parameter values. Scientific "assessments" usually are more than passive assessments; they often attempt to forge a consensus. As a result, in addition to providing a guide to policymakers, they have a feedback on the evolution of science. In a Delphic probability analysis, by contrast, we take the science as we find it. If the experts disagree, we make no effort to broker a compromise or pick the theory that is most likely to be correct—we simply try to ensure that the simulations reflect the fact that there is a difference of opinion. Thus, while the need to forge a consensus tends to discourage assessment panels from including those with dissenting views, such inclusion is essential in a Delphic analysis, lest the results artificially "compress the tails of the distribution" (*i.e.*, lest we mislead the reader regarding how certain the future really is).

For purposes of this chapter, the most important group of dissenting scientists are those who believe that the "mainstream" drastically overestimates the likely warming resulting from greenhouse gases. Since the original NAS (1979) assessment was published, Sherwood Idso of the U.S. Department of Agriculture in Tempe, Arizona has published dozens of publications disputing the estimate that a doubling of CO_2 would warm the Earth 1.5 to 4.5˚C. The second NAS (1982) assessment devoted about 10 percent of the main body of its report to taking issue with the findings of Idso and other dissenters.[25]

Nevertheless, there is a group of rational scientists that rejects the consensus view that the Earth will warm 1.5 to 4.5˚C from a CO_2 doubling and who (1) have an internally consistent theory for rejecting the consensus view, (2) are continually analyzing empirical data on the question, and (3) have a theory that will be

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[24] Tom Wigley subsequently relocated to the University Corporation for Atmospheric Research in Boulder, Colorado.

[25] Our own studies of climate impacts (*e.g.*, Barth & Titus 1984; Titus 1986; Titus 1991; Titus et al. 1991; Titus 1992) have generally attributed little information content to the dissenters; but our recommendations for coastal policies have always assumed that there is a substantial chance that the rise in sea level will be negligible.

impossible to completely prove or disprove for at least a decade. Two dozen of them met in 1990 and developed a proposed research agenda (Balling et al. 1990). Therefore, we asked Robert Balling of Arizona State University to review the draft report and provide comments reflecting the viewpoints of this important group of "greenhouse skeptics."

What is the most reasonable way of combining the different distributions suggested by the reviewers? It depends on where one draws the boundaries of "expertise." If we had been able to incorporate the judgments of fifty or sixty reviewers of this chapter, we might have defined "expert" on a parameter-specific basis. Thus, for example, the estimate for π might have been based primarily on the judgments of one-dimensional modelers such as Martin Hoffert and Wigley & Raper, while the estimates for ΔT_{2XCO2} would be based on the opinions of three-dimensional modelers such as David Rind and Syukuro Manabe. With only eight reviewers, however, such a procedure would leave us with only one or two opinions for most of the parameters.

At the other extreme, we might have secured the opinions of each reviewer for every parameter in the entire study; but such an approach would go too far in the other direction. Therefore, we divided the reviews by chapter and weighted the assessments of each reviewer equally; for example, there are 1250 simulations drawing from the distributions preferred by each of the eight reviewers listed in Table 3-4. When the reviews came in, it became apparent that some of the glaciologists reviewing Chapters 4 and 5 had expertise regarding polar precipitation changes, while several of the climate reviewers chose not to comment on precipitation. Therefore, precipitation is considered separately later in this chapter.

We now describe the probability distributions requested by the expert reviewers. Table 3-6 summarizes the most important assumptions.

Climate Sensitivity

With the exception of Robert Balling, all of the reviewers accepted the 1.5 to 4.5˚C range as the equilibrium surface warming from a CO_2 doubling; most reviewers accepted our initial characterization of this range as σ limits. Wigley & Raper suggested treating this range as a 90 percent confidence interval (*i.e.*, 1.5 and 4.5˚C are 1.65σ limits) due to the information that has accumulated since the original NAS (1979) report. Manabe agreed that 1.5 to 4.5˚C is a reasonable estimate of a 90 percent confidence range for how a randomly chosen general circulation model would respond to CO_2 doubling. However, because the future response of the actual atmosphere is less certain than the response of a climate model, Manabe suggested that we retain the assumption that 1.5 and 4.5˚C represent σ limits, not the 90-percent confidence interval. MacCracken agreed with Manabe's assessment, largely because the general circulation models do not currently include mode switching or ozone chemistry.[26]

Robert Balling concluded that, based on Idso & Balling (1991), ΔT_{2X} should be normally distributed with a mean of 0.35 and σ limits of 0 and 0.7. Balling was also concerned that the draft report suggested that there was no chance that the Earth would cool. Because a negative climate sensitivity is impossible given the scheme of a one-dimensional upwelling/diffusion model, we set negative values equal to zero. Neverthe-less, we incorporated the possibility of cooling by adding to all simulations a stochastic component, which we discuss below.

We also had to make a nonstandard interpretation of climate sensitivity to faithfully incorporate Balling's suggestions. One-dimensional models assume that the initial forcing from a CO_2 doubling is 4.4 W/m^2 regardless of climate sensitivity—enough to warm the Earth 1.2˚C in equilibrium—and that the remaining forcing results from climate feedbacks that increase linearly with temperature. As a result, to the extent that the deep oceans delay the warming from an increased forcing, they also delay the increased forcing associated with those feedbacks, further delaying the actual warming in high scenarios. For climate sensitivities less than 1.2˚C, however, the effect is the opposite: negative feedbacks increase with temperatures. Thus, the model would show an initial increase in radiative forcing followed by a decline in forcing over time. The Idso & Balling study, however, is based on the assumption that climate warming has at most a trivial delay.[27] To be consistent with this assumption, our Balling simulations adjust direct forcing downward and assume no long-term temperature-driven feedback; in the extreme case where climate sensitivity is zero, we simply assume no change in greenhouse forcing.

Baseline Stochastic Variability

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[26] However, MacCracken did suggest that we truncate the distribution at an upper limit of 9˚C, given the lack of evidence that the warming could be greater.

[27] In effect, Idso & Balling assume that the negative feedbacks occur rapidly (*e.g.*, the feedbacks are *forcing-dependent*).

TABLE 3-6
GLOBAL CLIMATE AND POLAR TEMPERATURE ASSUMPTIONS

	Balling	Bretherton/ Draft	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley[c] & Raper
GLOBAL CLIMATE PARAMETERS								
ΔT_{2X}								
σ-low	0.0[n,t0]	1.5	1.5	1.5	1.5	1.5	1.5	1.86[c]
σ-high	0.7[n]	4.5	4.5	4.5[t9]	4.5	4.5	4.5	3.62[c]
π								
2σ-low	0.2[d]	0.2[d]	0.2,P_{Green}	0.04	0.2	P_{Green},0.0	0.2	–0.04[c]
2σ-high	1.0[d]	1.0[d]	1.0,P_{Green}	1.0[t1]	0.2	P_{Green},1.0	1.0	0.58[c]
$\mathbf{w}/\mathbf{w}_0$ given $\Delta T = 4^\circ C$ (in cases where **w** changes)								
2σ-low	0.27[d]	0.27[d]	0.27, 0.075	0.27	0.4	0.2	0.27, 0.2	N.A.
2σ-high	1.0[d]	1.0[d]	1.0, 0.445	1.0	0.4	1.8	1.0, 1.8	N.A.
PROBABILITY OF ALTERNATIVE SPECIFICATIONS OF CHANGES IN UPWELLING								
OM1	50[d]	50[d]	50	35	0	80	50	100
OM2	50[d]	50[d]	0	35	0	5	20	0
OM2.1	0	0	0	0	0	5	15	0
OM3	0	0	0	30	0	5	10	0
OM4	0	0	0	0	0	5	5	0
OM5	—	—	50	—	—	—	—	—
OM6	—	—	0	—	100	—	—	—
POLAR TEMPERATURE CHANGES								
P_{Ant}								
σ-low	0.67[d]	0.67[d]	2.38[c]	0.5[n]	0.67[d]	1.63[c]	0.5	0.62[c]
σ-high	1.5[d]	1.5[d]	3.36[c]	1.5[n]	1.5[d]	2.45[c]	2.0	1.21[c]
P_{cdw}								
σ-low	0.25[d]	0.25[d]	1.0–2.0[h]	0.25[d]	1.0	1.0	0.5	N.A.
σ-high	1.0[d]	1.0[d]	1.0–4.0[h]	1.0[d]	1.0	3.0	2.0	N.A.
τ_{cdw} (years)								
σ-low	20[d]	20[d]	57[c]	20[d]	100	80?	20?	N.A.
σ-high	80[d]	80[d]	131[c]	80[d]	300	90?	80?	N.A.
$P_{Greenland}$								
2σ-low	1.0[d]	1.0[d]	1.0–2.0[h]	0.5	0.5	1.0	0.5	0.93[c]
2σ-high	2.0[d]	2.0[d]	1.0–4.0[h]	2.0	1.0	3.0	3.5	2.15[c]

OM1: The original Wigley & Raper (1992) specification with fixed $\mathbf{w}=\mathbf{w}_0$ and specified distribution of π.
OM2: **w** declines geometrically: $\mathbf{w}=\mathbf{w}_0\,(1-\theta)^{\Delta T}$; $\theta>0$.
OM2.1: **w** increases geometrically: $\mathbf{w}=\mathbf{w}_0\,(1-\theta)^{\Delta T}$; $\theta<0$.
OM3: **w** declines suddenly by 80 percent when ΔT exceeds a threshold T_w. The threshold is between 1 and 4˚C, with the higher values more likely; the cumulative probability distribution is: $F(T_w)=(T_w-1)^2/9$ for $1<T_w<4$.
OM4: **w** increases suddenly by 80 percent when ΔT exceeds the threshold T_w, whose distribution is the same as in OM3.
OM5 **w** and π are fixed for the first 1˚C of warming, after which **w** declines linearly to 0.05 $\mathbf{w}_0$ by the time ΔT reaches a threshold T_w. π increases linearly from its initial value to the (transient) polar amplification parameter by the time T reaches T_w. T_w is uniformly distributed between 4 and 6˚C.
OM6 π is fixed at 0.2, and **w** declines *linearly* with temperature: $\mathbf{w}=(1-0.15\Delta T)\,\mathbf{w}_0$ for $0<\Delta T<6$, and $\mathbf{w}=0.1$ for $\Delta T>6$.
$P_{Green} = P_{Greenland}$
c Reviewer’s estimate was a “round number” but specified with respect to a different probability level than σ or 2σ used here.
d Did not disagree with the draft’s suggested value, but did not explicitly endorse parameter value either.
— Reviewer did not consider OM5 and/or OM6; those options were proposed *sua sponte* by Hoffert and Manabe, respectively.
h Hoffert assumes that P=1 for $\Delta T<1$. For $1<\Delta T<T_w$, he assumes that P_{Green} and dT_{cdw}/dT (as opposed to P_{cdw}) rise linearly to a maximum value as shown. T_w is uniformly distributed between 4 and 6˚C.
n Normal distribution.
r Rectangular (uniform) distribution with limits as specified.
tN Distribution truncated at a value of N.
? Rind and Schneider subsequently revised their estimates of τ to 20–100 and 20–200, respectively. Although these revisions have offsetting impacts on median T_{cdw} projections, they would broaden the range somewhat.

In response to Balling's comments, we also polled the various reviewers on the best way to characterize a baseline nongreenhouse forcing. IPCC (1990) points out that there has been a variation of about 0.3˚C on a century time scale, and that another 0.3˚C variation could result from anthropogenic aerosols.

Comments forwarded by the Dutch Delegation to the IPCC suggested that we use the autoregressive-moving average (ARMA) approach popularized by Box & Jenkins (1976). For example, the Dutch noted that Tol & Vos (1993) fit the following model:

$$\Delta T = -4.6 + 0.015\ CO_2(t-20) + \varepsilon(t),$$

where

$$\varepsilon(t) - 1.07\ \varepsilon(t-1) + 0.18\ \varepsilon(t-2) = u(t) - 0.68\ u(t-1) - 0.67\ u(t-2),$$

$u(t)$ is random noise with σ_u=0.11˚C, and (**t**) represents the average value of a particular variable during the year **t**.

There are two ways to fully implement this model: (1) use the ARMA model estimated by Tol & Vos or (2) fit a one-dimensional model to the historic data while simultaneously estimating an ARMA model of the residuals. We lacked the time to do the latter, which in any event might have required a different ARMA model for each value of π and ΔT_{2X}. We also decided not to use the Tol & Vos parameter estimates directly: Their model implies a decadal variation of 0.16˚C, which only increases to about 0.176˚C for time scales of a century and longer, which is too small.[28]

Therefore, we adopt a simpler approach: A first-order autoregressive model describing a random component that we add to the mixed-layer temperature calculated by the 1-D model at the end of each time period:

$$\text{noise}(t) = 0.9975\ \text{noise}(t-1) + u(t),$$

where σ_u=0.011˚C and u is normally distributed. Although **noise**(**t**) is expressed in terms of temperature, for practical purposes we are assuming that there is a serially correlated atmospheric forcing that causes the 1-D model to miss the surface temperature in time period **t** by **noise**(**t**). Like other forcings, the noise is propagated downward during succeeding years. Figure 3-12 compares ocean model runs for IPCC (1992) emissions scenario A, with and without the noise forcing for a random series of u over the period 1765–2065.

The figure also illustrates the potential increase in uncertainty due to factors other than greenhouse gases and aerosol forcing. This uncertainty increases from the annual variation of 0.011˚C that we took from Tol & Vos, to 0.1˚C on a decadal time scale, 0.4˚C on a century time scale, 0.55˚C on a two-century time scale, and 0.62˚C on a four-century time scale.[29] This assumption seems reasonable: Although modeling by Wigley & Raper (1990) suggests natural variability of about 0.3˚C/century, increases or decreases on the order of 0.5˚C/century appear to occur about three times per millennia.[30]

Ocean Model

All eight reviewers agreed with the fundamental approach of using the Wigley & Raper one-dimensional model to project transient temperatures and thermal expansion.

Nevertheless, David Rind questioned our sole reliance on this model, on the grounds that 1-D models inherently provide a limited view of the spatial distribution of ocean temperature changes. For example, the GFDL and Church et al. (1991) models appear to result in more thermal expansion for a given warming than does the Wigley & Raper model. Our futile efforts in Figure 3-6 to pick combinations of π and θ that duplicate both transient temperature and thermal expansion from the GFDL model, he suggested, further highlight the inability of 1-D models to adequately summarize the insights available from 3-D models. Still, given the unfeasibility of running 3-D models in this exercise, he agreed that it was a good idea to fit 1-D models into 3-D results, but that we should do so for several models. We agreed with this suggestion and had planned to implement it; but unexpected budgetary limitations forced us to defer doing so until a subsequent analysis.

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[28] Their purpose in estimating the ARMA model was to remove short-term noise to get a better parameter estimate for the coefficients relating temperature to CO_2. By contrast, our objective here is solely to characterize the century-scale variation, as long as we do not severely overstate the short-term variation.

[29] By itself, the autoregressive equation we have used would simply increase as follows: $\sigma_{noise,t}=(0.0112+\sigma_{noise,t-1})^{1/2}$, which would imply values of 0.03, 0.1, and 0.13˚C. But the 1-D model's lag between forcing and temperature response further increases the effective serial correlation.

[30] *See e.g.,* IPCC (1990) at Fig. 7.1; and Schneider (1994) at 346.

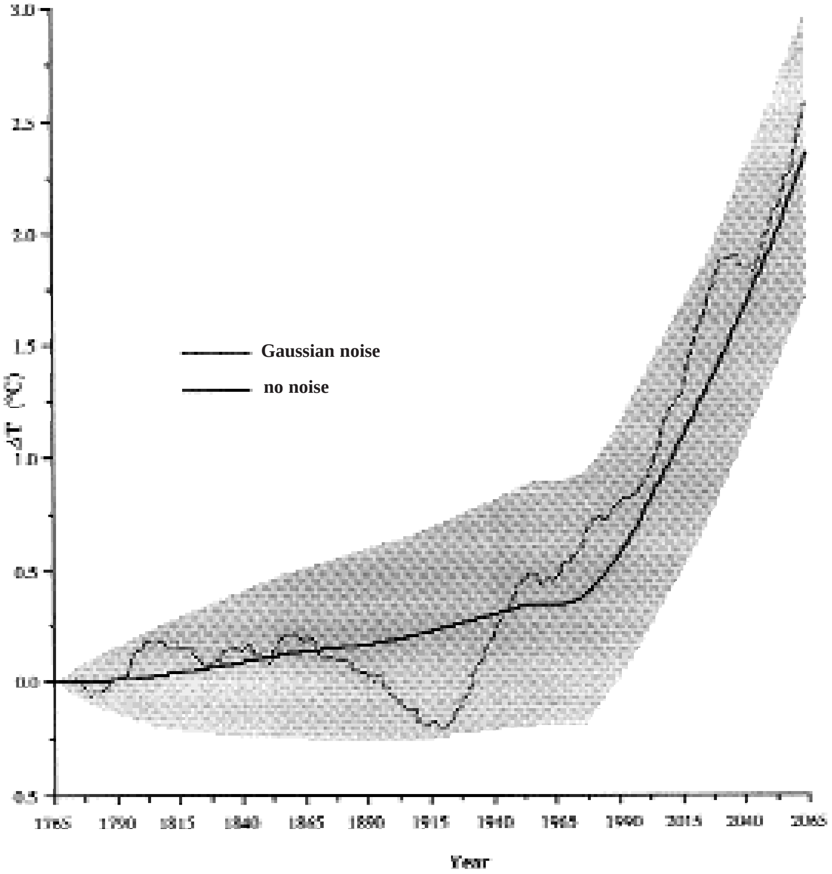

Figure 3-12. Surface Temperatures 1765–2065, With and Without an Illustrative Serially Correlated Nongreenhouse Forcing. The shaded area illustrates the σ limits of the nongreenhouse forcing; variation increases from 0.1°C on a decadal time scale to 0.4°C on a century time scale. All scenarios are based on IPCC (1992) emissions scenario A.

Robert Balling and Francis Bretherton concluded that they might have selected different parameter distributions had they undertaken the analysis, but that the initial values in the draft report were close enough to what they would have chosen. Thus, they decided that additional specification on their part would not be worthwhile. The other six reviewers had extensive comments on both the model specifications and the actual parameters employed.

Model Specifications. While the draft report switched between two alternative specifications, the expert reviewers suggested a total of seven different ocean models:

OM1 The original Wigley & Raper (1992) specification with fixed $\mathbf{w}=\mathbf{w}_0$.

OM2 Like the draft report's variable-**w** model, that is, **w** changes geometrically: $\mathbf{w}=\mathbf{w}_0\,\theta^{\Delta T}$. But unlike the draft report, where $\pi=0.2$, π is also drawn from a distribution.

OM2.1 The same as OM2, but θ is greater than 1.0 and thus upwelling increases.

OM3 **w** declines suddenly by 80 percent when ΔT exceeds a threshold T_w. The threshold is between 1 and 4°C, with the higher values more likely; the cumulative probability distribution is: $F(T_w)=(T_w-1)^{2/9}$ for $1<T_w<4$.

OM4 **w** increases suddenly by 80 percent when ΔT exceeds the threshold T_w, whose distribution is the same as in OM3.

OM5 **w** and π are fixed for the first 1°C of warming, after which **w** declines linearly to 0.05 $\mathbf{w}_0$ by the time ΔT reaches a threshold T_w. π increases linearly from its initial value to the (transient) polar amplification parameter by the time T reaches T_w. T_w is uniformly distributed between 4 and 6˚C.

OM6 Very similar to the draft report's variable-**w** model. π fixed at 0.2, and **w** declines *linearly* with temperature: $\mathbf{w}=(1-0.15\Delta T)\mathbf{w}_0$ for $0<\Delta T<6$, and $\mathbf{w}=0.1$ for $\Delta T>6$.

We discuss the specifications from each of the reviewers in turn.

Wigley & Raper recommended that we run their initial specification (OM1) for all of the simulations. While acknowledging the possibility that **w** would change over time, they did not believe that such an assumption would improve the projections. They suggested higher values of **k** (and hence $\mathbf{w}_0$): median of 1 cm^2/sec (3154 m^2/yr) with 90 percent (1.65σ) limits of 0.5 and 2.0 cm^2/sec (1576 and 6307 m^2/yr). For reasons discussed in Wigley & Raper (1991), they believe that low values of π are appropriate even with a fixed upwelling velocity. They recommend a shifted lognormal distribution, in which $\pi+0.4$ is lognormal with a median of 0.6 and 1.65σ limits of 0.4 and 0.9; the net effect of this assumption is that (a) the median is 0.2 and (b) 90 percent of the observations are between 0 and 0.5.

Syukuro Manabe also favors low values of π, but believes that downwelling is likely to decline. He recommends that we use a value for π of 0.2 and assume that **w** would decline as suggested by a graph published in Manabe & Stouffer (1993). We fit a linear regression equation of downwelling on transient temperature, which yielded a coefficient of 15 percent per degree (C), down to the point where downwelling has declined by 90 percent. We refer to this set of assumptions as OM6.

Michael MacCracken was the first of several reviewers to note the possibility of a sudden decline in bottom-water formation, suggesting that the probability of such a switch would rise to about 30 percent for a 4˚C warming; he accepted David Rind's functional specification regarding the uncertainty of the threshold T_w, *i.e.*, OM3, discussed below. MacCracken assumed that the fixed-**w** specification OM1 and the variable-**w** specification OM2 should each be used 35 percent of the time. For all three models, π has a median of 0.2 and 2σ limits of 0.04 and 1, with the distribution truncated at 1. For OM2, MacCracken retained the initial assumptions of the draft report that θ has a median of 0.85 (*i.e.*, **w** declines 15%/˚C) and 2σ limits of 0.72^2 (*i.e.*, 0.852) and 1.

MacCracken also explicitly assumed a 0.5 correlation between π and θ, which implies that lower values of π are accompanied by a greater decline in downwelling. This assumption was motivated in part by comparing his own comments with those of David Rind. He observed that there appear to be two schools of thought on what will happen with deepwater formation.

Some scientists, such as MacCracken and Manabe, believe that decreased Antarctic sea ice or increased high latitude precipitation could cause a decline in deepwater formation. The water that does sink will warm much less than the global average because (a) downwelling in the Southern Hemisphere continues to be caused largely by seaice formation, and (b) the North Atlantic Deep Water cannot sink if it warms too much (compared with the temperature of the thermocline). This view implies that π is low and that upwelling is sensitive to temperature.

Others view the downwelling as driven by a conveyor that is influenced by the equatorial upwelling, which could conceivably *increase* due to the enhanced evaporation at higher temperatures. Thus, polar waters could continue to sink even at higher temperatures. This view implies a higher value of π but a lower decline—and possibly even an increase—in downwelling.

David Rind preferred to assume a fixed **w** (OM1) 80 percent of the time. He divided the remaining 20 percent of simulations equally between (a) OM2, with a gradual decrease in **w**, using a median and 2σ limits for θ as specified in the draft report; (b) OM2.1, with its gradual increase in **w**, using a median and 2σ limits equal to the reciprocal of those specified for OM2; (c) OM3, with its sudden 80 percent decrease in upwelling; and (d) OM4, with its sudden 80 percent increase in upwelling. Rind's justification for the 80 percent change in upwelling was that deepwater formation apparently was 80 percent less during the last ice age. For both OM3 and OM4, he suggested that the probability density of a sudden change in upwelling should increase linearly from zero, for a warming less than 1˚C, to a maximum which is reached at 4˚C—hence the quadratic cumulative distribution function.

Unlike the previous reviewers, Rind recommended relatively high values for π. In the Northern Hemisphere, π_{NH} is perfectly correlated with the polar amplification parameter and lognormally distributed with 2σ limits of 1 and 3; in the Southern Hemisphere, π_{SH} is uniformly distributed between 0 and 1. Because only 20 percent of the downwelling occurs in the Northern Hemisphere, the net effect is that the global π has a median value of about 0.75.

Stephen Schneider made structurally similar recommendations, although he allocated the probabilities differently: OM1—50%; OM2—25%; OM2.1—10%; OM3—10%; and OM4—5%. For all cases, he used the initial distribution that the draft report applied for OM1; for example, π had a lognormal distribution with 2σ limits of 0.2 and 1.

Martin Hoffert favored devoting 50 percent of the simulations to OM1, using the initial assumptions of the draft report for all of the ocean model parameters. Based on Hoffert (1990), he allocated the remaining 50 percent to OM5. This model assumes that π and **w** are fixed for $\Delta T<1^\circ C$. For $1<\Delta T<T_w$, **w** declines linearly; for $\Delta T>T_w$, w remains fixed at 7.5 percent of its initial value $\mathbf{w}_0$.[31] Although Hoffert (1990) suggested that $T_w=4^\circ C$, for purposes of this study Hoffert suggests that T_w is uniformly distributed between 4 and 6˚C.

Hoffert also assumes a gradual increase in the value of π. For $\Delta T<1^\circ C$, $\pi=1.0$. For $\Delta T>T_w$, Hoffert sets π equal to the transient polar amplification; *i.e.*, sinking water warms by the same amount as circumpolar ocean water. For $1<\Delta T<T_w$, π rises linearly between 1 and the polar amplification associated with a global warming of T_w. Thus, sinking water temperatures warm by the same amount as global temperatures for a warming less than 1˚C; but as ΔT approaches T_w, the rise in sinking water temperatures gradually approaches the warming of the polar ocean water. Because of the drastic declines in **w**, however, the practical importance of π declines as ΔT rises from 1 to T_w.

Greenland Temperature

Most of the reviewers thought that Greenland is likely to warm more than the global average,[32] but most wanted some change to our initial assumption that P_7—the Greenland amplification parameter—has 2σ limits of 1 and 2. Wigley & Raper suggested that this range be viewed as 1.65σ (90 percent) limits. At the high end, Martin Hoffert suggested that Hoffert & Covey (1992) implies 2σ limits of 2 and 4 times the average global warming; Stephen Schneider suggested 2σ limits of 0.5 and 3.5. Noting that summer warming could be less than the annual average warming and that high altitude warming could be less than warming at sea level, Mike MacCracken suggested 2σ limits of 0.5 and 2.

At the low end of the spectrum, Syukuro Manabe suggested σ limits of 0.5 to 1, noting that the reduced North Atlantic deepwater formation projected by the GFDL model would reduce the warming from the Gulf Stream. In the cases where **w** declines drastically (OM3), David Rind made the similar assumption that $P_7=0.5$. Otherwise, he suggested that 2σ limits of 1 to 3 are more appropriate. Nevertheless, in cases where **w** changes gradually, he assumes a 0.5 correlation between θ and P_7, implying that low polar amplification accompanies reductions in deepwater formation. Rind points out that, according to IPCC (1990), Green-land was about 4˚C warmer during the Eemian interglacial when global temperatures were 1 to 2˚C warmer (Velichko et al. 1982). Moreover, during the Pliocene (3.3 to 4.3 million years ago), Greenland summers were 10˚C warmer than today, while the mid-latitude Northern Hemisphere summers were only 3 to 4˚C warmer (Budyko & Izrael 1987). Finally, during the Holocene climatic optimum, Greenland summer was about 3˚C warmer than today, while the mid-latitude regions were only about 1˚C warmer than today (Budyko & Izrael 1987).

Although David Rind was the only reviewer to explicitly suggest a correlation between P_7 (Greenland amplification) and θ (the change in downwelling), the combined impact of the reviewer assumptions also bears out such a correlation. Manabe and MacCracken see substantial declines in **w** and relatively low polar amplification. Wigley & Raper's simulations and 80 percent of Rind's simulations have no change in **w** and relatively large polar amplification. Schneider shows a slightly greater tendency for a decline in **w** than Rind, as well as a slightly lower polar amplification. Only Hoffert falls outside of this pattern, expecting a sharp decline in sea ice, which would contribute both to a high polar amplification and a large drop in downwelling.

All of the reviewers agreed with our assumption

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[31] Hoffert justified this assumption, like most of his comments, on the paleoclimatic record. Specifically, based on the Cretaceous period, he estimates that the ratio $(T_b-T_p)/(T_m-T_p)$ did not rise above 10/18, where $\mathbf{T_b}$ is the bottomwater temperature, $\mathbf{T_p}$ is the polar ocean temperature, and $\mathbf{T_m}$ is the mixed-layer temperature. Solving the 1-D model for its equilibrium depth-temperature profile, Hoffert finds that the ratio of 10/18 is consistent with a 92.5 percent decline in upwelling.

[32] *But cf.* Karl et al. (1995, in press) at Figure 2 (Greenland has cooled—perhaps due to sulfate aerosol forcing—as global temperatures warmed over last half century).

that Greenland warming would not lag significantly behind global warming. Martin Hoffert, however, assumes that polar amplification would initially be less than P_7. To be consistent with Hoffert (1990), he suggested that the amplification factor is 1.0 for the first degree of warming. He treats P_7 not as an equilibrium amplification factor, but rather as what the amplification factor would be once $\Delta T > T_w$. He then assumes that as ΔT increases from 1.0 to T_w, the polar amplification factor increases linearly from 1.0 to P_7. For example, if $T_w=5$ and $P_7=3$, then $\Delta T=1$, 2, and 3˚C imply amplification factors of 1, 1.5, and 2, resulting in $\Delta T_{Greenland}=1$, 3, and 6˚C, respectively. Thus, Hoffert's assumptions imply a Greenland warming similar to the projections of Manabe for the first degree, Wigley & Raper for the second degree, and Rind for the third degree. After that point, Hoffert's assumptions imply much greater warming for Greenland than any of the other reviewers.

Antarctic Air Temperatures

The Antarctic contribution to sea level depends on changes in both air and water temperatures. As discussed in Chapter 6, the melting of Antarctic ice shelves is assumed to respond to both declines in sea ice and warmer water temperatures. Warmer air temperatures contribute both to declines in sea ice, discussed in the previous section of this chapter, and the countervailing impact of increased precipitation, discussed in Chapter 3B.

Most of the reviewers focused on the more important Antarctic water temperatures and let stand our initial draft assumptions for the equilibrium southern polar amplification and the speed at which the adjustment takes place. MacCracken suggested that declines in Antarctic sea ice could possibly allow summer air temperatures to cool; therefore, he suggested that we use a normal distribution with σ limits of 0.5 and 1.5 for the summer amplification parameter P_1, which implies a 2 percent chance that Antarctic summers will cool if global temperatures warm. Wigley & Raper also suggested a range of 0.5 to 1.5, albeit for a lognormal distribution and 90-percent limits. Schneider retained our initial assumptions for winter warming; he thought that summer warming was most likely to be equal to average global warming, but suggested 2σ limits of 0.5 and 2 times the global warming. Hoffert, by contrast, suggested 2σ limits of 2 and 4, consistent with his Northern Hemi-sphere assumptions. Rind assumed a median amplification of 2, with 2σ limits of 1.33 and 3.

Hoffert and Wigley & Raper were the only reviewers to change the simple first-order linear adjustment by which Antarctic temperatures respond to transient global temperatures. Hoffert adopted the specification that he employed for Greenland temperatures. Wigley & Raper assumed no additional lag.

Circumpolar Ocean Warming

The reviewers generally agreed with the draft report's assumption that circumpolar ocean temperatures will respond more slowly than Antarctic and Greenland air temperatures. Three of the reviewers suggested no change to our initial assumptions of an amplification (P_3) with σ limits of 0.25 and 1.0, along with an adjustment time (P_4) with 2σ limits of 20 and 80 years. Manabe suggested that the circumpolar ocean will eventually warm as much as the global average warming, but with an adjustment time of 100 to 300 years (σ limits). For the year 2100, this assumption yields about the same circumpolar warming as our initial median assumptions.

Three of the reviewers, however, suggested substantially higher sensitivities than reflected in the initial draft report. Schneider agreed with Manabe that the most likely long-term amplification would be 1 but retained our initial assumptions regarding the likely lag. He also suggested a relatively wide uncertainty range, involving 2σ limits of 0.5 and 2. While agreeing with the initial adjustment times from the draft report, he added that the adjustment would be (relatively) slower in cases where the warming is more rapid. Therefore, he suggested a 0.5 correlation between the adjustment time and both emissions and temperature sensitivity.

Rind and Hoffert both suggested that circumpolar ocean temperatures should warm more than the global average, in equilibrium. Rind suggested 2σ limits of 1 and 3, the same as his suggested range for air temperatures. He noted, however, that the North Atlantic deep water tends to stabilize both sea ice and circumpolar water temperatures, so that very little warming could occur until warmer North Atlantic water arrived. Based on Broecker & Takahashi's (1981) estimate that it takes 80 to 90 years for deep water to arrive from the North Atlantic, Rind specified an absolute lag of 80 to 90 years; *i.e.*, rather than assuming a linear adjustment in which some warming occurs immediately, he assumed that the global warming in a given year alters the circumpolar ocean temperatures 80 to 90 years later.

Hoffert also suggested that the impact of global warming on water temperatures could eventually be as great as the impact on air temperatures. As with polar air temperatures, however, he assumed that the amplification factor starts out at 1 and rises with temperatures up to a maximum value of P_3, as ΔT rises from 1 to T_w; P_3 has 2σ limits of 2 and 4. However, unlike air temperatures, where the amplification factor is the ratio $\Delta T_{polar}/\Delta T$, for water temperatures this amplification factor represents the derivative dT_{cdw}/dT. For example, for his median assumptions of P_3=3 and T_w=5, and using values of ΔT=1, 2, and 3˚C, his assumptions imply derivatives of 1, 1.5, and 2, and ΔT_{cdw}=1, 2.25, and 4˚C, respectively. For a warming of 5˚C, however, Hoffert's median assumptions imply equilibrium circumpolar ocean warming of 7˚C. Thus, Hoffert assumes that for each degree of global warming, the circumpolar ocean warms in equilibrium by less than the polar air temperatures, until $\Delta T=T_w$. At this point, Hoffert assumes that permanent sea ice would disappear, removing the primary process that prevents the circumpolar ocean from warming as much as polar air temperatures. Hoffert assumes that the circumpolar ocean warming lags behind global warming with a linear adjustment. He assumes a median e-folding time of 86 years, with 3σ limits of 25 and 300 years, which implies 2σ limits of approximately 40 and 200 years. Thus, Hoffert, Rind, and—to a lesser extent—Manabe expect greater equilibrium warming of the polar ocean than assumed in the draft report; but they also expect a slower adjustment.

Sea Ice

Only two of the reviewers recommended a change in our sea ice assumptions. Rind suggested that, for the most part, the Parkinson & Bindschadler (1982) study (*i.e.*, a 5˚C warming causes a 50 percent reduction) overestimated the response of sea ice, because it omitted the stabilizing influence of North Atlantic Deep Water. He therefore suggested that it would be more appropriate to assume that the decline is only one-half as great as assumed in the draft report. In the (10 percent) cases where deepwater formation declines, however, this stabilizing influence would be diminished, and thus the initial draft assumptions would be more appropriate.

Hoffert, by contrast, thought that the Parkinson & Bindschadler study *under*stated the decline in sea ice. Hoffert (1990), for example, suggested that a 4˚C global warming would eliminate all of the permanent sea ice. However, because the Antarctic models employed in Chapter 5 depend on annual seaice formation, not the total extent of sea ice, we used the Parkinson & Bindschadler sensitivities for the Hoffert simulations.

Implications of Reviewer Comments for Projecting Sea Level

The net effect of the comments from the reviewers of Chapter 3 is to substantially widen the uncertainty range compared with the initial report. At the low end of the spectrum, the incorporation of Robert Balling's comments ensures that approximately one-eighth of the simulations assume temperature sensitivities (ΔT_{2X}) well below the low end of the consensus range adopted by the NAS (1979), IPCC (1990), and others. The net effect is that the median and mean values of ΔT_{2X} are 2.4 and 2.7˚C (as opposed to 2.6 and 3.0˚C in the draft), with 25 percent of the simulations using values below 1.5˚C.

At the high end of the spectrum, the reviewer comments tend to slightly depress projections of future temperatures. Three of the eight reviewers—Balling, MacCracken, and Wigley & Raper—compressed the upper end of the distribution in some fashion, but the overall effect is relatively small, with 13 percent of the simulations having values of ΔT_{2X} that exceed 4.5˚C, and 5 percent exceeding 6˚C.

The reviewer comments for π and **w** have a greater impact at the high end of the range: The combined comments of Manabe, Hoffert, Rind, Schneider, and MacCracken imply that **w** declines by at least 80 percent for about one-fifth of the simulations in which warming eventually exceeds 5˚C (in addition to the more modest declines that occurred in about half the simulations in the draft report). Given the 0.5 to 0.75˚C cooling that Figure 3-4 shows for the more modest decline in upwelling, this greater decline reduces warming by about 1˚C by the year 2100. In addition, two reviewers suggested substantially higher values of π. For a small warming, the Rind and Hoffert comments imply that about 20 percent of the simulations have a value of π exceeding 0.6, with about 15 percent having a value greater than 1.0. As Figure 3-4 shows, this higher value could decrease warming by about 0.5˚C in the median temperature scenario.[33]

The slower warming, however, is offset by the increased thermal expansion implied by reduced upwelling. As Figure 3-4 shows, even a modest decline in **w** results in a one-third increase in the warming at a depth of 500 m; and the resulting expansion of the thermocline more than offsets the reduced expansion of the mixed layer that results from the smaller surface warming. Higher values of π enable the deep ocean to warm more; a value of π=1 results in 20 percent more expansion after 100 years than a value of 0.2. Thus, five of the

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[33] The 1%-high temperature estimate for the year 2050 from Schneider's assumptions is almost twice the estimate implied by Manabe's assumptions. The only material difference in their assumptions are the values for π and **w**: Schneider allows thermohaline circulation to increase in some scenarios, while Manabe has a substantial decrease. *See* Appendix 1 and Figure 3-13, *infra*.

eight reviewers increased the upper estimates of thermal expansion for a given level of atmospheric forcing by about 15 percent. Of the remaining reviewers, the Balling and Wigley & Raper assumptions both implied substantially lower 1%-high estimates. All of Balling's estimates had low sensitivities, and because of their narrower range for ΔT_{2X} Wigley & Raper also had a downward impact. But these moderating assumptions had a small impact on the high end of the range for the overall assessment, for two reasons. First, these comments removed only about 10 percent of the high-temperature simulations. Second, the mathematics of, for example, a normal distribution are such that even if *half* of the reviewers eliminated *all* of their high-scenario estimates, the overall 1%-high estimates would rise if the other half of the reviewers increased σ by 15 percent.

Perhaps most important, the reviewers expanded the high end of the uncertainty range regarding the polar temperature estimates that the Greenland and Antarctic models use in Chapters 4 and 5. Three of the reviewers substantially increased the high estimates of Greenland temperature sensitivity, outweighing any downward impact on the high end from the revisions suggested by Manabe and MacCracken; the low end of the range was also broadened.

Similarly, half of the reviewers suggested that eventually, the Antarctic circumpolar ocean is likely to warm as much as the Earth's average temperature warms, with three of the reviewers suggesting that the polar water could warm twice as much. Even assuming a lag on the order of one hundred years, such a sensitivity suggests that the Antarctic ocean could warm by 6 to 8˚C in the next two centuries. By comparison, studies of the potential sensitivity of Antarctica have assumed only a 1˚C circumpolar ocean warming (see Chapter 6). If, as the reviewers suggest, there is a significant risk that circumpolar ocean temperatures could warm 4 to 8˚C, recent assessments of the vulnerability of Antarctica may have overlooked the most plausible scenario by which a disintegration of the West Antarctic Ice Sheet could occur.

Final Results

Table 3-7 and Figure 3-13 summarize the cumulative probability distribution for thermal expansion and global temperatures. The net effect of the reviewer suggestions was to lower the median estimate of global warming from 3.1˚C in the draft report down to 2.0˚C. A small part of this lowering resulted from including the Balling estimates; but even when his assumptions are excluded, the median estimate is 2.2˚C. The primary reason the reviewer assumption lowered our estimate is that our median forcing estimate for the year 2100 was 4.9 W/m^2, 20 percent less than the median value from the draft report. At the high end of the spectrum, the temperature estimates are also about one-third lower. As a result of the random forcing, the low end of the distribution includes a 2 percent chance that temperatures will decline.

The median thermal expansion estimates were also lowered by about one-third as a result of the reviewer assumptions. At the high end of the spectrum, however, the reviewer assumptions only decrease the estimate slightly: In those cases, the lower forcing and temperature estimates are mostly offset by the large declines in thermohaline circulation, which enables the thermocline to warm more.

The importance of the different assumptions for π and **w** increases over time. By 2100, the Manabe assumptions imply a median thermal expansion 27 percent greater than the Schneider median, which is depressed by an assumed 20 percent chance of increased upwelling; by 2200, this ratio grows to 37 percent. The difference is reversed for the upper tails of the distribution because some of Schneider's runs have large declines in **w** and high values of π, which increase thermal expansion. Wigley & Raper's low values for π and θ—as well as a narrower range for ΔT_{2X}—result in the least risk of a large thermal expansion. The global temperature projections show small variation across reviewers other than for Balling and Wigley & Raper.

Figures 3-14 and 3-15 illustrate the dynamics of thermal expansion and global temperatures for selected simulations. Between 2060 and 2090, three of the simulations include a sudden decrease in deepwater formation, which results in a global cooling of about 1.5˚C over a ten-year period. For the next century, the rates of warming are mostly between 0 and 0.3˚C per decade; but 5 to 10 percent of the simulations warm more than 0.5˚C during at least one decade. After the year 2100, temperatures continue to rise in all but a few cases; but the rate of warming is less than 0.25˚C per decade in all but a handful of cases. The rates of thermal expansion, by contrast, do not exhibit the deceleration evident for the rate of global warming.[34]

The polar temperature estimates (Figures 3-16 and 3-17) show considerably more variation across review-

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[34] *See* Figure 3-4 and accompanying text for an explanation.

TABLE 3-7
CUMULATIVE PROBABILITY DISTRIBUTION OF GLOBAL WARMING
AND THERMAL EXPANSION OVER 1990 LEVELS

Cumulative Probability (%)	Change In Temperatures (˚C)			Thermal Expansion (cm)		
	2050	2100	2200	2050	2100	2200
1[a]	–0.13	–0.12	–0.17	–0.5	–0.8	–1.6
5[a]	0.12	0.26	0.37	1.1	2.3	3.8
10	0.31	0.57	0.84	2.5	5.1	9.9
20	0.55	1.0	1.6	4.7	10	20
30	0.73	1.4	2.2	6.2	14	28
40	0.88	1.7	2.8	7.4	17	36
50	1.0	2.0	3.4	8.6	20	44
60	1.2	2.4	4.0	9.8	23	52
70	1.4	2.7	4.8	11	26	62
80	1.6	3.2	5.8	13	31	76
90	1.9	4.0	7.4	16	38	99
95	2.2	4.7	9.1	18	45	120
97.5	2.5	5.4	10.9	21	50	139
99	2.9	6.3	12.7	23	58	163
99.5[a]	3.1	6.9	14.1	25	64	181
99.9[a]	5.0	8.7	18.5	32	73	215
Mean	1.08	2.2	3.9	9.7	21	50
σ	0.66	1.4	2.7	3.4	13	36

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

ers than global temperatures and thermal expansion. Manabe's suggested lag of 100 to 300 years, for example, implies that, for the year 2100, Prob($\Delta T_{cdw}<1.0$)=75% and Prob($\Delta T_{cdw}<2.0$)=98%. By contrast, Schneider's more rapid response implies that Prob($\Delta T_{cdw}>1.0$)=80% and Prob($\Delta T_{cdw}>4.0$)=5%. Although Hoffert and Rind believe that, in equilibrium, ΔT_{cdw} could be two to four times ΔT, their long adjustment times keep their estimates of ΔT_{cdw} from exceeding those of Schneider until after 2100. Combining all the distributions, the median estimate of ΔT_{cdw} for the year 2100 is 0.85˚C; and 6 percent of the simulations had values greater than 3˚C. The variation for Greenland temperatures is even greater. Combining all the assumptions, the median estimate for $\Delta T_{Greenland}$ is 2.5˚C, but Green-land temperatures rise more than 10˚C in 2.5 percent of the simulations.

Because the reviewers all assumed that Greenland warming would be a simple multiple of global warming, the dynamics of Greenland temperatures follow the same overall pattern as that of global temperature change (Figure 3-16a). Thus, temperatures in Greenland decline 1.0 to 1.5˚C for the three simulations where deepwater formation declines suddenly.[35] The dynamics of circumpolar ocean temperatures, by contrast, are very different from that of global temperatures as a result of the 50-to-100-year adjustment peri-

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[35] Our simple approach implies that the decline in Greenland temperatures (resulting from a shutdown in deepwater formation) depends on the amount of global warming. A more realistic model might make the polar-equator temperature difference depend on deepwater formation for a given global temperature.

[36] Rind's assumed fixed lag implies that the bumps in Greenland temperatures are reproduced 80 to 90 years later in CDW.

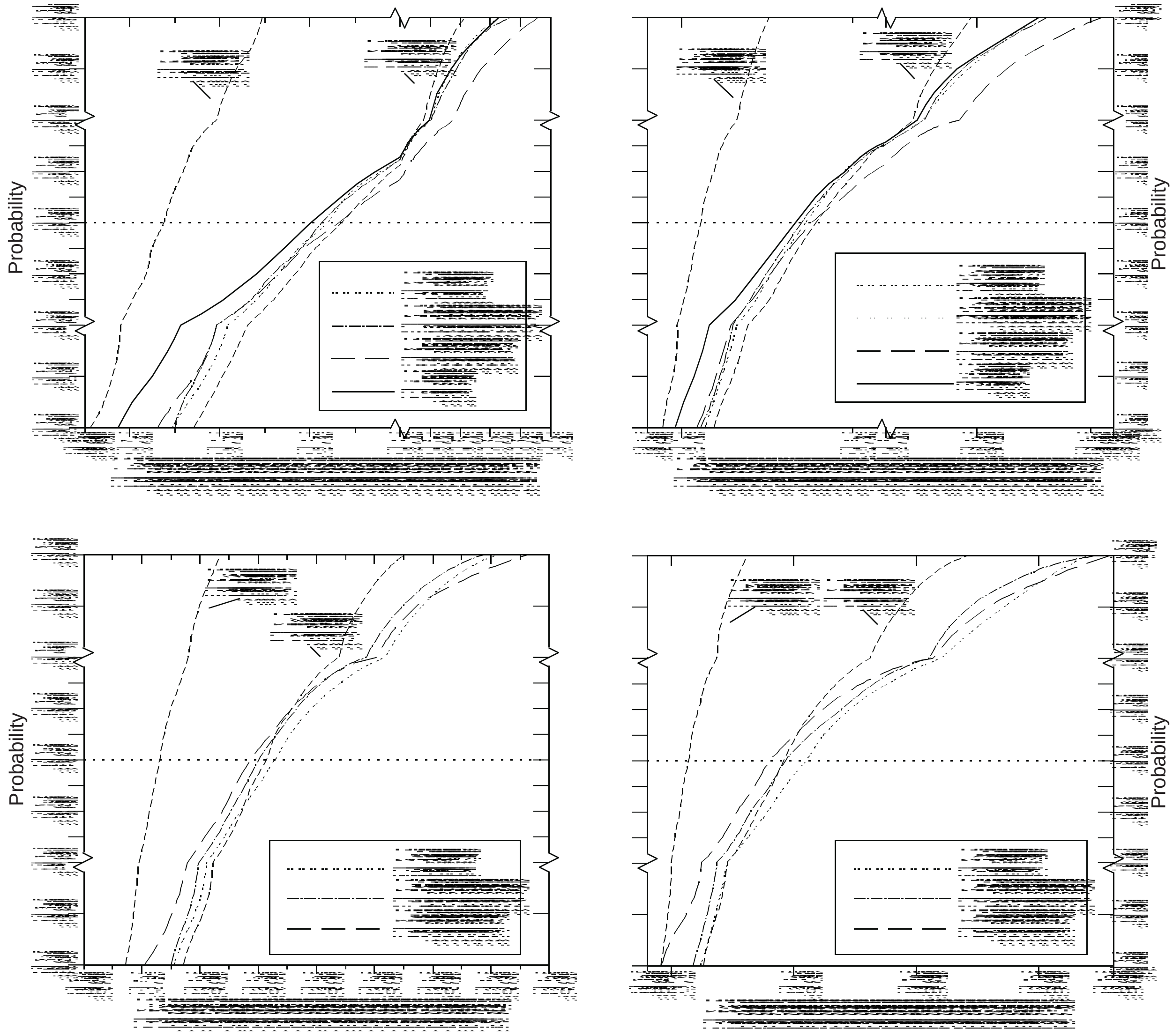
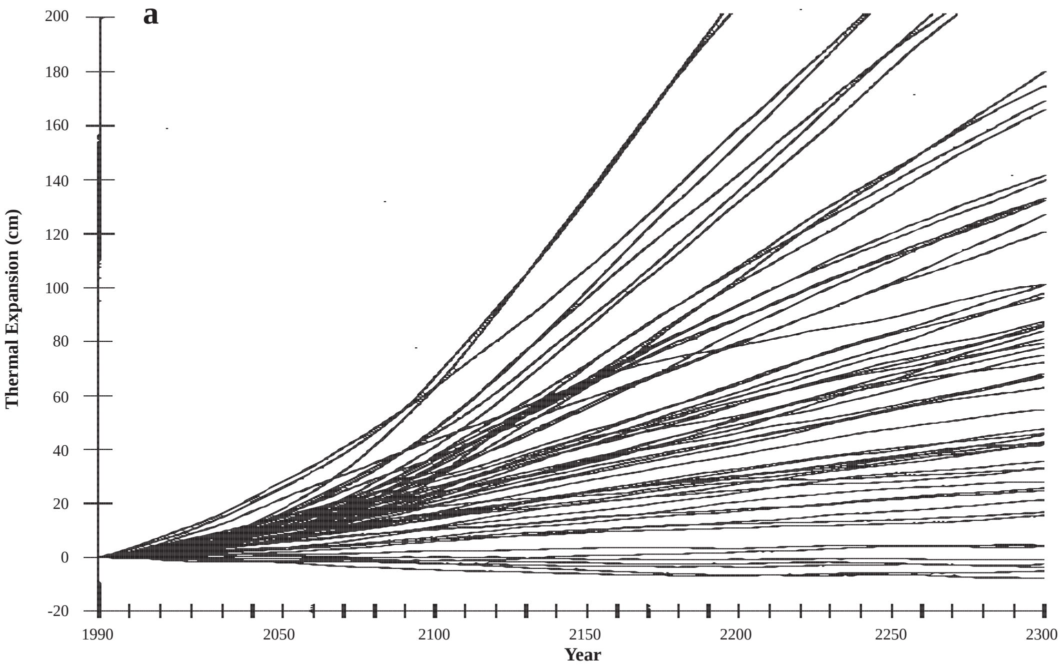


Figure 3-13. **Cumulative Probability Distributions of Surface Warming and Thermal Expansion by Reviewer.** Several curves were removed for clarity. The Rind estimates generally track Schneider because both include the possibility of both increased and decreased upwelling, along with high values of π. The Bretherton and Manabe estimates generally track MacCracken, but Manabe's thermal expansion estimates are closer to those of Hoffert due to the large decline in upwelling both researchers expect.

od (Figure 3-17a). The net effect is to smooth the

“bumpy” changes in global temperatures, except for



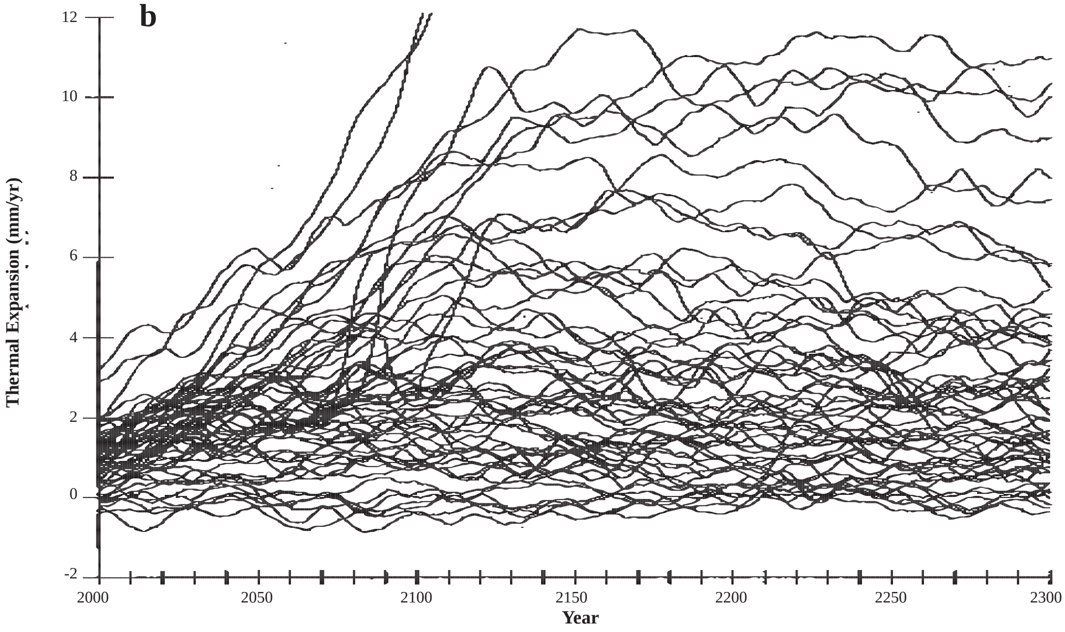


Figure 3-14. Spaghetti Diagrams of Thermal Expansion. Selected simulations for (a) thermal expansion and (b) rate of thermal expansion for the years 1990-2300. See Figure 2-5 and accompanying text for additional explanation of the scenarios selected.

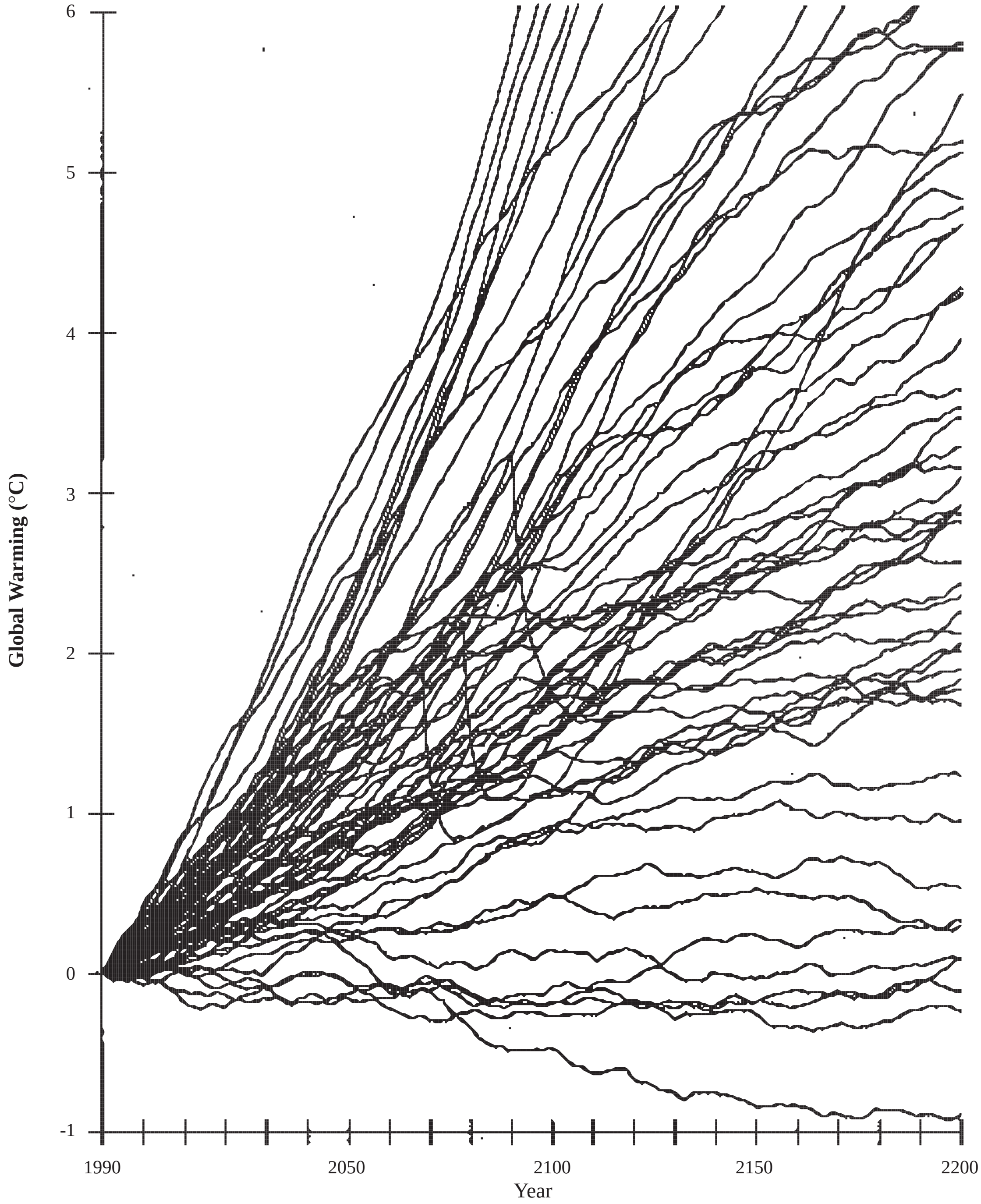
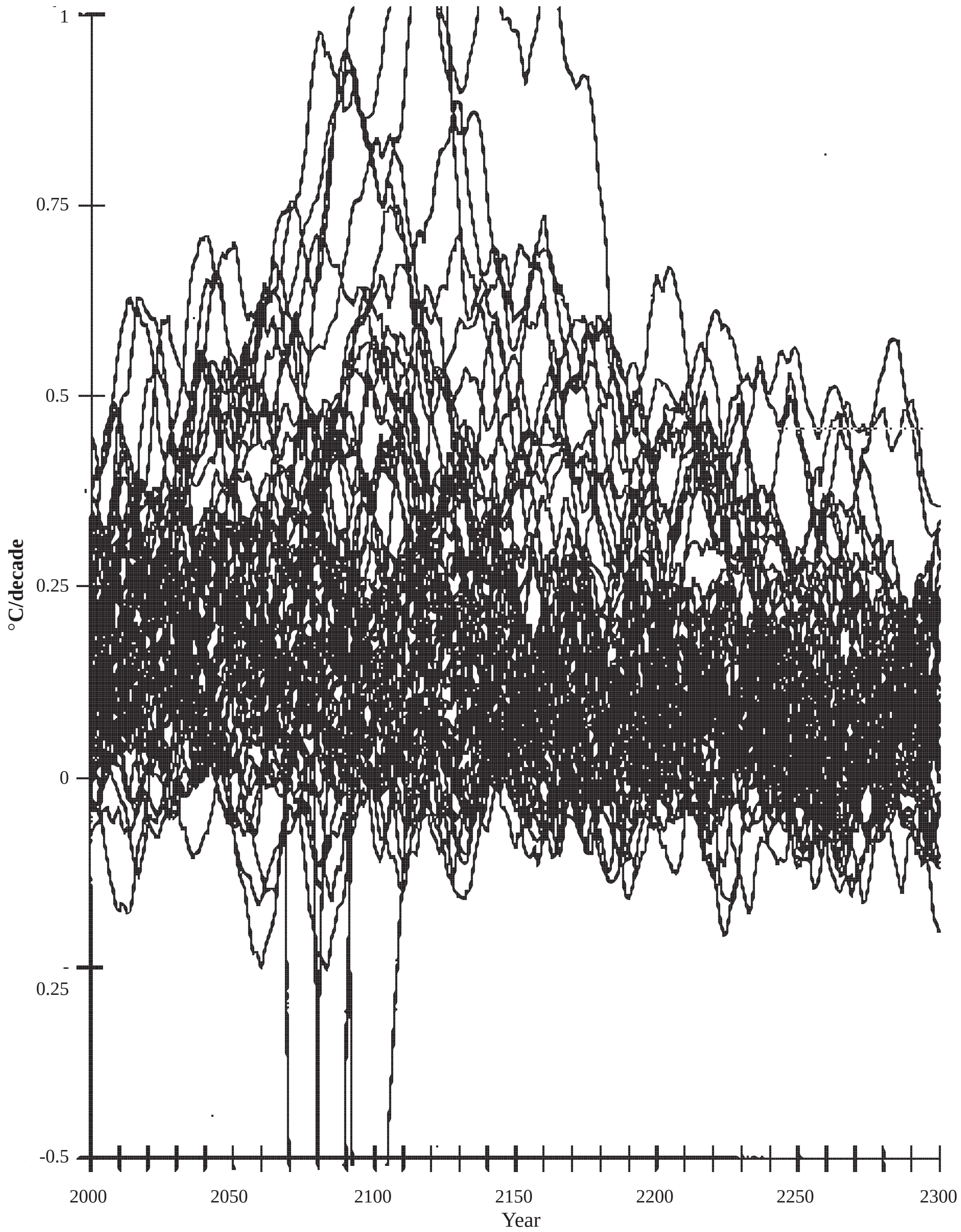


Figure 3-15. Spaghetti Diagrams of Global Warming. Selected simulations for (a) global temperatures and



(b) rate of global warming through 2300. See Figure 2-5 and accompanying text for additional explanation of the scenarios selected.

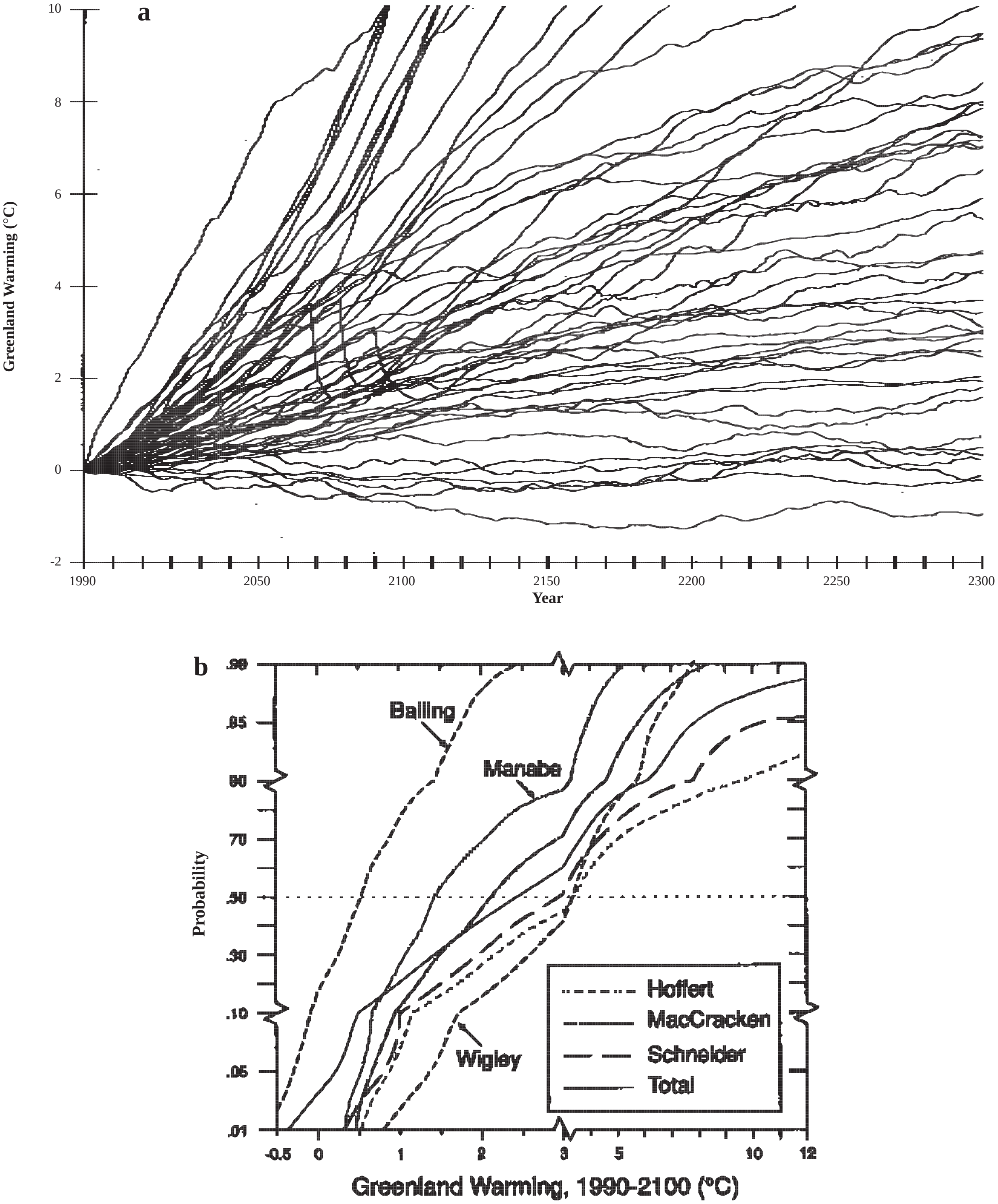


Figure 3-16. Greenland Warming. (a) Selected simulations for the period 1990–2300 and (b) cumulative probability distribution by the year 2100 for various reviewer assumptions.

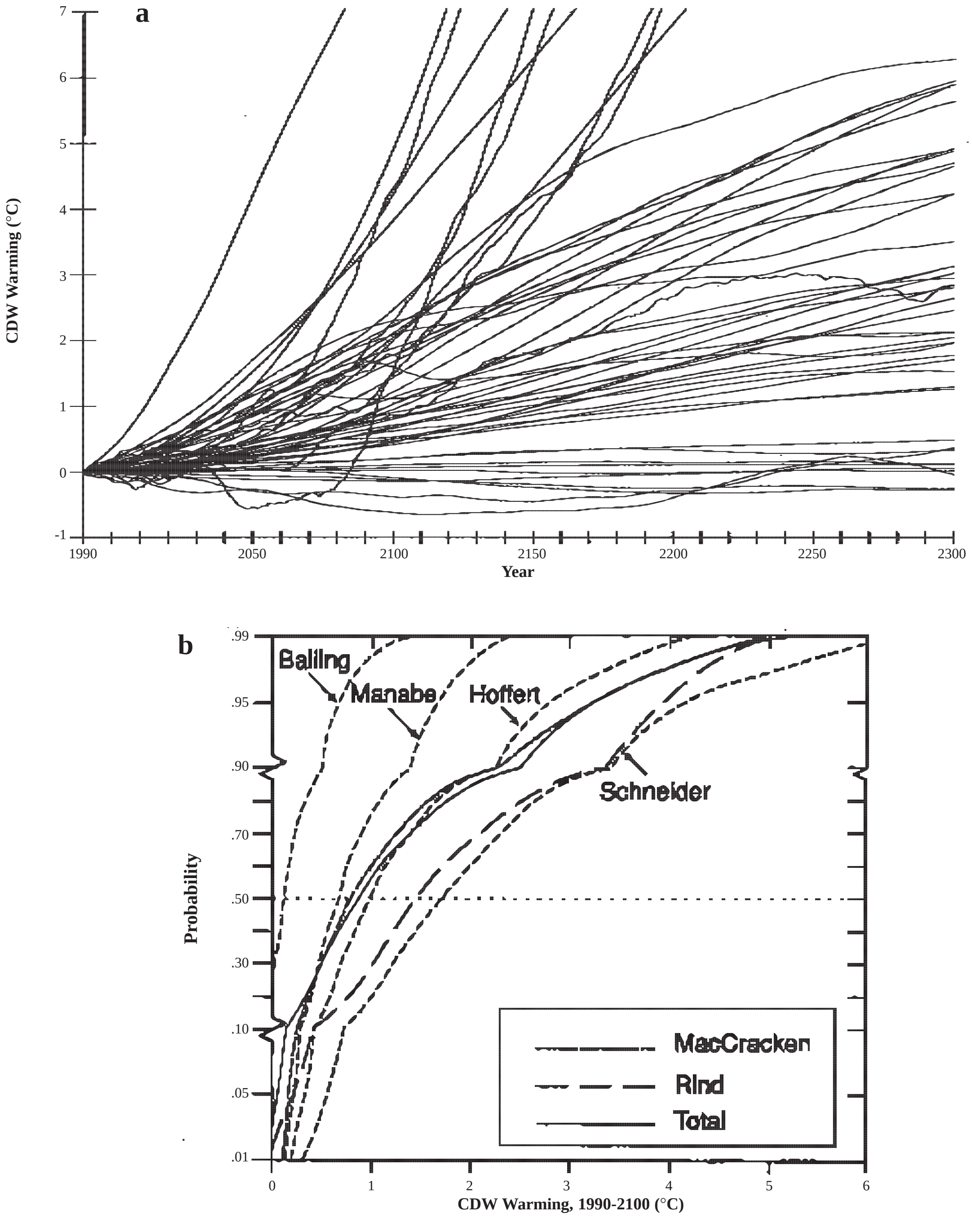


Figure 3-17. Circumpolar Ocean Warming. (a) Selected simulations for the period 1990–2300 and (b) cumulative probability distribution of circumpolar ocean warming by the year 2100 for various reviewer assumptions.

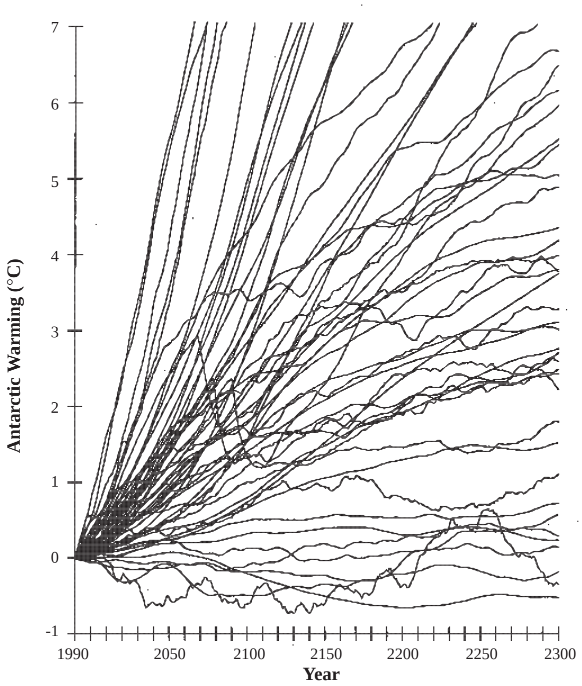


Figure 3-18. Spaghetti Diagram of Antarctic Air Temperatures. Selected simulations showing the change in Antarctic air temperatures for the period 1990–2300. See Figure 2-5 and accompanying text for additional explanation of the scenarios selected.

those simulations representing the Rind assumptions.[36]

PART B: CHANGES IN POLAR PRECIPITATION

Chapters 4 and 5 show that warmer temperatures could increase the rates of melting in Green-land and Antarctica and thereby contribute to sea level. These contributions could be offset, however, by the increased snowfall that would probably accompany warmer temperatures—particularly in Antarctica. If nothing else changed, a doubling of precipitation over Greenland would lower sea level 1.3 mm/yr (*Cf.* Ohmura & Reeh 1991); a doubling over Antarctica would lower sea level 4.2 or 5.6 mm/yr (Bentley & Giovinetto 1990), depending upon whether one includes the precipitation that falls onto the ice shelves.[37]

Greenland

Previous assessments of the likely impact of global warming (*e.g.*, Huybrechts & Oerlemans 1990) have modeled changes in precipitation based on changes in the saturation vapor pressure V(T) (*i.e.*, the amount of water vapor held by a saturated atmosphere at a given temperature and pressure). The simplest approach is to assume that precipitation is proportional to saturation vapor pressure:

$$\text{Precip}_t = V(T_t)/V(T_0)\ \text{Precip}_0 \qquad \text{(A).}$$

If snowstorms release all (or a fixed portion) of the water vapor in an air mass, such a representation is reasonable. On the other hand, if rainstorms involve cooling of a fixed number of degrees N, then precipitation should be proportional with the change in saturation vapor pressure that results from this cooling:

$$\text{Precip}_t = \frac{V(T_t) - V(T_t - N)}{V(T_0) - V(T_0 - N)}\ \text{Precip}_0 \qquad \text{(B).}$$

Huybrechts & Oerlemans (1990) use a similar specification, which is equal to the limit of equation (B) as **N** approaches zero:

$$\text{Precip}_t = V'(T_t)/V'(T_0)\ \text{Precip}_0 \qquad \text{(C),}$$

where $V' = dV/dT$.

The draft assumed that precipitation changes are lognormally distributed, with equations (A) and (C) treated as the 2σ limits and **T** representing air temperatures at sea level. Following the convention of IPCC (1990) among others, we based precipitation changes on $T_{Greenland}$, rather than on T_{global}. In cases where Greenland temperature warmed less than the global temperature, however, we used global temperature. The primary justification is that the circumstances most likely to cause Greenland to warm less than the global average would involve declines in the formation of North Atlantic Deep Water, caused by increases in North Atlantic precipitation.[38]

These representations are crude, failing to allow for seaice retreat and the resulting increase in moist convection, possible changes in the lapse rate, and

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[37] Precipitation on the floating ice shelves does not directly lower sea level; however, several of the models used in Chapter 5 assume that thinning of the ice shelves eventually affects sea level by increasing the rate at which ice streams flow into the shelves.

[38] The practical significance of this assumption is that it allows for the possibility of an increase in the Greenland Ice Sheet, when significant increases in precipitation caused by a general rise in global temperatures coincide with a small increase in melting caused by a smaller rise in Greenland temperatures. In the final results, this is most likely to happen in the Manabe-based simulations and the 5 percent of the time that Rind projects a drastic decline in upwelling, as well as some of the MacCracken runs.

TABLE 3-8
INCREASES IN ANTARCTIC ACCUMULATION WITH 1˚C WARMING
(Gigatons/˚C)

	Using Saturation Vapor Pressure		Regression		
	Absolute	Derivative	95%-Low	Mean	95%-High
Interior	61.6 (7%)	57.1	43.6	50.2 (5.7%)	56.8
Coastal	60.0 (6.4%)	55.5	-9.2	21.1 (2.2%)	51.4
Shelf	18.4 (6.5%)	17.0	23.7	32.8 (11.4%)	41.9

SOURCE: Fortuin & Oerlemans (1990).

TABLE 3-9
ANTARCTIC PRECIPITATION BASINS EMPLOYED IN THIS REPORT

Regions Employed Herein	Corresponding Grouping from Oerlemans Analysis	Accumulation (km^3/yr)
W. Antarctic ice shelves	Ice Shelves	286.9
Antarctic Peninsula	Escarpment	937.4
West Antarctica	Antarctic Interior	106.5
East Antarctica	Antarctic Interior	773.5

SOURCE: Fortuin & Oerlemans (1990).

other changes in meridional circulation. Some of these changes are addressed by general circulation models (GCMs); future studies should compare their results with the implications of these assumptions.

Antarctica

As with Greenland, previous assessments have assumed that precipitation will change with saturation vapor pressure. However, Fortuin & Oerlemans (1990) have done more empirical work on the relationship, with a cross-sectional analysis of 876 annual surface mass balance measurements and 927 temperature measurements. Because the analysis used cross-sectional regression rather than time series, it is possible that it incorrectly assumed that temperature differences are responsible for differences in accumulation rates that are, in reality, caused by other factors such as proximity to the coast. Nevertheless, we follow IPCC's (1990) convention of using this analysis.

The draft did not seasonally disaggregate precipitation changes. Because winter precipitation is generally much less than summer precipitation, the use of an annual average tends to overstate precipitation increases in regions where winter warming is greater than summer warming.[39]

Superficially, the Fortuin & Oerlemans Antarctic work also differs from the Huybrechts & Oerlemans Greenland study in that the former use the temperature of the "free atmosphere" (*i.e.*, the altitude below which air temperatures increase with increasing altitude in the stable Antarctic atmosphere). However, because they assume that $T_{free}=0.67T_{surface}-1.19$, rather than using independent measurements, the regressions are mathematically equivalent to using surface temperatures. Table 3-8 compares the results from the regression with those obtained using saturation vapor pressure or its derivative with respect to temperatures.

The draft assumed that the regression equations and the equations based on saturation vapor pressure have equal validity. Therefore, we sampled (a) 50 percent of the time from a distribution whose σ limits are the results obtained from the saturation vapor pressure and the derivative of saturation vapor pressure and (b) 50 percent of the time from the distribution implied by the Fortuin & Oerlemans (1990) regression equations, treating their 95 percent confidence interval as 1.96σ limits in a lognormal distribu-

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[39] Because $P_1>P_2$ most of the time, this will generally be the case for our scenarios of Antarctica.

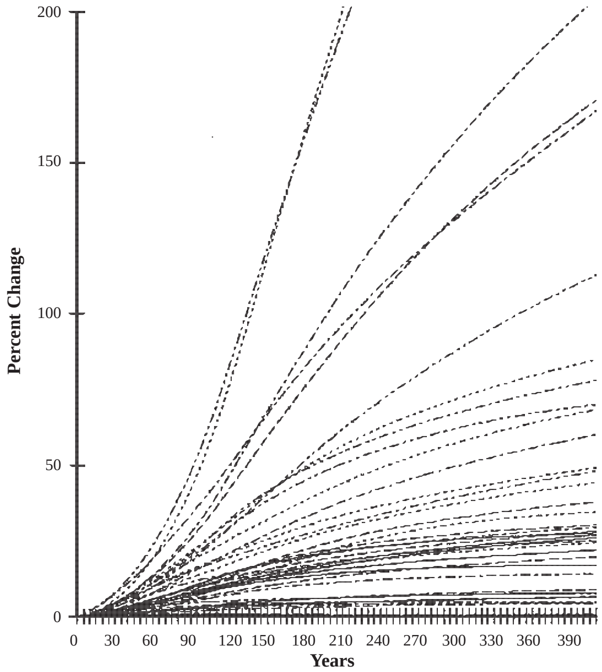

Figure 3-19. Antarctic Precipitation for Selected Scenarios in the Draft Analysis. A doubling of precipitation would lower the rate of sea level rise by 4.2 to 5.6 mm/yr, holding everything else constant.

tion. We divided the continent into four regions, as shown in Table 3-9.

Because disaggregation should not diminish our uncertainty about total precipitation, the draft also assumed that the uncertainties regarding precipitation changes for the four regions were perfectly correlated. Figure 3-19 illustrates the draft precipitation results for selected simulations.

Expert Judgment

We did not set out to have a different set of reviewers for the precipitation portion of this chapter. The alternative set resulted from reviewer self-selection. Most of the climate modeling reviewers of Chapter 3 chose not to provide comments on the precipitation portion of this chapter. On the other hand, three of the glaciology reviewers chose to provide comments on polar precipitation even though we had originally assumed that they would confine their recommendations to Chapters 4 and 5. Although projecting polar precipitation is, in principle, a climate modeling question, it is clearly a greater practical concern to glaciologists and others who study the polar regions (see Table 3-10).

The climate modelers did not substantially change the precipitation scenarios. Schneider and MacCraken were satisfied with our initial specifications; Rind's only comment was to use the saturation vapor pressures for both hemispheres. One of the polar researchers, Michael Kuhn, endorsed the approach of relying on absolute saturation vapor pressure, noting that regressions may yield results based on synoptic anomalies.

The other two polar researchers, by contrast, substantially widened the uncertainty range. Richard Alley suggested that relying on thermodynamic relations such as saturation vapor pressure may overstate precipitation changes by at least a factor of two. He argued that many years of Danish work (*e.g.*, Clausen et al. 1988) have shown empirically that precipitation increases by only

TABLE 3-10
REVIEWERS OF PRECIPITATION ASSUMPTIONS

Richard Alley	Pennsylvania State University	University Park, PA
Michael Kuhn	Innsbruck University	Innsbruck, Austria
Michael MacCracken	Lawrence Livermore National Laboratories	Livermore, CA
David Rind	NASA/Goddard Institute for Space Studies	New York, NY
Stephen Schneider	National Center for Atmospheric Research	Boulder, CO
Jay Zwally	NASA/Goddard Space Flight Center	Greenbelt, MD

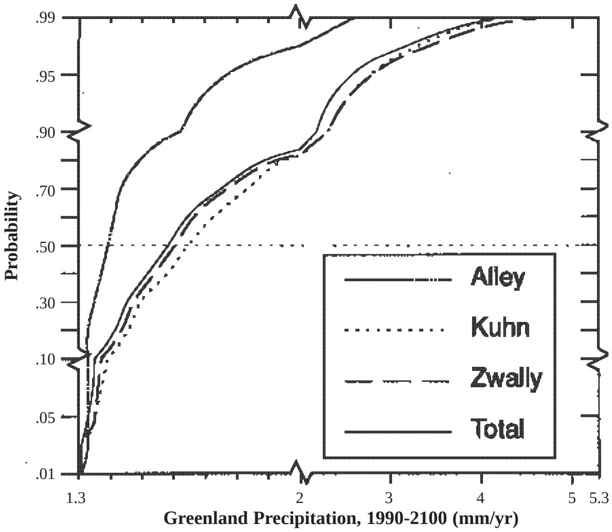

Figure 3-20. Changes in Greenland Precipitation, Sea Level Equivalent. Cumulative probability distribution for the year 2100, assuming that the current rate is 1.33 mm/yr; the Rind, MacCracken, and Schneider precipitation assumptions were essentially the same as those of Kuhn.

5 percent per degree (C) rather than the 10%/˚C implied by saturation vapor pressure. Moreover, he noted that during the Holocene, the sensitivity may have been as low as 1%/˚C (Kapsner 1994; Kapsner et al. 1993). We treated these observations as σ limits for the sensitivity of Greenland precipitation (*see also* Kapsner et al. 1995).

For Antarctica, Alley views the thermodynamic sensitivity of 10%/˚C as a bit more reasonable than for Greenland, but suggests that it is probably on the high side; we treat it as his 1/2 σ-high limit. He also states that the σ-low should be no higher and possibly lower than 5%/˚C; we treat 4%/˚C as his σ-low limit. Assuming a normal distribution, Alley's assumptions imply a median of 8%/˚C and a σ-high limit of 12%/˚C.

Jay Zwally suggested even more uncertainty regarding future precipitation changes. In Zwally (1989), he showed in a footnote that the existing literature supports sensitivities ranging from 5 to 20%/˚C. Since that time, however, ice core data has been published suggesting a sensitivity of about 3%/˚C. Therefore, Zwally recommends 2σ limits of 3%/˚C and 20%/˚C for both Greenland and Antarctica.

Final Results

The combined assumptions imply a 50 percent

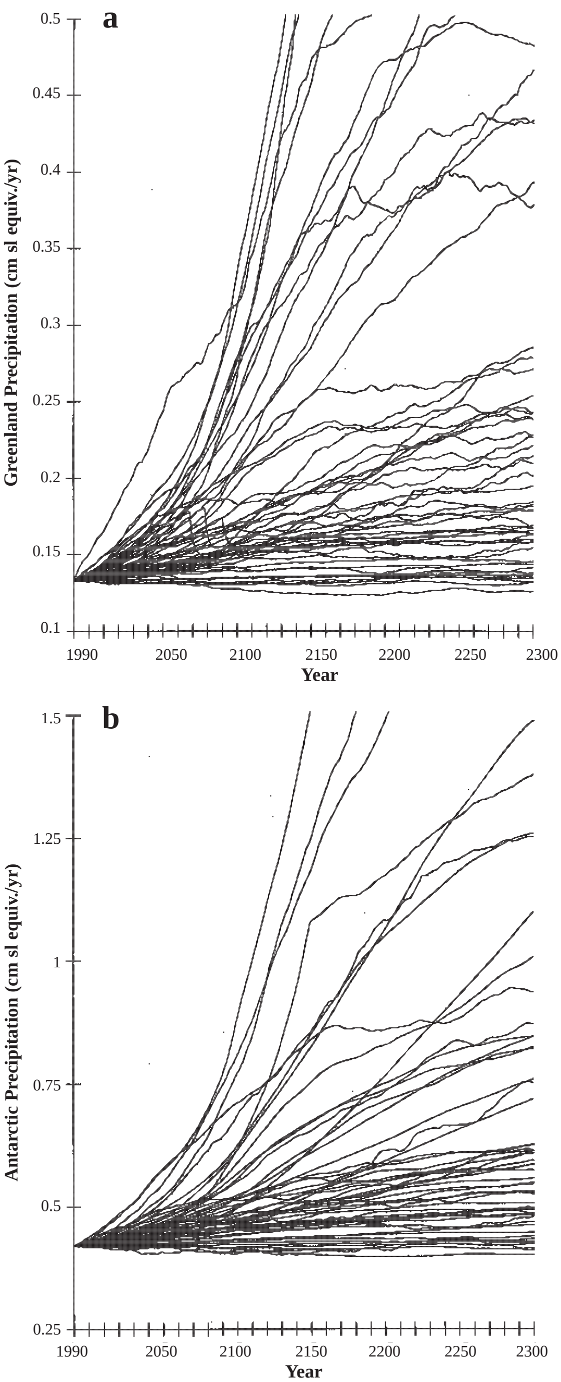

Figure 3-21. Spaghetti Diagram for Polar Precipitation, Sea Level Equivalent. Changes in (a) Greenland and (b) Antarctic precipitation for selected simulations, 1990–2300. Current rates of precipitation lower the rate of sea level rise by 1.3 and 4–5 mm/yr for Greenland and Antarctica, respectively. See Figure 2-5 and accompanying text for an explanation of the scenarios illustrated.

chance that, by 2100, Greenland precipitation will increase 20 percent, and a 5 percent chance that it will double, as shown in Figure 3-19. Figure 3-20 shows that the changes in Antarctic precipitation follow a similar pattern. As discussed in Chapter 5, the increased precipitation in Antarctica more than offsets the melting effect of warmer temperatures for most scenarios. In Greenland, by contrast, the precipitation is small compared with the increased melting.

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CHAPTER 4

GREENLAND ICE SHEET

If the Greenland Ice Sheet melted completely, sea level would rise 7.6 meters (Hollin & Barry 1979). Even with today's climate, the ice sheet is melting at a rate greater than the annual snowfall in places where the surface is within about fifteen hundred meters of sea level. This elevation, where melting and snowfall are equal, is known as the "equilibrium line." The ice sheet continues to exist because most of the ice sheet is above the equilibrium line.

For about one hundred meters above the equilibrium line, ice melts and runs off to the sea, albeit at a rate less than the annual accumulation rate. Above this elevation, known as the "runoff line," some melting occurs, but all of the water refreezes in place. Consider the land-based analogy: Small storms and small springs form puddles and ponds whose water does not run off to the sea, while larger storms and springs form floods and rivers whose water does flow to the sea. Analogously, unless the amount of melting exceeds a certain level, the melt water will not form the conduits necessary to reach the surface and subterranean "streams" that extend up to the runoff line. As we discuss below, melt water appears to run off only where annual melting is at least 58 to 70 percent of the annual snowfall. Finally, about one hundred meters above the runoff line is the "melt line," above which there is typically no melting.

Greenland would have to warm about 15 to 20˚C to place the entire ice sheet below the equilibrium line. Nevertheless, a more moderate warming will increase both (1) the elevation below which melting and runoff take place and (2) the rate of melting in areas where melt water is already running off into the sea. Counteracting those effects, warmer temperatures could increase precipitation rates. Like previous studies, this analysis concludes that enhanced melting will probably exceed the increased precipitation.

IPCC (1990) cites four models of the sensitivity of the Greenland Ice Sheet to warmer temperatures. We base our model on the earliest of those models, Bindschadler (1985). For most practical purposes, the results would not be substantially different had we used the other models.[1] The model characterizes Greenland's cross-section as a parabola. It assumes that, below the runoff line, annual melting and runoff is a linear function of altitude and that accumulation in the form of snowfall is constant throughout the ice sheet. Thus, the impact of warmer temperature scenarios from Chapter 3 is a higher runoff line, which implies increased melting at all elevations below that line; the impact of precipitation changes (also from Chapter 3) offsets some (and in some cases all) of that increased runoff. The model assumes that all precipitation is in the form of snowfall; hence, it does not consider the direct runoff or accelerated melting that might result if warmer temperatures changed the physical state of precipitation from snow to rain.

We make four modifications to Bindschadler's model to (1) allow for ablation (mostly melting[2]) and runoff in areas where melting is less than precipitation; (2) explicitly constrain the mass implied by the model to the actual mass of the Greenland ice sheet; (3) consider the lag between warming and runoff due to refreezing; and (4) adjust the profile of the glacier after each timestep.

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[1] Aside from being the earliest model, the Bindschadler model is perhaps the simplest. In a review of the draft manuscript, Roger J. Braithewaite of the Geological Survey of Greenland in Copenhagen states:

> The Bindschadler model...is very simple, but later and supposedly better models do not give dramatically different results.
>
> The best model of Greenland's contribution to sea level is by Huybrechts et al. (1991), which combines ablation, dynamics, and bedrock in a 3D distributed grid. This was developed in Germany but also uses information and ideas from [the Geological Survey of Greenland]. Our approach is to collect new data sets from Greenland, in cooperation with other European groups, to remedy shortcomings in the model rather than simply tinkering with it....
>
> The Huybrechts model has whistles and bells so even with a CRAY-2 you don't have much room [to consider other processes]....In the meanwhile, under the European Ice Sheet Modelling Initiative, Niehls Reeh of the Danish Polar Centre is developing a more portable version of the ablation part of the Huybrechts model. When finished, it will be used to calculate the short-term response of the surface balance to climate sce-narios without the longer term dynamic response....Sadly for [this EPA report,] this model is not available yet....

[2] Ablation includes melting, sublimation, and evaporation. We focus on melting because (1) the change in ablation resulting from climate change is likely to result mostly from increased melting, and (2) to the extent that sublimation and evaporation are significant, the impacts of warmer temperatures are roughly proportional to the impact on melting.

Ablation

Bindschadler treats Greenland's cross-section as a parabola whose altitude is described as:

$$y = H_{peak}\,(1 - x/L)^{1/2}$$

with $\mathbf{H}_{peak}$=3250 m representing the altitude of the glacier and **L** representing the distance from the apex to the coast, a variable for which he solves.[3]

Bindschadler assumes that annual (net) ablation (**b**) is a linear function of altitude:

$$\begin{aligned} b &= d\,(H_e - y) && \text{for} && y < H_e \\ &= 0 && \text{for} && y \geq H_e \\ a &= 0.35 \text{ m/yr} && \text{for} && y > H_e \\ &= 0 && \text{for} && y \leq H_e, \end{aligned}$$

where **a** is the annual accumulation rate (defined here as precipitation minus sublimation); $\mathbf{H}_e$ is the altitude of the equilibrium line (*i.e.*, where annual accumulation equals annual ablation, estimated as 1500 m); and **d**=*d*b/*d*h, which has been estimated to be 1.53 m/yr per kilometer of elevation.[4] Given Bindschadler's assumptions, **b** and **a** are not literally net ablation or net accumulation. Rather, **b** should be viewed as "*net* ablation in areas where there is net ablation," while **a** represents "net accumulation in areas where there is net accumulation." Defining net accumulation as **a**–**b**, these assumptions imply a discontinuity in net accumulation at the equilibrium line, as shown in Figure 4-1a.

To remove these discontinuities, we let **a** and **b** represent *absolute* accumulation and ablation:

$$\begin{aligned} a &= 0.35 \text{ m/yr} && \text{everywhere, and} \\ b &= a + d\,(H_e - y) && \text{for } y<H_e + a/d \ (\textit{i.e.}, y<1729 \text{ m}) \\ &= 0 && \text{for } y\geq H_e + a/d \ (\textit{i.e.}, y\geq 1729 \text{ m}). \end{aligned}$$

The only functional difference between Bindschadler's approach and ours is that the former assumes that ablation (and hence runoff) declines linearly with altitude up to the equilibrium line where it equals accumulation, beyond which it drops to zero. Our approach, by contrast, assumes that runoff continues to fall off linearly above the equilibrium line until it reaches zero at the runoff line (1729 m). (We return to this distinction below, when we discuss the delay caused by refreezing.[5])

Following Bindschadler, we calculate **B**, the total ablation for a given cross-section, by integrating over areas where there is ablation—in our case values of **x** in which $y<H_e+a/d$, that is $L\{1-([H_e+a/d]/H_{peak})^2\} <x<L$,

$$\begin{aligned} B &= \int_{L-L\left[\frac{H_e+a/d}{H_{peak}}\right]^2}^{L} a + d\,(H_e - y)\, dx \\ &= \int_{L-L\left[\frac{H_e+a/d}{H_{peak}}\right]^2}^{L} a + d(H_e - H_{peak}(1 - x/L)^{1/2})\, dx \\ &= \frac{d\,L\,(H_e + a/d)^3}{3\,H_{peak}^2}. \end{aligned}$$

Thus, for example, using Bindschadler's assumptions that H_e=1.5 km, H_{peak}=3.25 km, and a=0.35 m/yr, and d=1.53 m/(yr km),

$$\begin{aligned} B &= \frac{1.53 \text{ m/(yr km) } L\ 1729^3 \text{m}^3}{3\text{x}3250^2 \text{ m}^2} \\ &= 0.00025\ L \text{ km}^2\text{/yr.} \end{aligned}$$

Bindschadler assumes that accumulation is constant over the entire ice sheet,

$$A = \int_0^L a\, dx = L\,a.$$

---

[3] We use different variable names than Bindschadler.

[4] Bindschadler omits the intercept (a) term in his equation 18.3. Such a specification implies no ablation above the equilibrium line. At first glance, one might interpret this as an equation explaining net ablation. However, Bindschadler's equation 18.4 treats accumulation as constant above the equilibrium line and zero below it; if it really means net accumulation in areas of net accumulation, it would subtract ablation at altitudes above the equilibrium line. Alternatively, it can be viewed as assuming that runoff occurs only below the equilibrium line.

[5] Put another way, Bindschadler's original model assumed that the runoff line was the equilibrium line, that is, the elevation where melting is 100 percent of precipitation; we assume that the runoff line is the melting line, that is, the point where melting equals zero. The elevation we used (1729 m) was probably a bit on the high side, while the 1500 m elevation Bindschadler used was certainly on the low side. We probably should have used an intermediate point where melting is 60 to 70 percent of precipitation. The practical significance is not great, however, because the melt rate at sea level is set so that the glacier is currently in balance, regardless of the equilibrium line elevation.

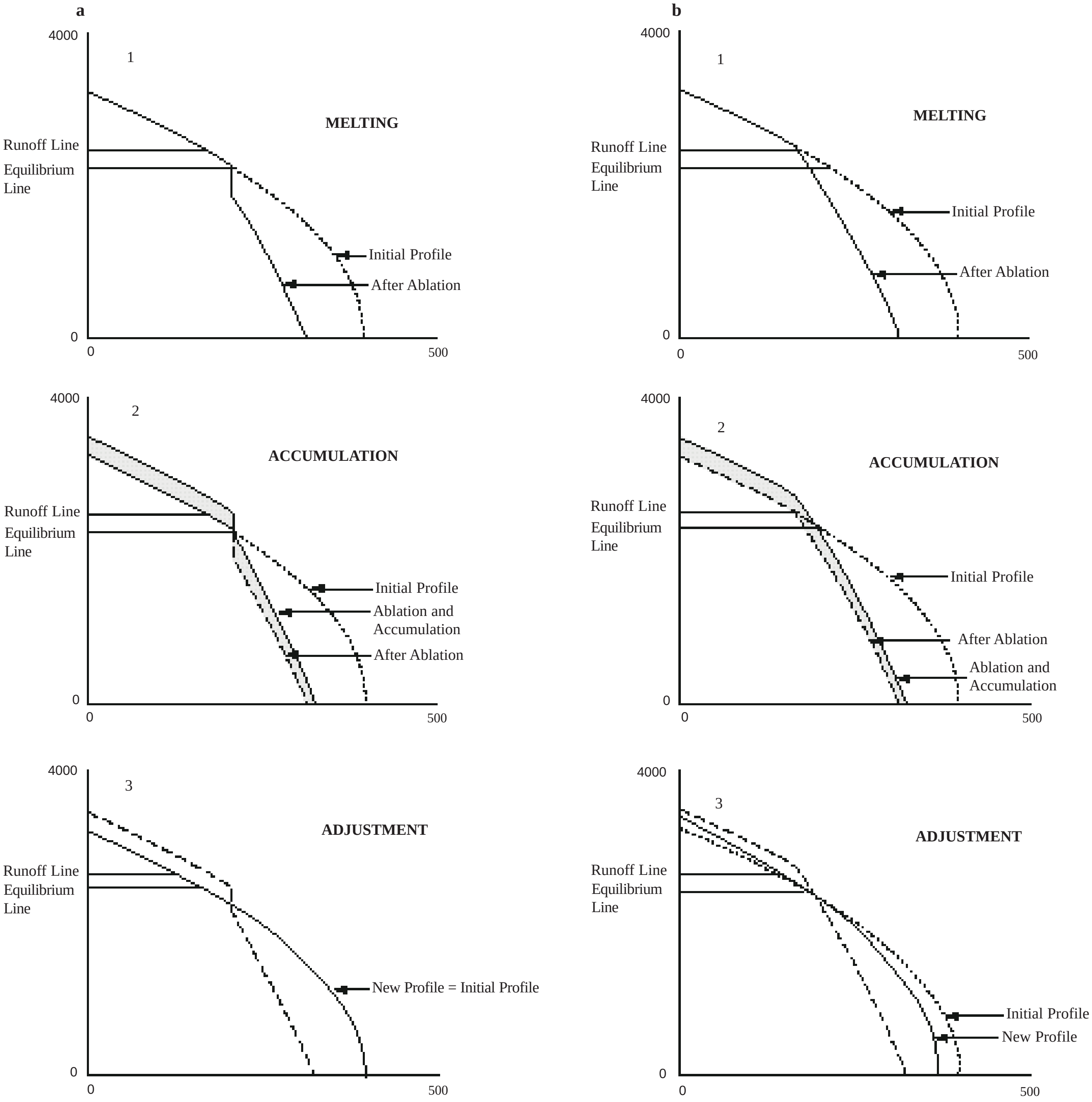

Figure 4-1. Two-Dimensional Schematic of the Greenland Ice Sheet. The profiles in (a) show the framework employed by Bindschadler; (b) shows our modification. In each case, the first diagram shows the initial profile (dotted) and a new profile (solid) after one period's melting. Note that the Bindschadler scheme assumes no runoff above the equilibrium line, implying a slight discontinuity; this is the main difference between the two approaches. The second diagram shades the accumulation that takes place, with the solid line showing the net impact of ablation and accumulation, and the dashed curve showing only the effect of ablation. The final diagram's solid line shows the profile adjustment after each time period. Bindschadler's model does not have a mass constraint (*i.e.*, the profile simply returns to its position at the previous time period). This analysis adjusts the profile by calculating a new parabola whose area is reduced by the net of ablation and accumulation.

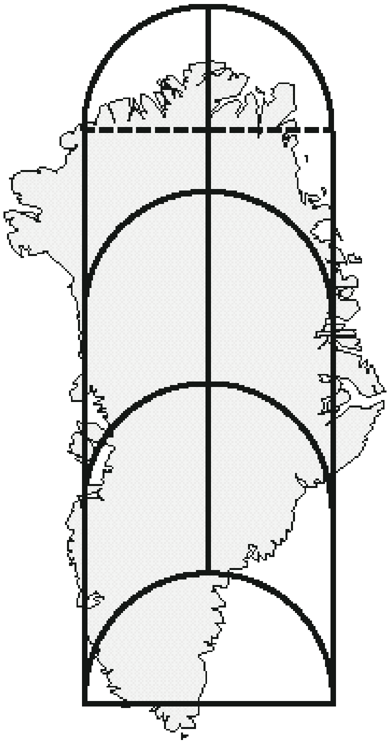

Figure 4-2. **Schematic of Bindschadler (1985) Model.** Extrapolating the 2-D model to three dimensions by a scaling factor of 5000 km is equivalent to assuming two parabolic cylinders back-to-back, with transverse (longitudinal) length of 2500 cm. Greenland is drawn to the same scale.

Scaling and Mass Constraint

At this point, we must discuss a second way by which we depart from Bindschadler's approach. Because the circumference of Greenland is approximately 5000 km, Bindschadler scales the two-dimensional model to three-dimensional reality by multiplying all results by 5000 km. Implicit in this assumption is that the Greenland ice sheet can be viewed as two parabolic cylinders back-to-back with a transversal length of 2500 km, as shown in Figure 4-2. The volume of such an ice sheet would be 3.85 million cubic kilometer, which is 28 percent more than the 3 million cubic kilometer of ice found on the continent (Hollin & Barry 1979).[6] Because Bindschadler did not adjust the mass after each timestep to reflect the net contribution to sea level, the volume implied by his assumptions was irrelevant.

We adopt a different procedure for two reasons. First, as we discuss below, this exercise keeps track of mass changes, so it is necessary to impose a meaningful mass constraint. Second, scaling by 5000 km implies that Greenland's current accumulation is 695 km^3, which is (coincidentally) 28 percent greater than the 535 km^3 annual flux suggested by recent observations (Ohmura & Reeh 1990). Thus, reducing our scaling factor to 3850 enables our assumptions to duplicate both the current rate of accumulation and the current volume of the ice sheet; so we adopt this scaling factor, which we call **LL**.

Parameter Values

Following Bindschadler, we assume that calving is 0.04 km^2/yr for each cross-section (*i.e.*, 0.04 km^3/yr per km of shoreline). Assuming that the estimated equilibrium-line elevation refers to a period when the entire Greenland Ice Sheet was neither growing nor shrinking,[7] accumulation equals ablation plus calving:

$$A = B + C;$$

and we solve for **L** as follows:

$$a\,L = \frac{d\,L\,(H_e + a/d)^3}{3\,H_{peak}^2} + .04$$

$$L = .04\left[a - \frac{d\,(H_e + a/d)^3}{3\,H_{peak}^2}\right]^{-1}.$$

Given the values for the parameters suggested by Bindschadler, **L**=397.86 km. To check our value of **LL** against the mass constraint, we consider **LL***, defined as the value of LL that satisfies the mass constraint. **LL*** can be calculated as the volume of the ice sheet divided by the cross-sectional area. The cross-sectional area under the parabola is simply 2/3 L H_{peak}=862 km^2; thus, LL*=3,000,000 km^3/862 km^2=3490 km, which is reasonably close to our scaling factor of 3895 km.

Using estimates of the other parameters, our equations for current ablation and accumulation become:

$$\text{Accumulation} = LL\ A = 397.86\ LL\ a/1000$$

$$\text{Ablation} = LL\ B = \frac{0.00153\ 397.86\ LL\ H_{zb}^3}{3\,H_{peak}^2}$$

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[6] The effect of this assumption is to assume that the base of the ice sheet is a plane tangent to the Earth's surface at sea level. In reviewing the draft manuscript, Robert Bindschadler told us that this is a reasonable assumption. Even if, for example, there are occasional mountains intruding upward into the ice sheet, the net effect of this assumption does not change total potential sea level rise because the volume is still constrained to 3 million km^3.

[7] Future reports could solve for the distribution of **L** implied by the distribution of uncertainty regarding the recent mass balance of Greenland.

where $H_{zb}=H_e+a/d$, that is, the altitude of the zero-ablation line, which is 1729 m under current conditions.

Given the equation explaining current runoff, the sensitivity to warmer temperatures shows up as the sensitivity of the zero-runoff line (H_{zb}) to warmer temperatures.[8] Bindschadler analyzes two scenarios based on previous estimates of the warming required to raise the equilibrium line by 100 m: 1.12˚C and 0.6˚C. This study employs these sensitivities as σ limits. Note, however, that because accumulation increases with warmer temperatures, the equilibrium line rises less than the runoff line. We estimate the change in the runoff line by assuming that a 0.6˚C warming would increase the baseline accumulation rate (35 cm/yr) by 1.8 cm/yr, and that a 1.1˚C warming would increase precipitation by 3.4 cm/yr.[9] Assuming that d=1.53 m of ablation per year for each kilometer of elevation, the runoff line would rise 100 m + 11.8 m for the 0.6˚C warming and 100 m + 22.2 m for the 1.1˚C warming, implying that $dH_{zb}/dT_{Greenland}$ has σ limits of 111.1 and 186.3 m per degree (C); we call this parameter G_1.

These values imply that, in areas where there is melting, a 1˚C warming increases annual melting by 17 to 28 cm. By contrast, even with the highest suggested precipitation sensitivity (see Chapter 3B) of 20 percent per degree (C), the model suggests that precipitation would only increase by about 6 cm/yr. Nevertheless, only about one quarter of the ice sheet is assumed to be below the runoff line of 1729 m[10]; thus, an additional 6 cm of precipitation would add about the same amount of mass as a 24 cm increase in the melt rate. Therefore, the increased precipitation could more than offset the increased melting in some of the extreme scenarios.

Substituting our equation explaining the elevation of the runoff line,

$$H_{zb} = 1729 \text{ m} + G_1 \, \Delta T_{Greenland}$$

into the previous equation, we have:

$$\text{Ablation} = \frac{0.00153 \; 397.86 \; LL \; (1729 \text{ m} + G_1\Delta T)^3}{3 \; H_{peak}^2.}$$

Thus, ablation is a cubic equation in temperature, with ΔT showing up raised to the 1, 2, and 3 powers. The linear term reflects the fact that once an area is within the ablation zone (*i.e.*, the area where net ablation is greater than zero), the rate of ablation is linear in temperature. The higher order terms reflect the fact that additional areas of the glacier are brought within the ablation zone: Had the glacier's profile been linear, ablation would have been a quadratic; because the area within the ablation zone is a quadratic, total ablation becomes a cubic.[11]

Refreezing

The impact of refreezing is important for two reasons: (1) after a part of the ice sheet is warmed, it would take time to form a conduit by which the water can flow to the sea; and (2) in areas where there is relatively little melting, all of the melt water may refreeze. For over a decade, glaciologist Mark Meier has warned that by neglecting refreezing, estimates of the sea level contribution from the Greenland Ice Sheet may be overstating the initial impact of global warming; we use the results of an analysis by Meier and his colleagues at the University of Colorado (Pfeffer et al. 1991).

The Lag Due to Refreezing

Suppose that the Greenland Ice Sheet warms and new areas are brought within the melting zone. If the ice sheet was a solid block of ice, the melt water would run off into the ocean and contribute to sea level. But there are many pores in the ice. Therefore, the initial effect of bringing new areas within the melting zone would not raise sea level at all; rather, the surface ice would melt, and the water would percolate downward and refreeze. Eventually, enough of the pores will be filled and frozen to enable melt water to flow to the sea through conduits formed by crevasses in the ice, rather than simply flowing downward into the ice.

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[8] Although the equation for ablation includes the equilibrium line elevation, the presence of the constant term in the linear equation implies that the term for equilibrium-line elevation is merely an intuitively appealing way to present the equation. Equilibrium elevation is, in fact, derived from existing data on elevation versus net ablation. Thus, the term refers to equilibrium elevation given current accumulation rates, not the equilibrium elevation that might occur from alternate changes in precipitation. Assuming increased precipitation, the actual equilibrium line will probably rise less than would be expected given the current lapse rate, but this is immaterial for estimating net ablation, since accumulation shows up directly in the model.

[9] *See* Chapter 3B for a discussion of the impact of warming on Greenland precipitation. These assumptions are based on the mean of the results from assuming that precipitation changes in proportion with the saturation vapor pressure or the derivative of the saturation vapor pressure.

[10] This assertion follows from the parabolic form: $y=3250(1–x/398)^{1/2}$. Setting x equal to 0, 285, and 398 gives elevations of 3250, 1729, and 0.

[11] Because G_1 is small compared with the initial elevation of the zero-melt line, the effect of cubing the sum leaves the impact of the cubed term smaller than the linear term until the warming exceeds 15˚C, even for high values of G_1.

Pfeffer et al. (1991) considered models with minimum and maximum delays due to refreezing. Their minimum model represents, for practical purposes, a near instantaneous formation of an "impermeable horizon 'perched' above the [ice sheet] which remains permeable even after the establishment of runoff."[12] This model implies essentially no lag between warming and runoff.

The maximum model, by contrast, assumes that no runoff takes place until pores between the ice are filled[13] between a depth of approximately 70 m and (for practical purposes) the surface. "This is an unrealistic requirement but results in a calculation of fill-in time that is longer than any other process and as such gives an upper limit on the time required to establish runoff at some new elevation."[14]

In testing these models, Pfeffer et al. assumed that the initial zero-runoff elevation is 1680 m (close to the elevation we used). They considered the impacts of a scenario in which temperatures warm linearly 4˚C and precipitation increases by 10 percent over the course of a century, and remains constant thereafter. The minimum model results in the zero-runoff elevation rising by 240 m after a century; the maximum model results in the runoff line rising 150 m after 100 years and 190 m after 150 years.[15] Simplifying the dynamics of the maximum model implies an e-folding adjustment time of 50 years for the maximum model.[16] We assume that the runoff line responds with an adjustment time of G_3.[17] Based on the Pfeffer et al. maximum model, the 2σ high limit is 50 years. For our median, we use 25 years, which is the average of the minimum and maximum models. Thus, our 2σ low is 12.5 years.[18]

Even with the 2σ lag of 50 years, the impact of refreezing is not large for a small warming. Figure 4-3d shows that for an instantaneous warming of 1˚C, this delay reduces the initial Greenland contribution by less than 7 percent. Refreezing has no impact on areas that were already below the runoff line; because the new area brought into the melting zone is small compared with the area where melt water was already running off, the area of refreezing is small. For a faster warming, by contrast, the area brought within the melting zone constitutes a greater portion of the total area where melting is taking place, and the consideration of refreeze has a greater proportional impact. Nevertheless, even for the extreme assumption of an instantaneous warming of 4˚C, refreeze reduces the initial contribution by only about 25 percent.[19]

Elevations Where All Melt Water Refreezes

In equilibrium, our calculations do not distinguish between the melt line and the runoff line; the latter simply approaches the former. Several authors, however, point out that even in equilibrium, the upper limit for runoff is below the zero-ablation line.[20] Moreover, the original incarnation of the Bindschadler model implicitly assumed that the runoff line is where melting is 100 percent of precipitation.

Failing to make this distinction could lead a model to overstate runoff for two reasons. Most directly, a model will tend to overestimate the elevation of the initial runoff line and, hence, annual runoff. Pfeffer et al. suggest that the Ambach & Kuhn (1989) model overstates runoff even without a change in climate; this systematic overstatement accounts for about 75 percent of the impact of refreeze they identify in the first 100 years of their simulation. Because the

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[12] Pfeffer et al. at 22,120.

[13] The pores only need to be filled to a "close-off density" of 83 g/cm^3. *Id.*

[14] *Id.* at 22,119.

[15] *See Id.* at 22,121, Figure 2.

[16] The equilibrium elevation of the zero-runoff line rises linearly with temperature. Assuming that the transient elevation H_{peak} adjusts linearly to its equilibrium value H_{zb},

$$H_{peak}(t) = H_{peak}(t-1) + c\,[H_{zb}(t) - H_{peak}(t-1)],$$

and 1/c is the e-folding time. A value of c=0.02 would imply elevation changes of 140 and 202 m after 100 and 150 years, which represent roughly equal under- and overestimates of the Pfeffer et al. estimates of 150 and 190 m for those years.

[17] Ignoring refreeze, we calculate runoff by integrating the melt rate from sea level up to the elevation where there is no melting, H_{zb}. When refreeze is incorporated, the integrand remains the same; *i.e.*, melting in areas below the old runoff line (which equalled the zero-melt line) increases by the same amount regardless of the impact of refreeze. The upper limit of integration, however, is reduced: We now integrate from sea level only up to the runoff line, which lags behind the zero-melt line.

[18] This estimate is slower than the instantaneous response implied by the Pfeffer et al. minimum model. Although that model is clearly unrealistic, we may have added a slight downward bias to some of our higher simulations.

[19] These estimates are consistent with the differences that Pfeffer et al. showed between the maximum and minimum models.

[20] *See* Pfeffer et al. (1991) (runoff line is elevation where melting equals 70 percent of precipitation); Huybrechts et al. (1991) (60 percent). Reviewer Roger Braithwaite (Greenland Geological Survey) adds: "I recently spent two years working on the meltwater refreezing problem and managed to refine Huybrechts 0.6 to 0.58, which is not a very impressive result...."

Bindschadler model uses an estimate of current runoff to solve for the model parameters, however, the impact of overestimating the elevation of the runoff line is offset by a lower initial melting rate at other elevations. In any event, our assumed initial runoff elevation of 1740 m is only slightly higher than the 1680 m elevation employed by Pfeffer et al.

The second consideration is that precipitation changes and refreeze could interact to decrease the sensitivity of the runoff line to increases in temperature. If precipitation increases, for example, the zero-runoff line would rise by less than the zero-melt line, even in equilibrium. Moreover, given the parabolic shape, the total portion of the glacier between these two lines would increase by a greater proportion than the vertical elevation differences. For both of these reasons, the area of Greenland that our model erroneously assumes to be contributing to sea level would increase.[21] Although the initial overstatement of melt area is counteracted by the model parameters, the increase is not. Given that the total impact of refreeze in the Pfeffer et al. paper is 4.3 cm over 150 years, however, the impact of our overstatement is unlikely to be more than 1 cm.[22]

Calving

No models have been developed showing how Greenland calving would respond to global warming. In the absence of any model, two reasonable assumptions would be (a) no change and (b) calving increases proportionately with melting. Bindschadler notes, however, that Sikonia (1982) found empirically that calving increases with the 0.57 power of ablation.

The draft assumed that calving increases with ablation raised to the G_2 power, with G_2 following a normal distribution with a mean of 0.57 and 2σ limits of 0 and 1.14.

Ice Sheet Dynamics and Changes in Profile

Bindschadler's calculations kept the profile constant over time, because for the 100-year period he considered, changes in the profile seemed unlikely to make much difference. Nevertheless, the altitude dependence of ablation implies that $\mathbf{H}_{peak}$ would increase, while **L** would decrease. Over longer periods of time, however, changes in ice sheet flow would at least partly offset any steepening of the glacier.

The current version of the draft ignores ice sheet dynamics and seeks merely to approximate the change in profile shape resulting from the differential ablation rate. Therefore, after the change in mass has been calculated, the values of **L** and $\mathbf{H}_{peak}$ are adjusted for each time period as follows:

- $\mathbf{H}_{peak}$ is increased by a(t)–a(0). Assuming that the ice sheet is currently in equilibrium, its height will increase only by the extent to which future accumulation rates exceed the current value.

- **L** is decreased to account for the change in mass and the adjustment to $\mathbf{H}_{peak}$, *i.e.*,

$$L_{t+1} = \frac{L_t H_{peak}(t)}{H_{peak}(t+1)} - \frac{3\Delta mass}{2H_{peak}(t+1)}.$$

Figure 4-3 compares projections of (a) the equilibrium line altitude; (b) the sea level contribution; and (c) the rate of sea level rise from the median, σ-low, and σ-high scenarios, assuming that precipitation and calving do not change and that Greenland temperatures rise 6˚C per century for the next two hundred years and remain constant thereafter.[23] During the first century, the total contribution in the median scenario is 10 cm; during the following century the contribution is 48 cm. Note that the equilibrium line reaches an elevation of 3200 m, bringing almost the entire glacier within the area of net melting. Once temperatures stabilize, Greenland's contribution to the rate of sea level rise tapers off slightly because the decline in the ice sheet's area leaves a slightly smaller surface on which melting can take place. Under the low scenario, however, the contribution is only 5 and 23 cm during the first and second centuries, roughly the magnitude of potential precipitation changes.

The calving and precipitation assumptions have a substantial net downward impact on these projec-

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[21] At least until the entire ice sheet is within the ablation zone, after which the area would decrease.

[22] According to the Pfeffer et al. analysis, 75 percent of the error from ignoring refreeze stems from overstating the initial runoff elevation, for which our parameter-selection compensates. Moreover, the adjustment-time difference between the maximum and minimum models accounts for at least half the remaining impact. Thus, the precipitation effect would be only one-eighth of the total impact of refreezing, that is, about 0.6 cm.

[23] This temperature assumption is consistent with the IPCC (1990) assumption of a global warming of 4˚C and a Greenland amplification of 1.5.

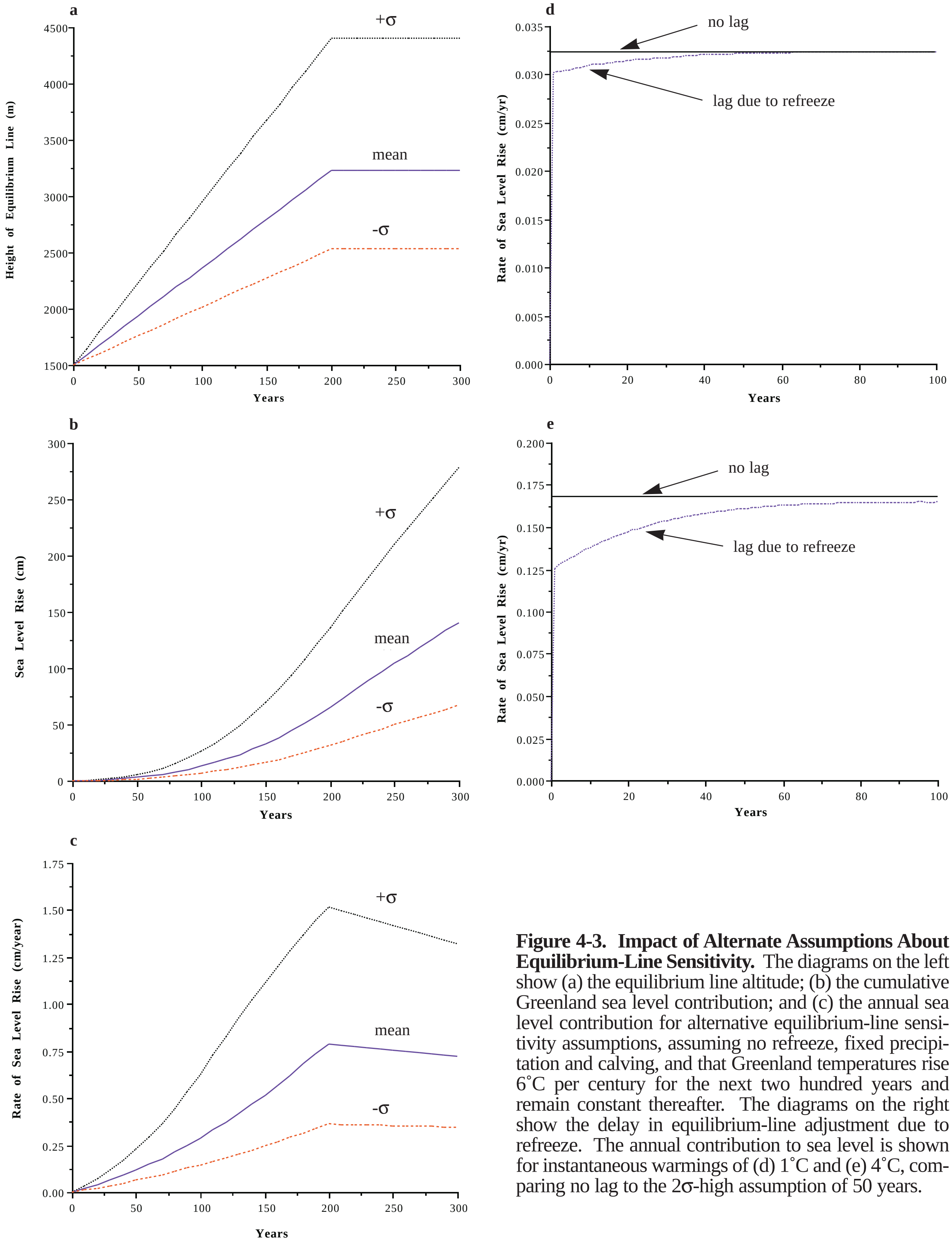

Figure 4-3. Impact of Alternate Assumptions About Equilibrium-Line Sensitivity. The diagrams on the left show (a) the equilibrium line altitude; (b) the cumulative Greenland sea level contribution; and (c) the annual sea level contribution for alternative equilibrium-line sensitivity assumptions, assuming no refreeze, fixed precipitation and calving, and that Greenland temperatures rise 6˚C per century for the next two hundred years and remain constant thereafter. The diagrams on the right show the delay in equilibrium-line adjustment due to refreeze. The annual contribution to sea level is shown for instantaneous warmings of (d) 1˚C and (e) 4˚C, comparing no lag to the 2σ-high assumption of 50 years.

tions. Figure 4-4 shows that when median values[24] are employed, calving increases the total contribution by about 20 percent, while precipitation reduces it by about 45 percent. The net effect is to lower the impact during the first century to 7.5 cm and during the second century to 36 cm.[25] Because increased precipitation in the median scenario is sufficient to lower sea level 5 cm during the first century and 18 cm during the second century, it has the potential to completely offset the Greenland contribution if equilibrium sensitivity proves to be at the low end of the range. Moreover, some of the high precipitation sensitivity assumptions imply almost twice the increase assumed in the median scenario; on the other hand, in about 10 percent of the simulations, precipitation barely increases at all (*see* Chapter 3).

The sensitivity analyses shown in Figures 4-3 and 4-4 suggest that our model is broadly consistent with the sensitivity of the IPCC assumptions, although we have a wider uncertainty range. Figure 4-4c shows that the IPCC estimates for the year 2100 were 2.9, 11.6, and 27.7 cm. Using the median assumptions but excluding refreeze, we get a rise of 11.9 cm for the 110th year. Our low and high assumptions in Figure 4-3b show rises of 8 and 33 cm by 2100; subtracting the 4 cm net downward impact due to calving and precipitation yields low and high estimates of 4 and 29 cm, implying that the uncertainty is slightly greater than sevenfold. The IPCC uncertainty is ninefold in part because its estimates were based on a Greenland warming of 4 to 9˚C; for a given warming, the IPCC uncertainty is only fivefold.[26] Thus, our model assumes a slightly greater uncertainty than does the IPCC analysis[27]; our uncertainty range is further expanded by the impacts of the polar temperature and precipitation uncertainties discussed in Chapter 3.

The long-term dynamics implied by our model are illustrated in Figure 4-5. All scenarios shown make the extreme assumptions of no increase in precipitation and σ-high ablation sensitivity, along with fixed calving; the same pattern would emerge for more moderate assumptions, but over a longer time period. Curve i illustrates a 6˚C warming, with the temperature staying at that level thereafter. The rate of sea level rise reaches a maximum of 4.2 mm/yr in the one-hundredth year and declines by about 4 percent in each of the following centuries; the rise in the equilibrium line has a lasting impact of bringing more of the ice sheet within the ablation zone, while the rate declines only slightly as the retreat of the ice sheet diminishes the total area.

Curves ii and iii examine the model's stability with respect to small and large changes in temperatures. In scenario ii, temperatures rise 6˚C during the first century and fall back to today's temperatures during the third century. For this relatively small initial sea level contribution (75 cm), the model is fairly stable, with a small persistent contribution of 0.02 mm/yr resulting from the fact that the melting during the first 300 years lowered the surface of the ice sheet, and thereby brought a greater portion of the glacier within the melting zone. By contrast, in scenario iii, we test a larger change, in which temperatures rise 6˚C per century for three centuries, remain constant for 350 years, fall back to today's temperatures over the next 300 years, and stay constant thereafter. A relatively high rate of sea level rise persists, illustrating the potential instability of the glacier for a large warming: The warming brings most (in this case all) of the glacier within the area of net melting; after several centuries, the elevation of the glacier is reduced to the point that, even after temperatures return to normal, more (or all) of the glacier is below the equilibrium line; thus, it continues to disintegrate.

Draft Results

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[24] For precipitation, we use the initial median assumption (see Table 1-1) rather than the lower median that we obtain when we include the lower projections of precipitation implied by Dr. Alley's review.

[25] The downward impact of precipitation in the median simulation, however, is somewhat less: Because one of the expert reviewers of Chapter 3 believes that precipitation is far less sensitive than we assumed initially, the median precipitation increase in the simulations is about 15 percent less than the median assumption shown in this sensitivity analysis.

[26] *See* IPCC at 276 (Greenland contribution is 1 to 5 mm/yr per degree (C).

[27] These estimates apply when holding calving and precipitation fixed at their median values. The uncertainty is approximately ninefold when those uncertainties are also included.

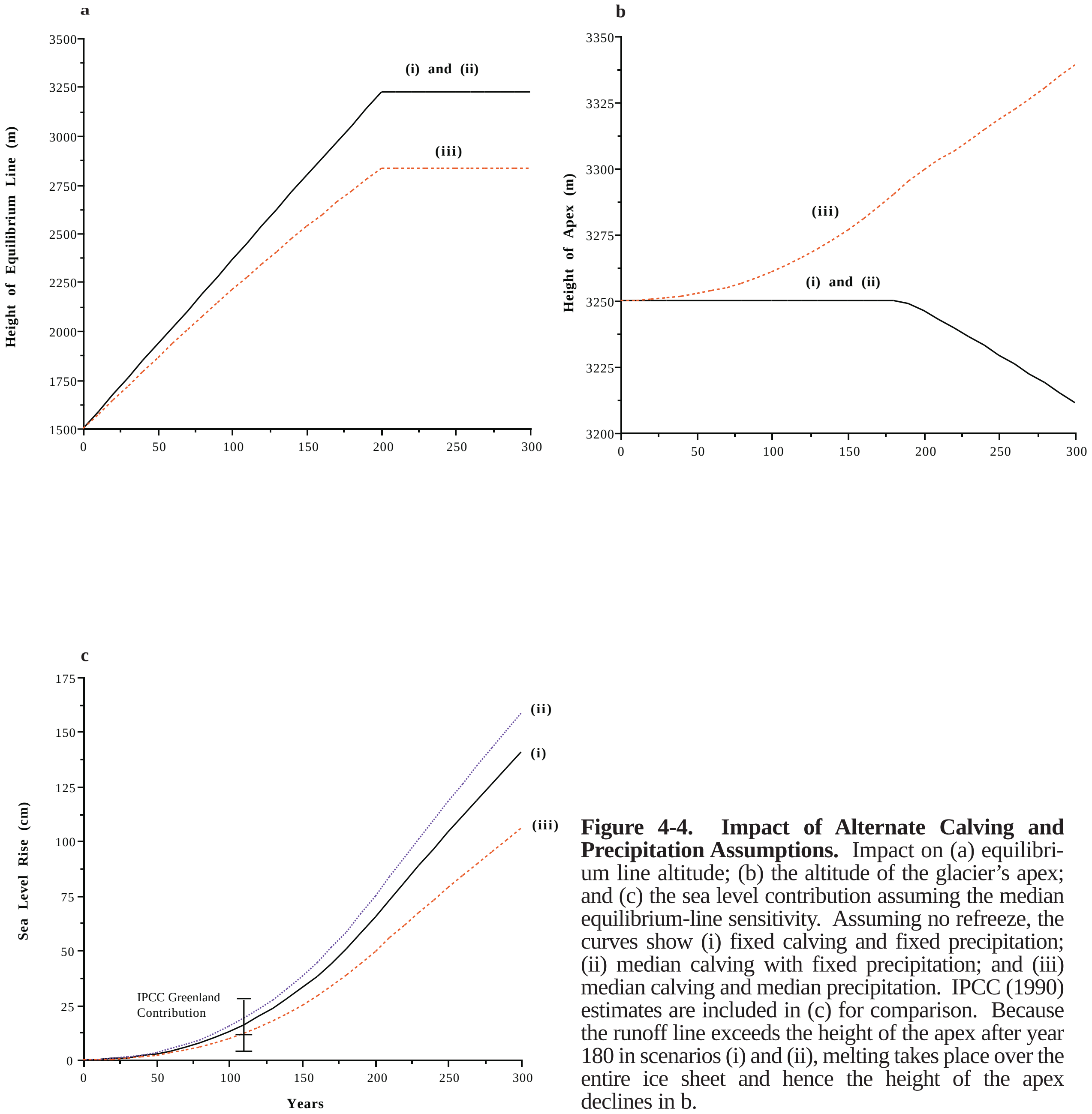

Figure 4-4. Impact of Alternate Calving and Precipitation Assumptions. Impact on (a) equilibrium line altitude; (b) the altitude of the glacier's apex; and (c) the sea level contribution assuming the median equilibrium-line sensitivity. Assuming no refreeze, the curves show (i) fixed calving and fixed precipitation; (ii) median calving with fixed precipitation; and (iii) median calving and median precipitation. IPCC (1990) estimates are included in (c) for comparison. Because the runoff line exceeds the height of the apex after year 180 in scenarios (i) and (ii), melting takes place over the entire ice sheet and hence the height of the apex declines in b.

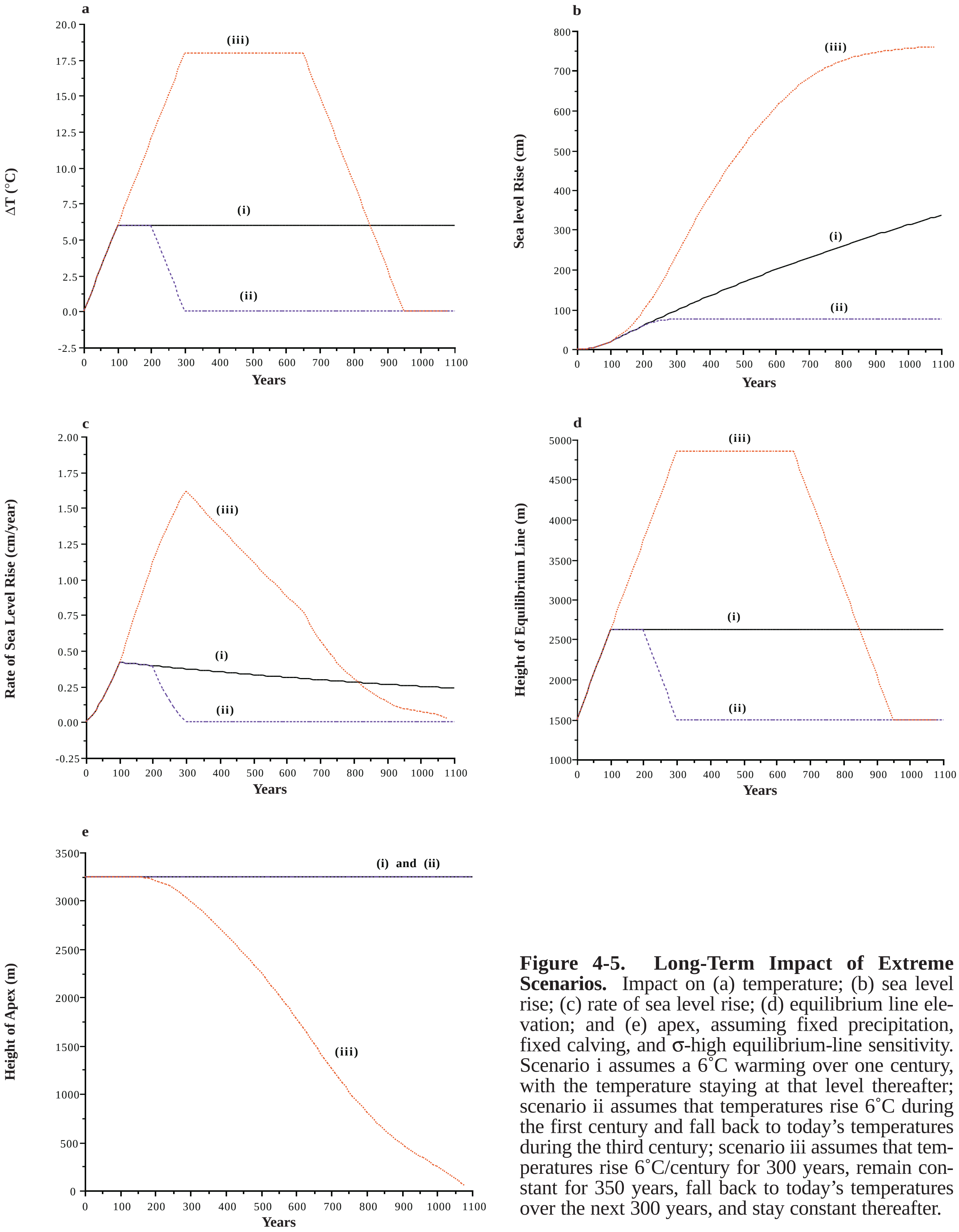

Figure 4-5. Long-Term Impact of Extreme Scenarios. Impact on (a) temperature; (b) sea level rise; (c) rate of sea level rise; (d) equilibrium line elevation; and (e) apex, assuming fixed precipitation, fixed calving, and σ-high equilibrium-line sensitivity. Scenario i assumes a 6˚C warming over one century, with the temperature staying at that level thereafter; scenario ii assumes that temperatures rise 6˚C during the first century and fall back to today's temperatures during the third century; scenario iii assumes that temperatures rise 6˚C/century for 300 years, remain constant for 350 years, fall back to today's temperatures over the next 300 years, and stay constant thereafter.

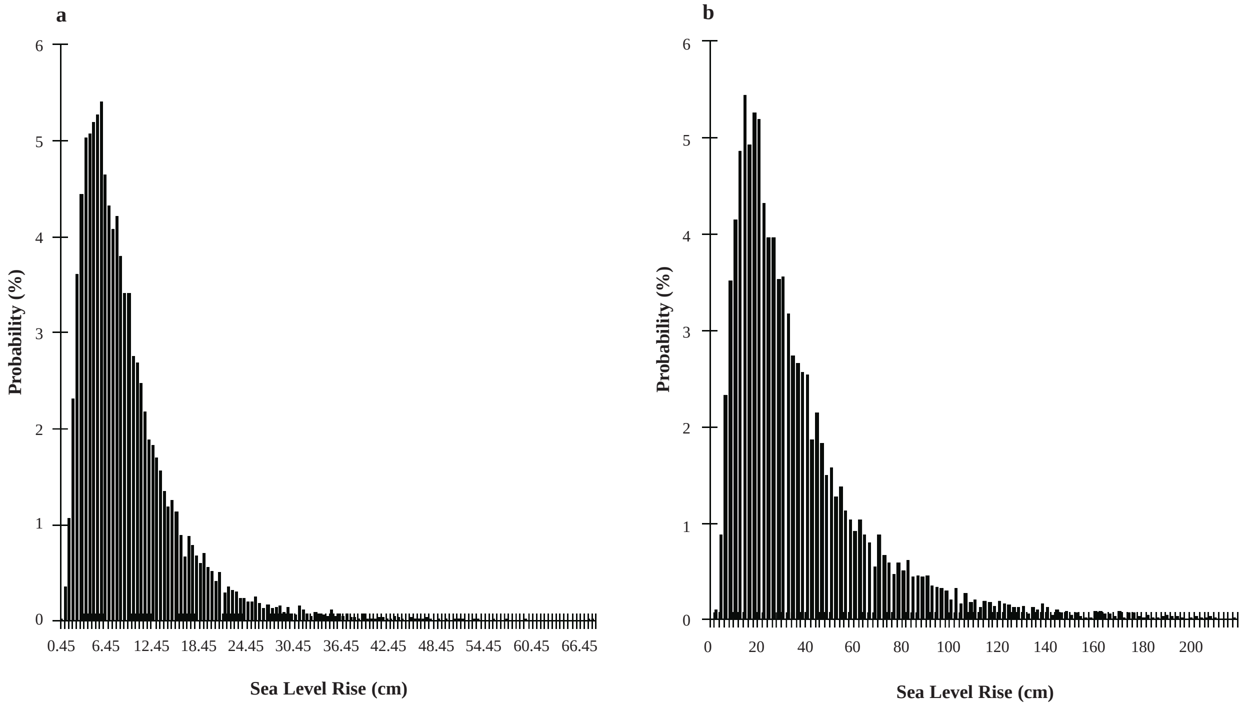

Figure 4-6. Probability Density of the Greenland Contribution to Sea Level: Draft Report. Contribution between 1990 and (a) 2100 and (b) 2200.

Figure 4-6 and Table 4-1 illustrate the frequency distribution for the draft's 10,000 simulations. Comparing these results with those of IPCC suggests that our results for the year 2100 have tracked the IPCC range quite closely. For example, the median estimate of 6.9 cm was 39 percent lower than the IPCC best guess of 11.65 cm; the 5%-low estimate was 25 percent less than the IPCC low (2.9 cm), and the 95%-high was 23 percent less than the IPCC high estimate (27.7 cm). Only 3 percent of the draft simulations exceeded the IPCC high estimate, while over 10 percent of the simulations fell below IPCC's low estimate for the year 2100. Figure 4-7 provides the corresponding spaghetti diagrams.

Expert Judgment

The expert reviewers are listed in Table 4-2. Because we only have three parameters, the basic model selection was as much an issue for reviewers as was the particular parameter values. The initial draft assumed that G_1 (melt-line sensitivity) would have 2σ limits of 111.1 and 186.3 based on two independent measurements. One reviewer suggested that these two estimates should be viewed as σ limits; no reviewer took issue with that suggested change. The initial draft did not incorporate refreeze. Two reviewers suggested that it should be included, and it was. Nevertheless, this mechanism was not incorporated with the level of detail that we would have employed had it been part of the original design. In particular, we would like to have explicitly assumed no runoff where melting is less than 58 to 70 percent of precipitation. Although the mass balance of the Bindschadler model helps to minimize the impact on errors regarding the initial elevation of the runoff line, such improvements would be conceptually more appealing. As the section on refreezing discusses, however, the results would probably not be much different.

The reviewers generally indicated that the Bindschadler model is adequate for our purposes. One reviewer, however, questioned why we did not disaggregate geographically. Our answer is that none of the authors of the more elaborate models were ready to provide us with the necessary computer code, and developing such a model ourselves would have required more resources than we had. Moreover, another reviewer noted that a portable and improved model of Greenland should be available relatively soon, but that the more elaborate models seem to yield essentially the same results anyway. Finally, one reviewer suggested

TABLE 4-1
DRAFT CUMULATIVE PROBABILITY DISTRIBUTION OF GREENLAND CONTRIBUTION TO SEA LEVEL

Cumulative Probability (%)	2030	2100	2200
1[a]	0.15	1.4	4
5[a]	0.25	2.2	7
10	0.3	2.8	10
20	0.4	3.9	14
30	0.5	4.8	18
40	0.6	5.7	22
50	0.7	6.9	26
60	0.8	8.1	32
70	1.0	9.9	40
80	1.2	12	52
90	1.5	17	76
95	1.8	21	100
97.5	2.1	26	126
99	2.6	34	163
Mean	0.82	8.6	36
σ	0.49	6.5	32

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

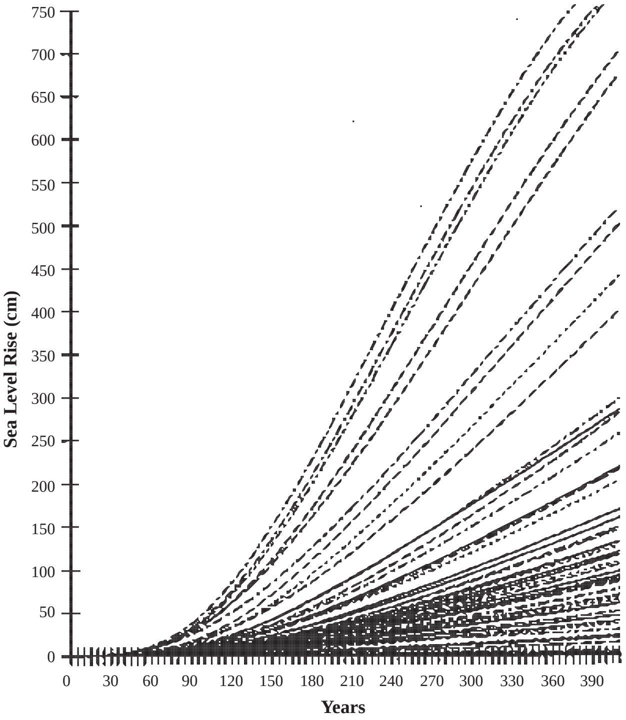

Figure 4-7. Draft Greenland Contribution for Selected Simulations, 1990-2400. See Figure 2-5 and accompanying text for description of these simulations.

that the initial equilibrium line may be on the high side; the possible implications of that observation, if valid, are discussed in the section on refreezing.

Unlike the previous chapter on ocean modeling and the next chapter on Antarctica, the reviewers did not provide divergent assessments of the magnitude and uncertainty surrounding the possible impact of temperature and precipitation changes on Greenland. Therefore, we did not develop separate distributions for each of the expert reviewers. For all but one-eighth of the simulations, the parameter values in Table 1-1 completely define the distributions employed by our analysis of the response of the Greenland Ice Sheet to changes in climate.[28]

One-eighth of our simulations for Chapters 3, 4, 5, and 6 represent the assumptions proposed by Wigley & Raper.[29] Their proposed model for Greenland was the IPCC (1990) equation:

$$dSL_{Greenland}/dt = \beta_G \, \Delta T_{Greenland},$$

where β_G has a mean of 0.3 and 1.65σ limits of 0.1 and 0.5, and dSL/dt is measured in mm/yr.

Final Results

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[28] We remind the reader, however, that the precipitation scenarios used in the *sensitivity analyses* of this chapter were based on our initial assumptions that precipitation will change with saturation vapor pressure or its derivative. One reviewer of Chapter 3, however, has done field research suggesting that precipitation may be much less. Including his assessment in our distributions has the net effect of lowering the projections of future precipitation increases.

[29] *See* **Correlations Between Assumptions**, Chapter 1, *supra.*

TABLE 4-2
EXPERT REVIEWERS OF CHAPTER 4

Walter Ambach	University of Innsbruck	Innsbruck, Austria
Robert Bindschadler	NASA/Goddard Space Flight Center	Greenbelt, MD
Roger Braithwaite	Geological Survey of Greenland	Copenhagen, Dnmk
Mark Meier	University of Colorado	Boulder, CO
Robert Thomas	Greenland Ice Core Project NASA Headquarters	Washington, DC
Jay Zwally	NASA/Goddard Space Flight Center	Greenbelt, MD

Figure 4-8 illustrates the cumulative probability distributions from the Greenland analysis. Combining the reviewer assumptions with the nonlinear Bindschadler model implies a median Greenland contribution of only about 2.9 cm by 2100, much less than the 7.5 cm implied by the linearity assumptions favored by Wigley & Raper. However, the 95 percent confidence range implied by the combined assumptions is –0.37 to 19 cm, while for Wigley & Raper it is 2.5 to 15 cm. By the year 2200, the assumptions imply a median contribution of 12 cm, but a 10 percent chance of a 50 cm contribution. Table 4-3 summarizes the cumulative probability distributions for 2050, 2100, and 2200.

The final median estimate is about half the estimate from the draft report, primarily for two reasons: (1) the revisions to atmospheric forcing (Chapter 2) resulted in lower estimates of global warming, as discussed in Chapter 3; and (2) two of the climate reviewers expect Greenland to warm 0.5 to 1.0 times the global warming, rather than 1.5 times the global warming assumed by IPCC (1990) and the draft median scenario. The delay due to refreeze also has a negative, but small, downward impact on the median estimate.

At the high end of the range, the final results are only slightly lower than the draft results. Although the reviewer assumptions resulted in a lower median estimate of Greenland warming, the 5%-high estimate of 8.06˚C by the year 2100 is as high as assumed in the draft report.

At the low end of the range, the reviewer assumptions imply a 5 percent chance that Greenland will have a negative contribution to sea level through the year 2100. Such a decline is possible for two reasons. First, in approximately 2 percent of the simulations, Greenland temperatures (and thus the annual rate of melting) *decline*, while in the draft, Greenland temperatures were projected to rise in all cases. Second, the Zwally precipitation assumptions (Chapter 3B) increase the risk of a very large increase in snowfall.

The spaghetti diagrams in Figures 4-9 and 4-10 illustrate the dynamics of the Greenland contribution. Because temperatures increase steadily throughout the period, so does the annual contribution to sea level; the median contribution rises from about 0.2 mm/yr in 2050, to about 0.6 mm/yr in 2100, to more than 1 mm/yr after about 200 years. Moreover, in about 15 percent of the cases, the annual contribution exceeds 3 mm/yr within the next two centuries.

In one simulation, however, the Greenland contribution peaks at about 0.3 mm/yr in 2100, but subsequently reverses, becomes negative, and drops off the bottom of the scale by 2270. This scenario is possible largely because precipitation rises exponentially with temperature, while annual melting is mostly linear.[30] At the high end of Zwally's assumptions, precipitation increases 20 percent per degree (C). Thus, the first degree increases precipitation from 1.33 to 1.59 mm/yr (sea level equivalent)—an increase of 0.26 mm/yr—while the fourth degree of warming increases precipitation from 2.3 to 2.76 mm/yr—an increase of 0.46 mm/yr.

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[30] As discussed above, melting is modeled as a cubic of temperature, but the linear term dominates.

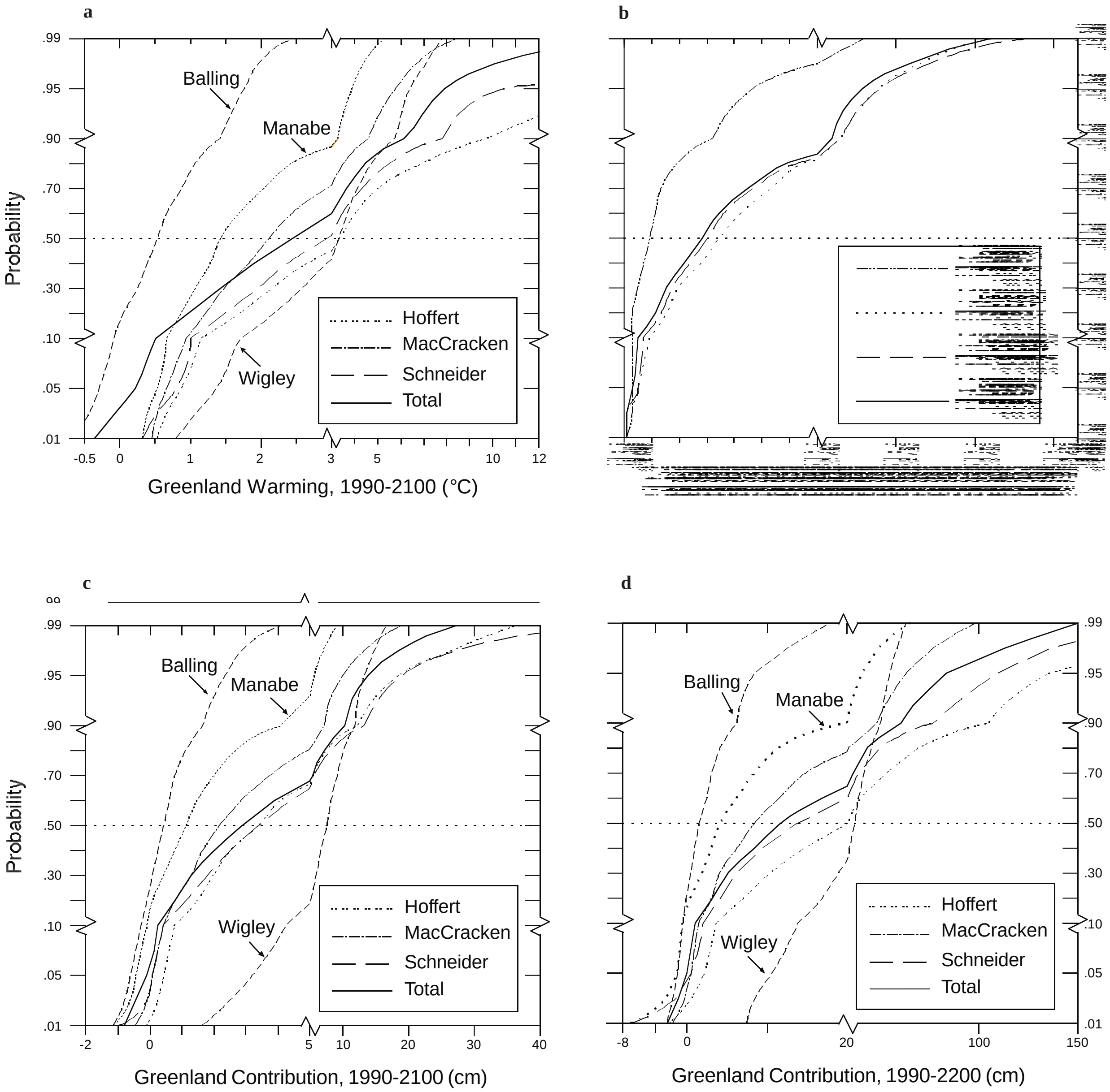

Figure 4-8. **Climate Change in Greenland.** Cumulative probability of (a) warming by the year 2100; (b) sea level equivalent of annual precipitation in 2100, assuming that the current rate is 1.33 mm/yr; and Greenland contribution to sea level through the years (c) 2100 and (d) 2200. The Rind, MacCracken, and Schneider precipitation assumptions were essentially the same as those of Kuhn. The contribution to sea level attributed to Wigley (and Raper) is based on their assumptions regarding both Greenland climate and the sensitivity of the ice sheet to warmer temperatures; all other estimates are based on the named reviewers' Greenland temperature assumptions, the precipitation reviewer assumptions, and the Bindshadler (1985) model employed with the consensus assumptions adopted by the glaciology reviewers.

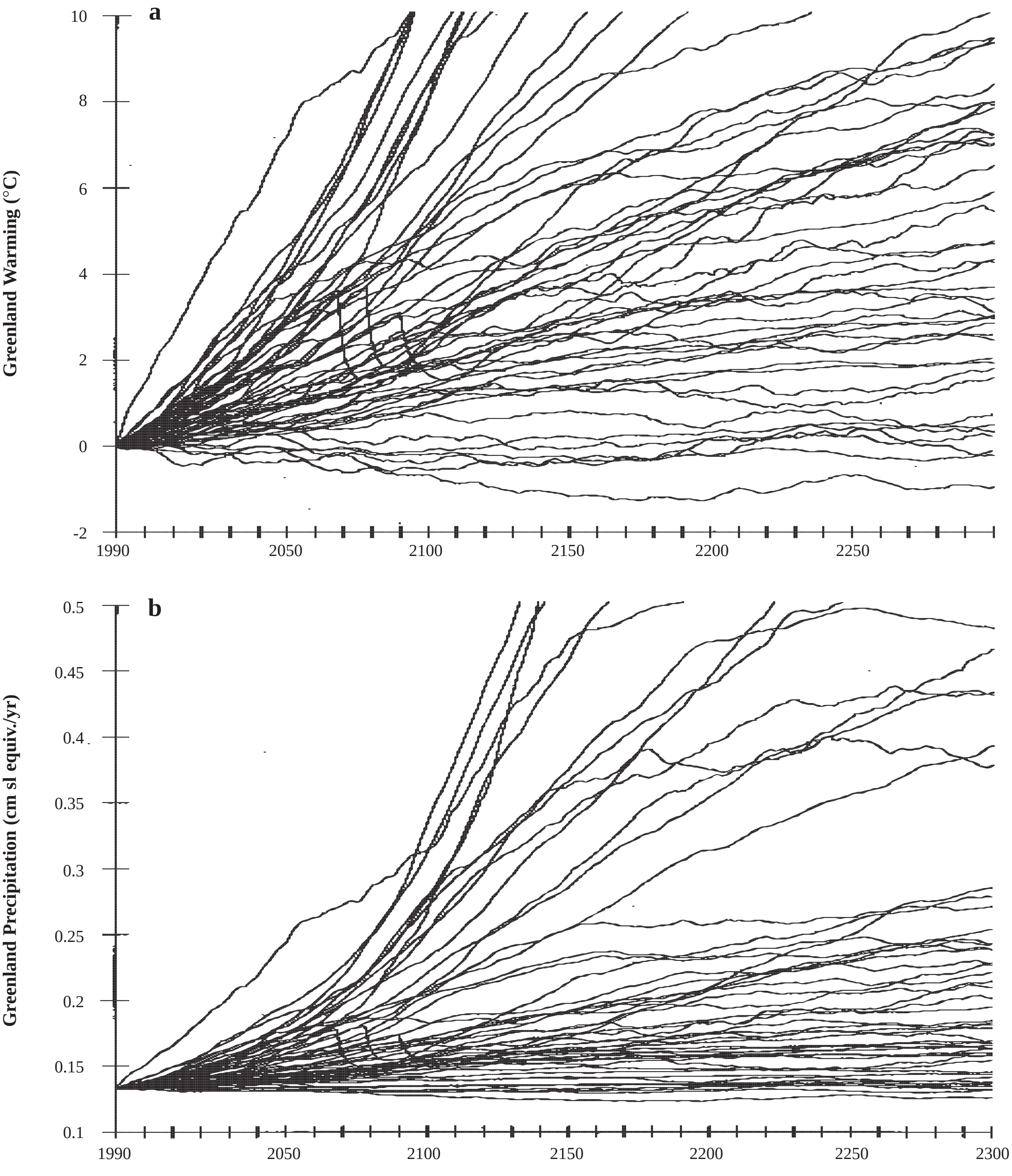

Figure 4-9. Spaghetti Diagram of Change in Greenland Climate. Increase in (a) temperatures and (b) precipitation over the Greenland Ice Sheet.

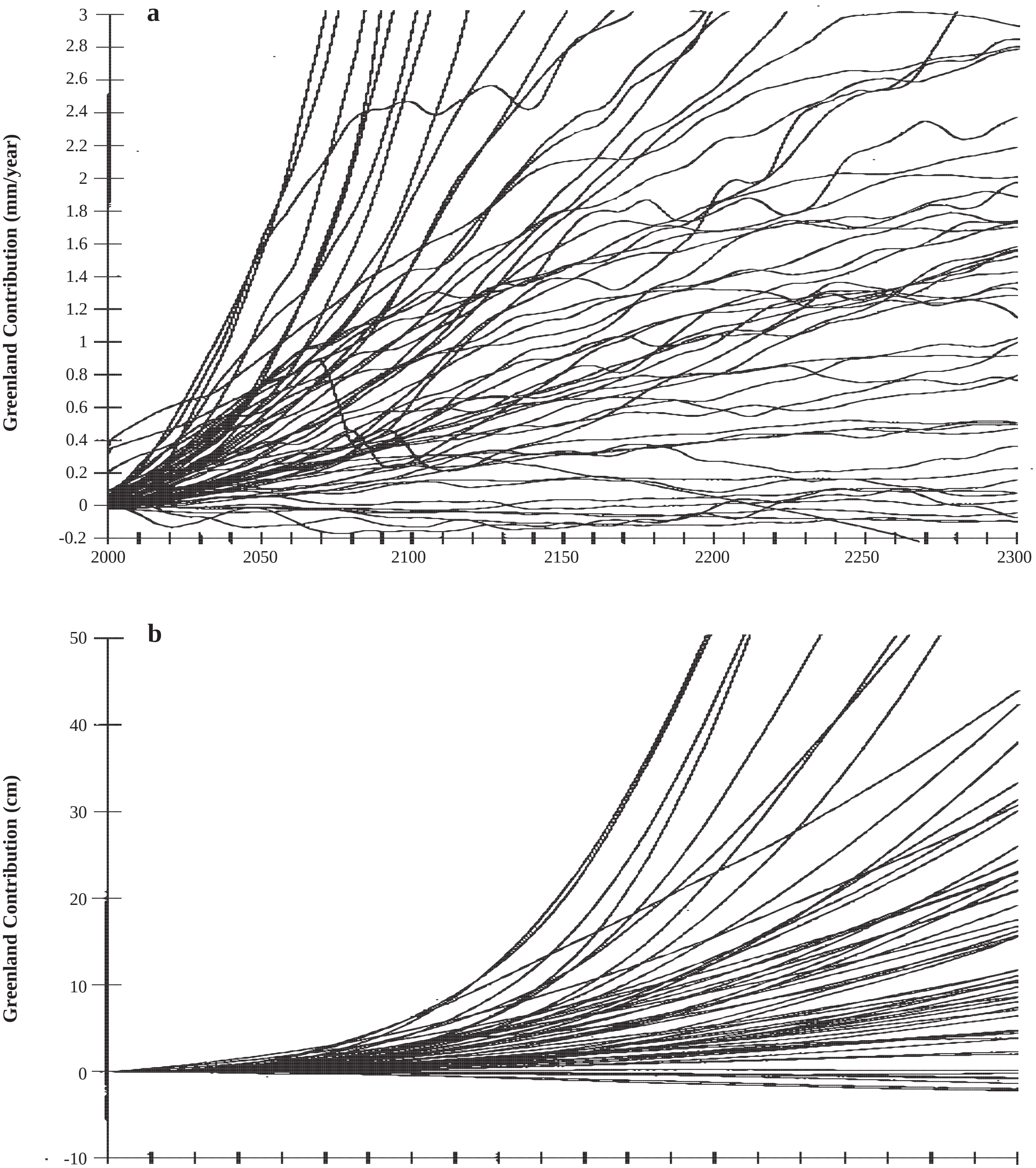

Figure 4-10. Spaghetti Diagram of Greenland Contribution to Sea Level. Selected simulations of (a) the rate of sea level contribution 1990–2300 and (b) total contribution 1990–2200. See Figure 2-5 for additional explanation on the scenarios chosen for this and other spaghetti diagrams.

TABLE 4-3
FINAL CUMULATIVE PROBABILITY DISTRIBUTION OF GREENLAND CONTRIBUTION TO SEA LEVEL

Cumulative Probability (%)	2050	2100	2200
0.1[a]	–0.9	–4.2	–11.4
0.5[a]	–0.4	–1.3	–5.8
1[a]	–0.3	–0.8	–2.7
5[a]	–0.2	–0.1	–1.1
10	–0.1	0.2	0.9
20	0.0	0.8	2.9
30	0.2	1.3	5.3
40	0.3	2.0	8.2
50	0.5	2.9	12.3
60	1.0	4.0	17.2
70	1.3	5.4	23.0
80	1.9	7.3	31.2
90	2.8	10.3	50.0
95	3.7	13.8	77.0
97.5	4.5	18.6	109.9
99	5.7	27.2	150.9
99.5[a]	6.7	36.1	190.2
99.9[a]	12.5	64.9	237.0
Mean	1.1	4.6	21.4
σ	1.6	6.3	29.8

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

Because Greenland melting in this scenario increases by about 0.4 mm/yr per degree (C), warming causes a net contribution for the first few degrees; but after a warming of about 3˚C, each additional degree increases the precipitation by more than it increases the melting. By the time the warming exceeds 5˚C, the increased precipitation exceeds the increased melting and the annual contribution becomes negative.

Although our simulations illustrate two mechanisms by which the Greenland contribution might be negative,[31] they are both based on our simplistic parameterization of Greenland climate. We ignore two other possibilities that may be equally important and could change the Greenland contribution in either direction. First, an increase in sulfate concentrations may have a greater impact on Greenland temperatures compared with the global impact. As a result, global temperatures could continue to rise while Greenland temperatures fall, which has been the pattern over the last fifty years (Karl et al. 1995). On the other hand, if SO_2 control in the United States reduces sulfate concentrations, the warming effect on Greenland could be greater than the effect on the global average temperature.

Second, changes in North Atlantic deepwater formation could cause Greenland to cool, and thus cause melting to decline, without necessarily causing precipitation to decrease as well. As discussed in Chapter 3, Manabe and others have suggested that deepwater formation could decline as a result of increased precipitation over the North Atlantic. Under such a scenario, precipitation may increase over Greenland as well, while the decline in deepwater formation slows the Gulf Stream, cools Greenland, and reduces melting. On the other hand, if precipitation barely increases around Greenland, as projected by Alley, the increased North Atlantic evaporation could strengthen thermohaline circulation and cause Greenland to warm much more than the global average warming.

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Chapter 4

CHAPTER 5

ANTARCTIC ICE SHEET

Background

Because of Antarctica's potential importance and the many processes by which it might contribute to sea level, our analysis of this ice sheet is somewhat more detailed than those employed by the previous EPA and IPCC assessments of future sea level rise. Studies *not* designed to forecast sea level in specific years, however, have employed several models at various levels of complexity. We briefly summarize previous efforts.

National Research Council (1985) estimated that warmer water temperatures could increase melting under the Ross Ice Shelf by about 1 to 3 m/yr (compared with 17 cm/yr today). The NRC's Polar Research Board adopted as its high scenario a model result reported in an appendix by Thomas (1985), in which the Antarctic contribution to sea level by the year 2100 is about 100 cm.[1]

Thomas (1985) employed two models to test the sensitivity of Antarctic ice sheets to scenarios in which the rate of basal shelf melting increases linearly by 1 m/yr or 3 m/yr by 2050 and remains constant thereafter. In the first model, the increased flow of ice from ice streams into the shelf exactly balances the increased basal melting. As a result, sea level rises about 30 and 90 cm by 2100 for the two scenarios.

The second model was an ice-stream model, which Thomas used to estimate the resulting discharge of ice from Ice Stream B, before extrapolating the results to all of Antarctica. The model assumes that higher ice-stream velocity and the resulting flow of ice shelves would increase total calving even if the seaward margins of the shelves remained in their present locations. Under the 1 m/yr and 3 m/yr shelf-melt scenarios, the model gave results of 13–30 cm and 55–130 cm. Thomas also considered an "enhanced calving" scenario "with ice fronts calving back to a line linking adjacent areas of grounded ice in the 2050s." These assumptions result in a rise of 92–239 cm and 121–295 cm by 2100, for the 1 m/yr and 3 m/yr scenarios, respectively.

Lingle (1985) used the same scenario of shelf thinning, but applied a model of Ice Stream E. The model suggests that for a 10 percent thinning of the ice shelf, the ice sheet/shelf system is stable. However, if the shelf thins 50 percent, it is unstable; *i.e.*, reduced backpressure from the shelf enables the ice stream to accelerate. The greater acceleration results in calving, rather than a (negative feedback) buildup of ice shelf mass. Complete disintegration of the West Antarctic Ice Sheet takes 660 years. However, for a 1 m/yr thinning rate, the contribution to sea level is only 3 to 5 cm over a 100-year period.

Huybrechts & Oerlemans (1990) analyzed the sensitivity of Antarctic mass to climate change and ice-shelf thinning. Given a scenario in which Antarctic annual temperatures rise 4.2˚C over a 250-year period, they estimated that sea level would fall 6 cm. Given current climate and an instantaneous increase in shelf thinning of 1 m/yr, they estimated a cumulative rise of 2, 5, 12, 20, and 30 cm after each of the next five centuries.

MacAyeal (1992) examined the impacts of climate change on the Antarctic ice sheets assuming that the ice-shelf basal melting remains constant. The analysis was based on ice stream bed frictional changes resulting from (a) warmer ambient temperatures and (b) precipitation changes. His analysis suggests that the loss of ice mass could be enough to raise sea level 60 cm or lower it on the order of 10 cm, with the latter condition being sufficiently more likely than the former so as to leave an expected change of about zero. He argued that, in principle, it would be possible to collect sufficient data on the stream bed characteristics (initial conditions) to establish which response is most likely, but that such data may be prohibitively expensive.

IPCC (1990) concluded that the Antarctic contribution (including increased precipitation) will be between zero and a decline in sea level of 0.6 mm/yr per degree (C) warming.

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[1] The NRC summary table explanations are somewhat inconsistent with the Thomas results on which it relies. On page 64, note 10 of the table states that the calculation assumed that the Ross Ice Shelf melts 3 m/yr and that all the ice in Antarctica responds as ice streams B and E, resulting in a 1 m contribution. However, Thomas gets a 1 m contribution from either (1) assuming 1 m/yr and all ice behaving as ice stream B or (2) assuming 3 m/yr and only enough glacial discharge to equal the melting that results. When Thomas uses both the 3 m/yr and the assumption that glacial discharge equals basal melting, he gets 2.2 m. Therefore, we interpret the table on page 64 of the NRC report as consistent with either (1) or (2), not both.

Drewry & Morris (1992) modeled the response of Antarctica to climate change by disaggregating it as (i) the interior of the ice sheet; (ii) the maritime margin of the continent; and (iii) the Antarctic peninsula. Their model indicates that for a 2˚C warming in mean annual surface temperature over a 40-year period, the peninsula is likely to make a net contribution of 0.5 mm to sea level.

To the extent that these models each represent how some researchers believe the Antarctic ice sheet could respond, the most desirable approach would be to run all the available models and assign probabilities to each. However, some of these models are too expensive to undertake several runs: MacAyeal's model, for example, takes tens of hours on a Cray computer.

Therefore, we are left with three models of the continent-wide contribution:

1. The IPCC model, which essentially assumes that the Antarctic contribution is zero (aside from changes in precipitation). We call this model AM1.

2. The ice-shelf basal melt rate model developed by the Polar Research Board report (NRC 1985).

3. The Thomas ice stream model.[2]

All of these models have important limitations: In a recent letter to the IPCC, the authors of the PRB report noted that the assumption of no ice-sheet response is a very poor characterization of the existing uncertainty range, even though it may not be a bad "median" estimate (see Appendix 3).

The estimate of basal melting, by itself, does not provide a sea level rise estimate, because the ice shelf is already floating. To estimate sea level rise requires an assumption regarding the response of the ice sheet to the shelf thinning. The simplest approach is to ignore this distinction by assuming that the melting reduces the backpressure of the shelves, allowing ice to flow from the sheet into the shelves until the shelves reach their original size; *i.e.*, the contribution to sea level equals the basal melting. At least in the short run, this simple model overstates how rapidly sea level rises by implying that the adjustment is instantaneous. Over long periods of time, however, it may understate sea level rise by assuming that the rate of calving does not increase.

Criticisms of the Thomas model fall into two categories: First, it may overstate the response of Ice Stream B to ice-shelf thinning, because it assumes that ice-shelf backpressure is the only force preventing Ice Stream B from reaching a maximum velocity of 20 km/yr. Second, the response of Ice Stream B to ice-shelf thinning is not typical of all Antarctic ice discharge. Ice streams account for a large fraction of ice discharge, but the streams that feed the major ice shelves account for only about 20 percent of the discharge. Since ice-shelf thinning would accelerate only those streams for which shelf backpressure is a major impediment to stream velocity, extrapolating to the entire continent overstates ice discharge.

Approach

Our overall approach is to consider the impacts of climate change on shelf melting, precipitation, and the flow rates of ice streams (see Figures 5-1 and 5-2). We divide the continent into seven regions: East Antarctica, the Antarctic Peninsula, the rest of West Antarctica (which is marine-based), and the Ross, Filchner/Ronne, Amery, and other ice shelves. Relying primarily on data compiled by Bentley & Giovenetti (1990), we use the annual mass balance estimates shown in Table 5-1, which reports accumulation, calving, melting, and the quantities of ice that the ice streams convey from the grounded ice sheets to the floating ice shelves. The table suggests that calving and basal ice-shelf melting almost balance accumulation and that ablation/runoff from grounded ice is negligible. As a result, the mass of the ice sheet is increasing enough to lower sea level 0.1 to 1.1 mm/yr; we incorporate this slightly positive mass balance into our background assumptions. Table 5-2 reports the mass and area of the four major regions into which Antarctica's ice can be divided: East Antarctica, West Antarctica, Antarctic Peninsula, and ice shelves.

Warmer temperatures will probably increase the amount of precipitation falling on Antarctica (*see* Chapter 3), which would tend to increase the rate at which mass *enters* the ice sheet. We consider three ways by which the rate at which ice *leaves* the continent might accelerate:

(1) warmer circumpolar ocean water accelerates the melting of ice shelves, which increases the rate at which grounded ice flows into these shelves;

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[2] We can also at least summarize the Oerlemans results with a function expressing the relationship between shelf melting and ice stream contribution. *See infra.*

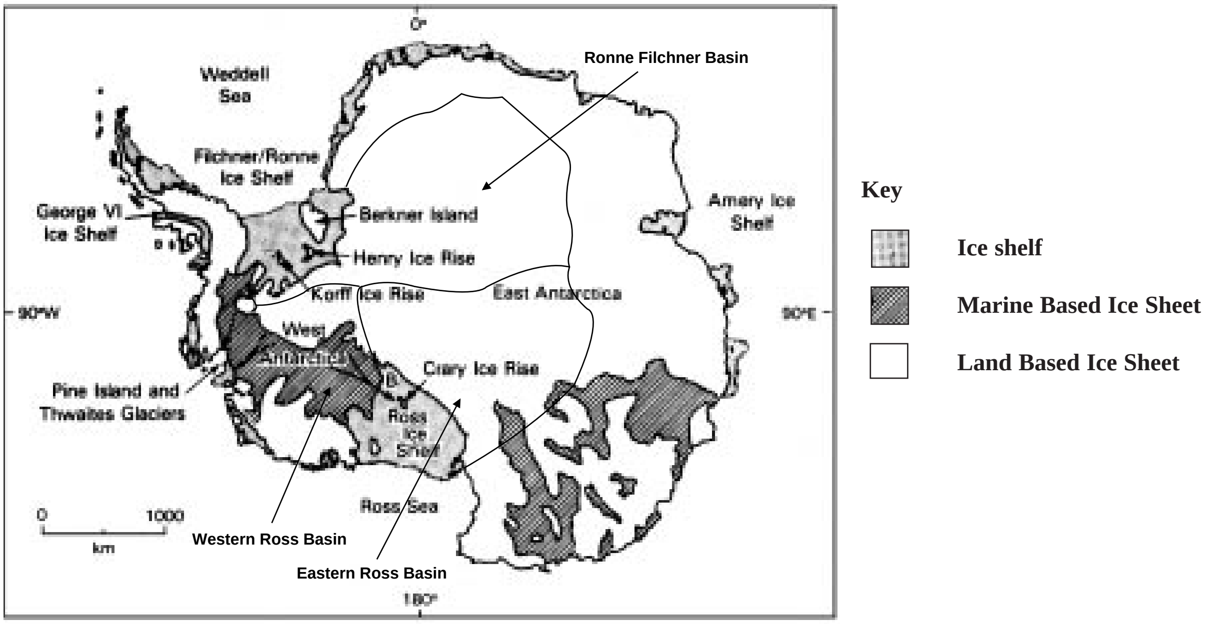

Figure 5-1. The Antarctic Basins Used in This Report.

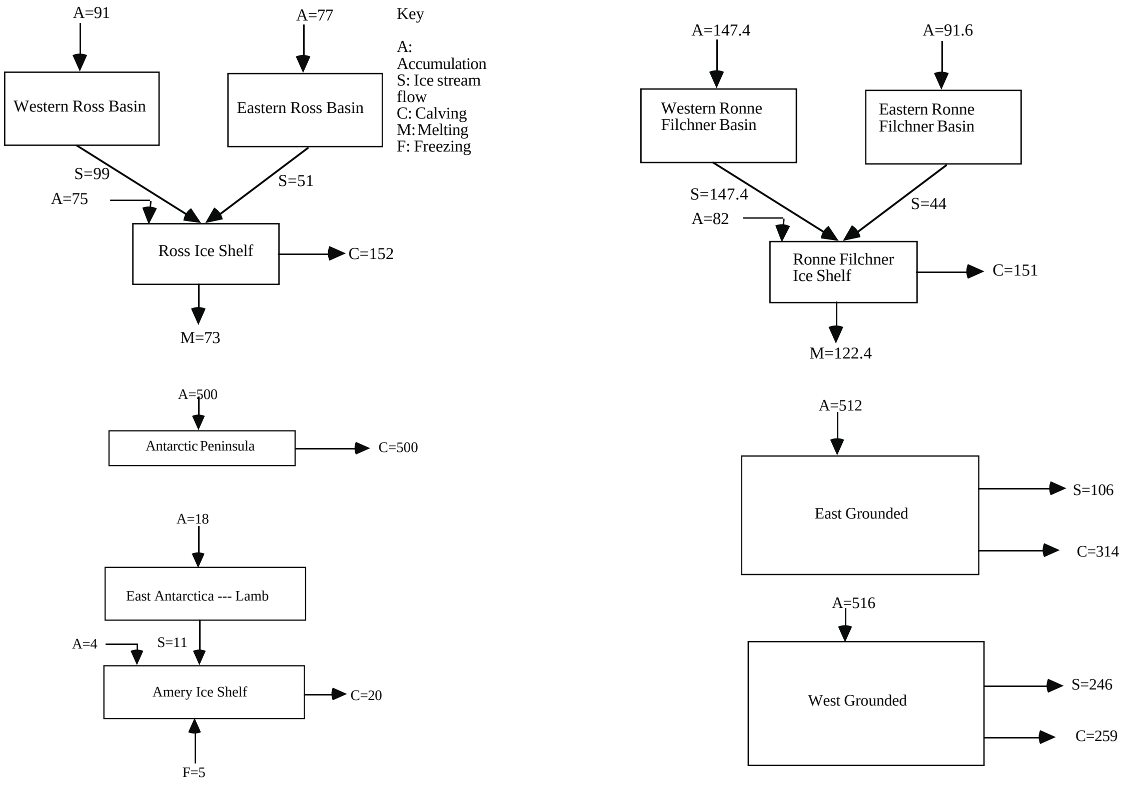

Figure 5-2. Schematic of the Antarctic Mass Flows Used in This Report.

TABLE 5-1
ANNUAL MASS BALANCE OF ANTARCTICA
(in gigatons)

	Accumulation[a]	Calving[b]	Stream[c]	Melt[d]	Mass Balance
<u>Specific Basins</u>					
Ronne/Filchner					
Western Basin	147.4	—	147.4	—	0
Eastern Basin	91.6	—	44	—	47.6
Ice Shelf	82	151	191.4	122.4	0
Ross					
Western Basin	91	—	99	—	-8
Eastern Basin	77	—	51	—	26
Ice Shelf	75	152	150	73	0
Other Parts of West Antarctica					
Antarctic Peninsula	500	500	—	—	0
West Other	257	146	—	93	18
East Antarctica					
Lambert Glacier	18	—	11	—	7
Amery Shelf	4	20	11	-5	0
East Other	143	131	—	0	12
Other Shelves	455	195.4	—	259.6	0
SUBTOTAL	1941	1295.4	352.4	543	102.6
Excluded Grounded[e]	203	203	—	0	0
West	20.3	20.3	—	0	0
East	182.7	182.7	—	0	0
TOTAL[f]	2144	1498.4	—	543	102.6
<u>Regions Used in This Analysis</u>					
East Grounded[g]	512	314	106	0	93
Ant Peninsula	500	500	0	0	0
West Marine Gr[h]	516	259	246	0	10
Shelves, Misc[i]	616	425	353	543	0
R/F Shelf	82	151	191	122	0
Ross Shelf	75	152	150	73	0
Amery Shelf	4	20	11	-5	0
Other Shelves	455	102	0	353	0

Accumulation ≡ Precipitation – sublimation over an area
Calving ≡ Discharge of icebergs from an ice shelf
Stream ≡ Amount of ice conveyed from grounded area to ice shelf
Melt ≡ Melting
Mass Balance ≡ Accumulation – Stream – Melt, for grounded areas
≡ Accumulation + Stream – Melt – Calving, for ice shelves

TABLE 5-1 (continued)

[a] From Bentley & Giovenetto (B&G) where possible. We allocate their estimates of accumulation in Ronne/Filchner (R/F) Basin between the shelves and grounded ice by assuming the same accumulation rate per unit area for that shelf as for Ross, and that the remaining accumulation is divided between east and west in the same proportions as would have been listed in B&G Table 3 had the typo been corrected for Eastern Ronne, which should say 123. West Other (WO) consists of Thwaites and Pine Island from Table 1 and George VI and Brunt from Table 3. East Other (EO) consists of Jutulstraumen, E. Queen, E. Enderby, and W. Wilkes from Table 1. AP is from Drewry (1992). Total and total shelf are from Jacobs et al. 1992; Other shelf is the difference between total shelf and those listed and thus includes George VI. Unmodeled represents areas not included by B&G other than the Antarctic peninsula and is the residual between total and those listed.

[b] Calving is from B&G outflow estimates for EO, WO, Ross, Amery, and Ronne/Filchner. For Antarctic Peninsula (AP), we assume that calving equals accumulation. For other shelves, we calculate calving rate necessary for shelf balance given calculated melt and inflow rates. For unmodeled, we assume that calving equals accumulation. For total, we add the various contributors, which gives the same result as calculating calving rate necessary for total continental mass balance to equal the mass balance of the modeled area, given accumulation and melt rates.

[c] Modeled stream outflows from B&G except for Western Ronne/Filchner, where we assume that the grounded ice in the basin has 0 mass balance, which is consistent with B&G Table 3's assertion that such an assumption is reasonable. By contrast, for the Eastern portion, where the assumption is viewed as unreasonable, we assume that flow is equal to the measured outflow for the basin, which results in a positive mass balance implied by B&G Table 3's assertion that 0 net balance is not reasonable. However, we do allow for enough melting to offset the precipitation over the shelf.

[d] Generally from B&G. WO is from Table 3, measured for Larsen at 1 m/yr and derived by B&G for George VI. For Ronne/Filchner, melt rate equals those derived and verified as reasonable by B&G for western region, plus a fraction of that derived and rejected for the eastern region. This latter fraction represents a melt rate sufficient to balance the eastern region of the shelf while leaving the grounded portion with the imbalance implied by the accumulation and outflow listed by B&G. Total melt from Jacobs et al. 1992. Other shelves estimate derived from Total minus those listed.

[e] Excluded area calculations based on the difference between subtotals from B&G data and totals from Jacobs et al. Arbitrary 90/10 division between east and west is based on the inspection of Figure 5 of B&G.

[f] Total Accumulation and Ice Shelf melting from Jacobs et al. Net balance is calculated based on conservative assumptions from Bentley; that is, mass balance outside of the area they studied is zero. Calving set consistent with those assumptions.

[g] Consists of E. Ross, E. R/F, E. Other, and E. Amery—Lambert.

[h] Consists of W. Ross, W. R/F, and WO, except that the 93 Gt/yr shelf melting that takes place in the WO basins is subtracted here and added back into shelves, below. To keep a balance, this 93 is added to calving. Similarly, 93 GT/yr is subtracted from calving for shelves.

[i] Consists of Ross, R/F, Amery, and other shelves. In addition, includes the shelf melting otherwise listed under West Other.

TABLE 5-2
VOLUME, AREA, AND THICKNESS ASSUMPTIONS FOR ANTARCTICA

	Volume ($10^6 km^3$)	Sea Level Equivalent[a] (m)	Area ($10^6 km^2$)	Thickness (m)
East Antarctica	25.92	65.78	9.86	2630
Antarctic Penin.	0.18	0.45	0.98	180
West Antarctica	3.22	8.17	1.36	2370
Shelves (total)	0.79	2.01[b]	1.62	490
Ross	0.21	0.53	0.40	525
Ronne/Filchner	0.23	0.58	0.40	575
Other[c]	0.35	0.89	0.80	450

[a] 394,0000 km^3 of ice would contribute 1 m of sea level rise.

[b] Melting ice shelves would not raise sea level because they are already floating.

[c] Includes Amery Ice Shelf.

SOURCE: Menard, H.W., and S.M. Smith. 1966. "Hypsometry of Ocean Provinces." *Journal of Geophysical Research* 4305-25.

(2) the increased temperatures in the Antarctic Peninsula increase the rate at which its ice flows toward the oceans; and

(3) increased (or decreased) mass of grounded ice increases (decreases) the forward pressure under which ice flows toward the ocean.

Because the Polar Research Board (NRC 1985) provided substantial analysis of how the first matter can be simplified, we focus primarily on that mechanism. We rely essentially on relationships presented in the summary report and appendices by Jacobs and Thomas, but formally generalize them in a common analytic framework. We first present the equations we use to operationalize the PRB's shelf melting assumptions. Next, we discuss several alternative models for describing the impact of shelf melt on Antarctic mass, along with two procedures by which we calculate the impact on mass without directly estimating the change in the shelves. Finally, we display the results for the Antarctic contribution to sea level.

The PRB approach consisted of two parts: (1) estimating the impact of warmer temperatures on shelf basal melt rates; and (2) estimating the resulting impact on the discharge of grounded ice into the ice shelves. We consider each in turn.

Basal Melting of Ice Shelves: Generalizing the Relations Expressed in the Polar Research Board Report

Ross Ice Shelf

Like the PRB, we started by employing the suggestion by Jacobs (1985) that net melting under the shelf results from "warm intrusions" that are currently 0.5˚C above the *in situ* melting point; *i.e.*, $^{-}1.4$˚C.[3] We treat this warm intrusion as a 5:1 mixture of shelf water at $^{-}1.9$˚C and circumpolar deep water (CDW) (currently at $^{+}1.1$˚C). Thus,

$$T_{warm} = \frac{T_{cdw} + 5(^{-}1.9)}{1 + 5}.$$

Reformulating the equation to allow for alternative sensitivities of the warm intrusion to CDW temperature,

$$T_{warm} = \frac{T_{cdw} - 1.9\ \mathrm{DILUTE}}{1 + \mathrm{DILUTE}}$$

where 1/(1 + DILUTE) represents the sensitivity of warm intrusion temperature to CDW temperature.[4]

If seaice formation declines, less shelf water will be created each year. (See Chapter 3 for our assumptions regarding seaice formation.) Therefore, we could assume that

$$\mathrm{DILUTE} = 5\ \mathrm{seaice}(t)/\mathrm{seaice}(0).$$

However, because the 5:1 assumption is merely an artifact of the observed temperatures, we have no reason to believe that it will persist, or even that mixing is the explanation for why the warm intrusions are 2.5˚C below the CDW temperature, which suggests:

$$T_{warm} = \frac{T_{cdw} - 1.9\ A_1\ \mathrm{SEAICE}}{1 + A_1\ \mathrm{SEAICE}}$$

where SEAICE=seaice(t)/seaice(0) and A_1 allows for alternative ratios of dilution. We assume that the median of the distribution of A_1 is 5.0. There is no *a priori* reason why the warm intrusion could not warm as much as the CDW, which occurs if $A_1=0$; by contrast, the equation explodes if $A_1={}^{-}1$. Therefore, we assume that (A_1+1) is lognormal, with a mean of 6 and 2σ limits of 1 and 36. The right hand of this distribution implies that the warm intrusions are very insensitive—perhaps unrealistically insensitive—to warming of CDW. Given our desire to use simple functions for probability distributions, we saw no way to avoid this situation.

However, this equation has to be modified, because it implies that the warm intrusion today has a temperature of $3/(1+A_1\mathrm{SEAICE})$ above the *in situ* melting temperature when, in fact, the temperature is 0.5˚C above the *in situ* melting temperature, regardless of the value for A_1. Therefore, we subtract $3/(1+A_1\mathrm{SEAICE}) - 0.5$. This adjustment is in turn multiplied by SEAICE; as

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[3] As discussed below, Jacobs now believes that colder, deeper high-salinity water, which is approximately 0.5˚C above the *in situ* freezing point at the *base* of the ice shelf, is more likely to be the explanation. *See* Jacobs et al. (1992).

[4] This formulation assumes that as CDW warms, there will not be additional cool shelf water to offset the impact of the warming. This linear specification effectively assumes that the portion of the excess heat (conveyed by the warm intrusion) that is transferred to the ice via melting will remain constant. As discussed in **Expert Judgment**, *infra*, one reviewer suggested that increased circulation between the circumpolar ocean and the subshelf cavity could result in a nonlinear response.

the dilution declines, so must the differences between the temperatures of CDW and the warm intrusion.

$$T_{warm} = \frac{T_{cdw} - 1.9\ A_1\ SEAICE}{1 + A_1\ SEAICE} - \frac{3\ SEAICE}{1 + A_1\ SEAICE} + 0.5\ SEAICE$$

The PRB also notes that there is a possibility that undiluted CDW would enter beneath the ice shelves, independent of the decline in dilution associated with decreased sea ice. Unfortunately, PRB specifies neither the probability of such an occurrence nor how that probability might change as a function of changing climate. In the above formulation, such an assumption implies that DILUTE=0.

In the absence of any such model, we assume that in the scenario analyzed by the PRB ($\Delta T_{cdw}=1$), the probability of such an occurrence is 5 percent. Moreover, we assume that the probability increases linearly with the warming of circumpolar ocean up to (the unlikely) warming of 5˚C, past which the probability of such a dilution remains at 25 percent no matter how much the Earth warms.

The PRB provides several indications of how much melting would take place with warmer intrusions. Assuming that net melting is proportional to the excess heat provided by the warm intrusion temperature, a 1˚C warming would triple the melt rate from 0.17 m/yr to 0.51 m/yr. The PRB report also suggests that a 3˚C warming associated with undiluted CDW flowing beneath the shelves would increase the thinning rate by 2 m/yr, but that the additional 1˚C warming could increase basal melting to 3 m/yr. Based on these observations, one could assume:

$$Melt = A_2\ (T_{warm} + 1.4)$$

where **Melt** refers to *increased* basal melting above the baseline, and $\mathbf{A_2}$ is lognormal with a median of 0.34 and 2σ limits of 0.17 and .68.

Figure 5-3 illustrates the CDW temperatures and resulting shelf-melt rates for alternate scenarios of global temperatures. The scenarios in the left half of the figure are based on the assumption that global temperatures rise for 100 years and are steady thereafter; those on the right side (other than scenario 3) involve global temperatures rising for 200 years. The relationships between the input temperature scenarios, as well as a few other scenarios that are used elsewhere in this chapter, are described in Figure 5-4 and Table 5-3.

Scenarios 3 and 4 both keep precipitation fixed, assume that global temperatures rise 4˚C per century, and employ median values for (a) the magnitude and timing of the CDW response to global temperatures; (b) the response of warm intrusion temperature to CDW; and (c) the response of basal shelf melting to warmer water temperatures. The only difference is that global temperatures stabilize after 100 years in scenario 3 and 200 years in scenario 4. Both scenarios imply that CDW warms 1.7˚C after 100 years; after 250 years the warming is 3.0˚C and 5.6˚C for the two scenarios, respectively. In both scenarios, the melt rates more than double in the first century from the current 0.17 m/yr to 0.421 m/yr; after 250 years they rise to 0.52 m/yr and 1.15 m/yr, respectively. Thus, for the next two centuries our median assumptions imply shelf-thinning rates well below the 1 m/yr generally viewed as a threshold for significant ice sheet responses—even when we assume a 4˚C/century global warming, which is almost twice our median temperature projection.

Only when we test the high-sensitivity sides of the distributions of our uncertainties do we obtain relatively high shelf thinning. Scenario 5, for example, assumes that the warm intrusion water will warm as much as CDW warms, even without the impact of declining SEAICE, allowing the shelf-thinning rate to exceed 1 m/yr after year 70; scenario 7 assumes that undiluted CDW penetrates the shelf after year 60, which increases the melt rate to 1.85 m/yr. Finally, scenario 10 is similar to scenario 5, except that (a) global temperatures warm for 200 years; (b) CDW is assumed to warm in equilibrium as much as the global warming, rather than only 3/4 as much; (c) the response time of CDW to global temperatures is assumed to be 20 instead of 40 years; and (d) the (offsetting) impact of increased precipitation is included. Given these plausible but unlikely assumptions, CDW warms 3.2˚C after 100 years and 7.9˚C after 250 years, leading to shelf-thinning rates of 5.9 and 10.6 m/yr, respectively.

Other Ice Shelves

Jenkins (1991) suggests that the average melt rate of the Ronne/Filchner Ice Shelf would increase by 3.333 m/yr per degree (C) warming of the Weddell Sea, while a previous study by the same researcher suggested that the melt rate would only increase by 1.91 m/yr. We use these rates as the 2σ limits of a

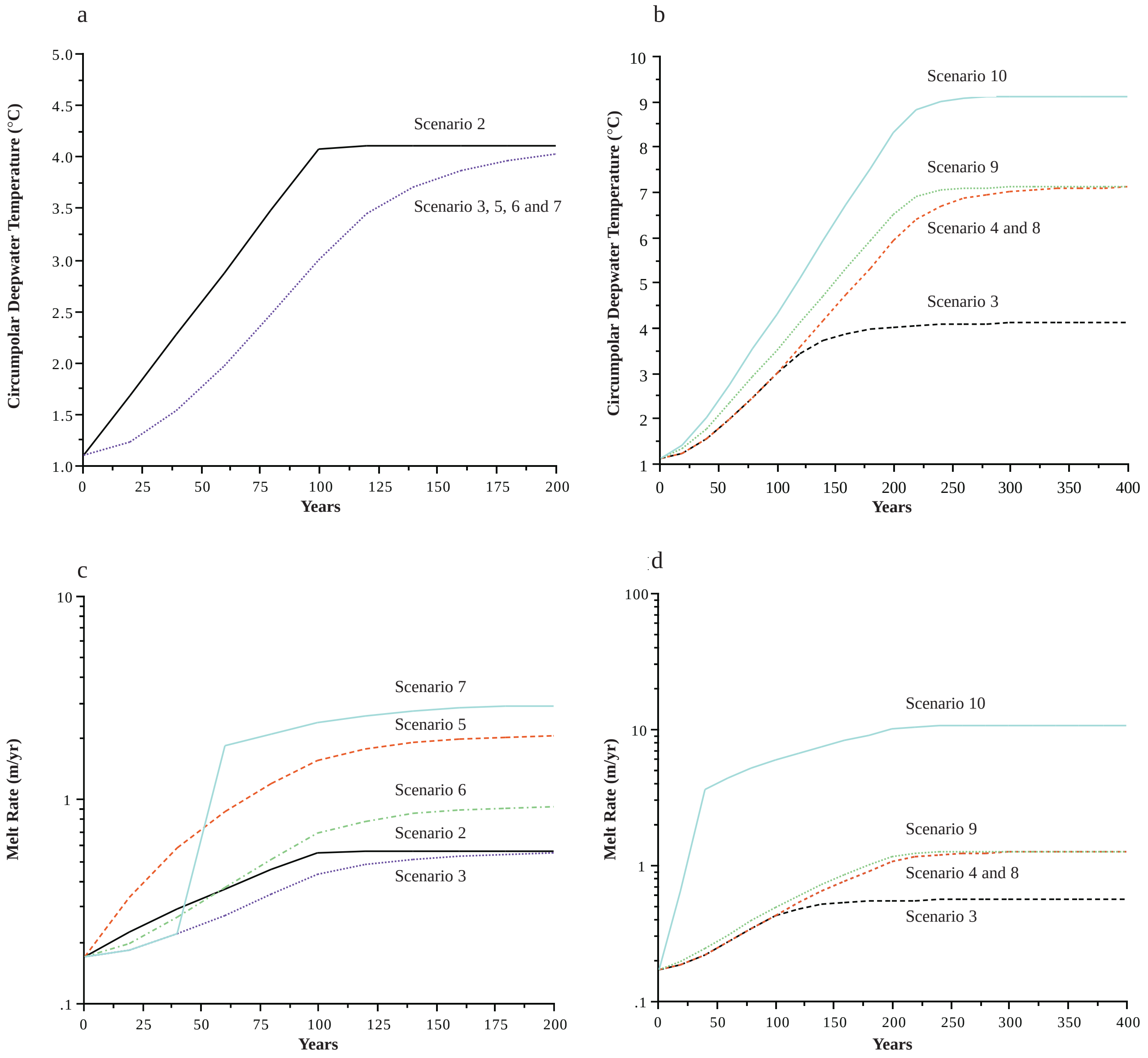

Figure 5-3. Circumpolar Deepwater Temperatures and Shelf Melt Rates for Various Scenarios. Scenarios defined in Table 5-3 are shown (a) for the first two hundred years and (b) for the first four hundred years. The corresponding shelf-melt rates are shown in (c) and (d). Scenario 3 is shown for comparison purposes in both the right and left sides. Note that this report assumes that the current rate of shelf melt is 0.17 m/yr, rather than the 0.25 m/yr used by the PRB report.

lognormal distribution. We assume that the Weddell Sea warms the same as circumpolar ocean.

The Amery Ice Shelf currently appears to have net basal freezing, as shown in Table 5-1. Lacking any better information, we assume that its melt rate would increase by 1 m/˚C warming of the circumpolar ocean.

Other shelves have varying melt rates. Most noteworthy are the Larsen and George VI ice shelves, which appear to have basal melt rates of 1 to 2 m/yr. Because most of these "other" ice shelves are relatively exposed to the circumpolar ocean, we assume that their melt rates would increase in proportion to the difference between circumpolar temperatures and the surface *in situ* freezing temperature of ⁻1.9˚C. Thus, 1˚C would increase melting by about 33 percent.

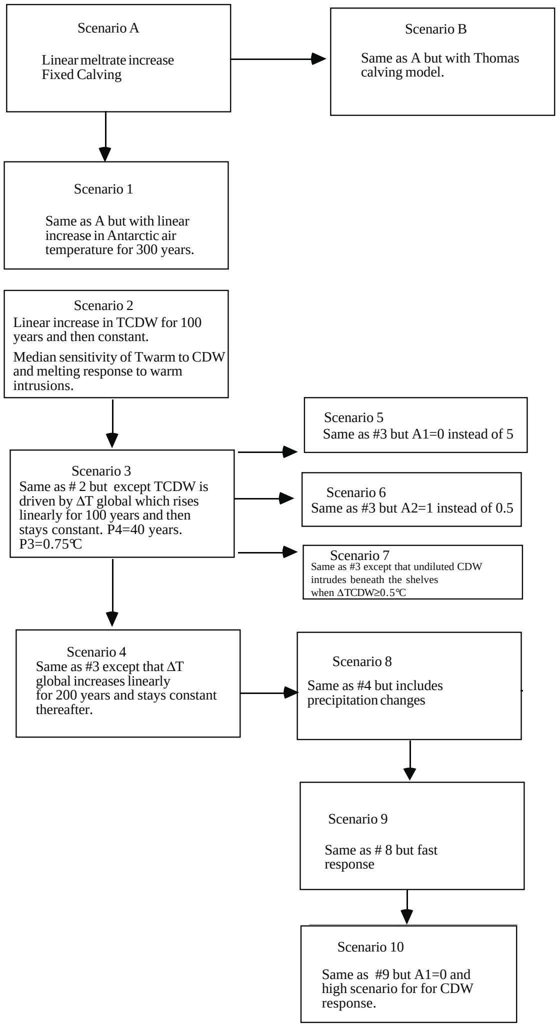

Figure 5-4. The Relationships Between the Sensitivity Runs.

Impact of Basal Melting on Grounded Ice

The draft employed five different models to describe the impact of ice-shelf melting on the ice stream contribution to sea level. We discuss each in turn.

Simple Model Based on Melting (AM2)

The simplest approach is to ignore the impact of ice streams and possible increased calving. Ice-shelf melting does not raise sea level, but a reasonable first approximation would be to assume that it does—at least eventually. In the most optimistic of cases, the increased melting comes entirely at the expense of decreased calving; in a pessimistic case, the thinner shelf permits faster ice flow and easier iceberg formation, and thereby increases calving. Lacking good models, the assumption that calving stays fixed is intuitively appealing.

Even in such a situation, the initial impact on sea level would be negligible because ice-shelf retreat would not automatically accelerate the ice streams. Nevertheless, even if the shelf exerted negligible backpressure on the ice streams, it does presumably exert backpressure on the part of the ice sheet immediately next to the ice shelf. Thus, if the shelf retreated to the grounding line, some grounded ice would flow onto the shelf to prevent the shelf from vanishing entirely. Therefore, even in the "melt-only" model, one can reasonably assume that the melt rate will continue after total melting has exceeded the current mass of the ice shelves.

Thus, the draft "melt-only" model assumed that shelf melt would make no contribution to sea level rise until A_7 percent of the shelves have melted, after which point the contribution is 1:1. We assume that A_7 follows a right-triangular distribution between 0 and 1 in which $pd(A_7)=2A_7$, where **pd** is the probability density function; that is, $F(A_7 \leq x)=x^2$, where **F** is the cumulative distribution function. For example, 75 percent of the time there will be no contribution to sea level rise until half the shelves have melted.

Figure 5-5 illustrates the Antarctic contribution resulting from the draft melt-only model given the same temperature scenarios shown on the right side of Figure 5-3 for alternative values of A_7.

TABLE 5-3
SCENARIOS USED FOR SENSITIVITY RUNS IN THIS CHAPTER

A. Ice shelf melt rate increases from 0 to 1 m/yr during first 50 years and remains 1 m/yr thereafter. Calving is fixed at current levels.

B. Same as A, but with Thomas's (nonenhanced) calving model.

1. Same as A except that Antarctic air and Antarctic summer temperatures rise 4˚C per century for first 300 years and remain constant thereafter, resulting in increased precipitation according to median scenario.

2. T_{cdw} rises 0.03˚C/yr for first 100 years and stays constant thereafter. Median scenarios for sensitivity of warm intrusion temperature to CDW (A_1=5.0; *i.e.*, holding SEAICE constant, intrusions warm 1/6 as much as CDW) and melting response to warm intrusions below the shelves (A_2=0.5 m/[˚C yr]). Undiluted CDW does not penetrate ice shelves. No change in precipitation.

3. Same as #2, except that T_{cdw} is driven by global temperatures, which rise 0.04˚C/yr for 100 years and stay constant thereafter. Adjustment time in excess of global adjustment time: P_4=40 years. Equilibrium CDW warming per degree of global warming: P_3=0.75˚C.

4. Same as #3, except that temperatures rise for 200 years and stay constant thereafter.

5. Same as #3, but A_1=0 instead of 5.

6. Same as #3, but A_2=1 instead of 0.5

7. Same as #3, except that undiluted CDW intrudes beneath the shelves as soon as CDW warms 0.5˚C.

8. Same as #4, but includes precipitation changes.

9. Same as #8, but fast response for CDW (*i.e.*, P4=20)

10. Same as #9, but (a) A_1=0 (*i.e.*, ignoring changes in sea ice, the warm water intruding beneath the shelves warms as much as CDW; as sea ice declines, the warm intrusion temperature approaches the CDW temperature) and (b) high scenario for total CDW response (*i.e.*, P_3=1).

<u>The Thomas Model</u> (AM3)

Thomas (1985) modeled Ice Stream B and extrapolated the results to the entire continent.

Ice Stream B. This two-dimensional model assumes that there is a single ice stream feeding an ice shelf. The two dimensions considered were altitude (*i.e.*, thickness of ice shelf) and longitude (*i.e.*, distance from grounding line to ocean/ice margin). The model parameters for ice-stream velocity and mass discharge were based on measurements for Ice Stream B. The distances from the grounding line to ice rises (pinning points) and to the ice margin, as well as the ice shelf's thickness, were based on the Ross Ice Shelf. The mass of the ice shelf was assumed to account for all the backpressure constraining the current ice-stream velocity. Thomas then picked an assumed velocity for a point about 200 km upstream of the grounding line, which provides the strain of the ice stream necessary to duplicate the observed velocity at the grounding line, given all the other parameters.

For a given acceleration in the rate of ice-shelf melting, the Thomas model calculates the resulting contribution to sea level, which we can view as:

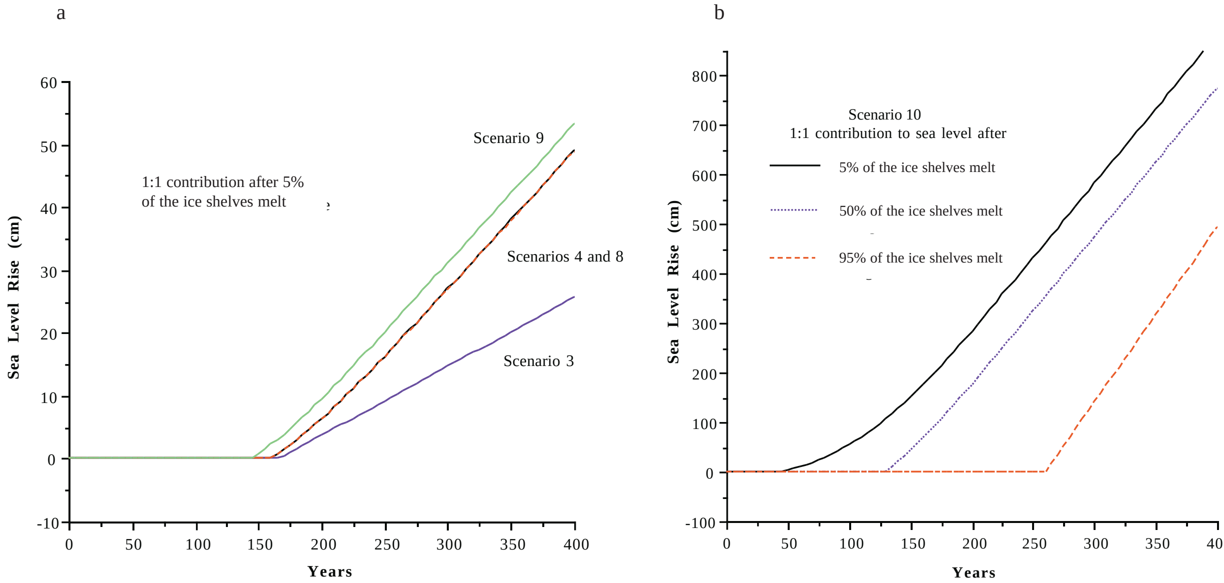

Figure 5-5. Antarctic Contribution for the Draft Melt-Only Model. Sea level contribution for (a) scenarios 3, 4, 8, and 9 (see Table 5-3), given the assumption that $(A_7)^{1/2}$ (the fraction of the ice sheet that must melt before melting contributes to sea level rise) is equal to 0.05, and (b) scenario 10 with A7 equal to .05, 0.5, and 0.95.

$$\Delta \text{ice stream discharge} = \Delta \text{melting} + \Delta \text{calving} + \Delta \text{shelf\_mass}.$$

A greater rate of ice-shelf melting initially thins the ice shelf, which reduces shelf backpressure, which in turn increases the ice-stream velocity. In Thomas's suggested formulation of the model, the ice front/calving margin remains in its current location. The higher stream (and shelf) velocity means that (1) the total area[5] of the ice shelf discharged in the form of icebergs in a given year is greater, but (2) the ice shelf is thinner, which implies that the icebergs do not draw as much water. Because shelf mass is proportional to the thickness of the ice shelf,

$$\text{calving} = \text{velocity} \times \text{shelf\_mass},$$

and thus,

$$\frac{\text{calving}_1}{\text{calving}_0} = \frac{\text{velocity}_1}{\text{velocity}_0}\ \frac{\text{shelf\_mass}_1}{\text{shelf\_mass}_0}$$

Because the velocity increases while the shelf mass decreases, it is not obvious *a priori* whether this model would project calving to increase or decrease.

Thomas also specified an enhanced calving scenario, in which the ice front retreats several hundred kilometers after shelf melting exceeds a threshold. Such a scenario might be explained, for example, because thinner ice is more easily broken off into icebergs.

Our draft report added a more conservative scenario, for several reasons. First, as shown in Figure 5-6c, Thomas's calving model implicitly embodies an instability by which any sustained increase in the shelf-melt rate leads to a continued thinning and gradual elimination of the ice shelf, with the ice-stream velocity increasing all the while. Second, as Figures 5-6a and 5-6b show, the Thomas' model projects that the Antarctic sea level contribution is greater than the contribution from melting, which implies that for every one cubic kilometer of ice that melts, more than one cubic kilometer of ice will flow into the shelf. Thus, the model implicitly assumes that the (mass) calving rate must increase—even though there is a thinner ice shelf.

Our more conservative fixed-calving scenario, by contrast, assumed that the ice shelf is stable. If the rate of shelf melt increases, the acceleration in ice-stream velocity contributes to the mass of the ice shelf, rather than to calving. This partial replacement of the mass loss due to increased melting serves as a negative feedback on melting. Over time, the ice shelf

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[5] Area is represented by length in this 2-D model.

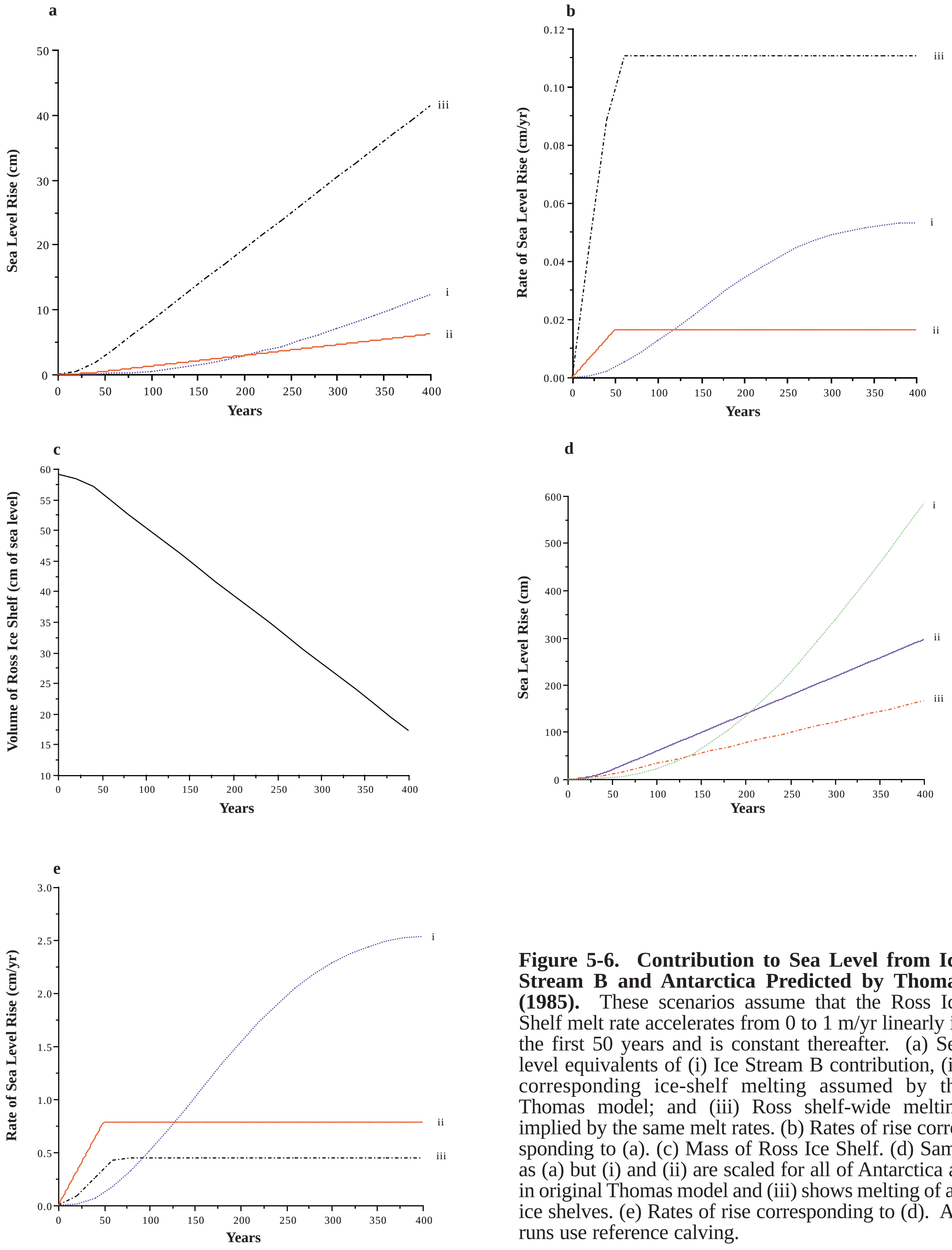

Figure 5-6. Contribution to Sea Level from Ice Stream B and Antarctica Predicted by Thomas (1985). These scenarios assume that the Ross Ice Shelf melt rate accelerates from 0 to 1 m/yr linearly in the first 50 years and is constant thereafter. (a) Sea level equivalents of (i) Ice Stream B contribution, (ii) corresponding ice-shelf melting assumed by the Thomas model; and (iii) Ross shelf-wide melting implied by the same melt rates. (b) Rates of rise corresponding to (a). (c) Mass of Ross Ice Shelf. (d) Same as (a) but (i) and (ii) are scaled for all of Antarctica as in original Thomas model and (iii) shows melting of all ice shelves. (e) Rates of rise corresponding to (d). All runs use reference calving.

approaches a new equilibrium mass, and the rate of sea level rise approaches the contribution due to melting. *The Thomas model with fixed calving is essentially a melt-only model: sea level rise lags behind melting, and the functional form of the lag is based on the physics of Ice Stream B* rather than the simple linear adjustment we have used elsewhere (*i.e.*, $dY/dt=a[Y-Y_{eq}]$).

The draft simulations used probabilities of 30 percent for Thomas's reference scenario; 0 percent for his enhanced calving scenario; and 70 percent for the fixed calving scenario. We hesitated to assume huge accelerations in mass contribution based on calving when the scant empirical and modeling data available only addressed basal melting. Nevertheless, the increased calving implied by Thomas's reference scenario was accepted by the Polar Research Board and, thus, may have been entitled to greater standing than assumed in the draft.

For each of the variations of the model, the draft employed as 2σ limits the ranges that Thomas tested in his sensitivity analysis; *i.e.*, the initial velocity (V_0) of Ice Stream B is between 100 and 300 m/yr, and the length of the ice stream over which backpressure from the shelf has an effect (L) is between 100 and 300 km.

Scaling. Because the Thomas model has only two dimensions, it must be scaled up by a third dimension to yield contributions to sea level. Figures 5.6a–5.6c use the width of Ice Stream B. Note that because we want this figure to illustrate the dynamics of the Thomas model, we must scale both melting and ice discharge by the same scalar; thus, the melting estimate applies not to any real ice shelf but to a hypothetical shelf whose width is the same as the width of Ice Stream B. For comparison purposes, we also show the results of scaling the melting by the area of the Ross Ice Shelf.

The differences between these two melt curves are at the crux of the dilemma one faces when scaling up the results to yield a three-dimensional estimate of ice contribution: scaling up a two-dimensional model implies that the ice shelf has the same width as the ice stream. If our scaling factor (**S**) is area (or volumetric melt rate) of the real 3-D ice shelves divided[6] by the length (or 2-D melt rate) of the 2-D ice shelf in Thomas's model, then the input to the Thomas model is a realistic estimate of melting. However, the output is only realistic if the total "capacity" of the ice streams happens to be **S** times the capacity of Ice Stream B. If **S** is the total volume of Antarctic ice conveyed by all (or a subset of) ice streams divided by the 2-D contribution of Ice Stream B, we are implicitly driving the model with an ice shelf whose area (or volumetric melt rate) is **S** times the area (or melt rate) of the hypothetical ice shelf used in the Thomas model. The resulting output (ice discharge) makes a certain amount of intuitive sense—since current rates are accurately predicted—but the input melt rate may bear little relationship to the size of the real ice shelf.

The melting estimates in Figures 5-6d and 5-6e illustrate the practical importance of this distinction. The lower curve shows continent-wide melting of ice shelves assuming 1 m/yr melt rate; the upper curve shows the extrapolated melt rate implied if **S**=47.6 (the continent-wide contribution of ice streams divided by Ice Stream B's contribution). *This scaling was used in the original Polar Research Board publication of this model*[7] and thus is one of the formulations (AM3) used in this draft. Because the extrapolated melting overstates the area-based estimate of melting by almost a factor of 2, AM3 is effectively driven by an overstatement of shelf melting. Thus, the 6.03 mm/yr rate of sea level rise (for the reference calving scenario) is probably an overstatement. (Another way of looking at this issue is that only about 20 percent of the ice leaving Antarctica goes through the Ross and Ronne/Filchner Ice Shelves; *see* discussion of AM4.)

Alternative Scaling of the Thomas Model

Given the limitations of AM3, we consider three additional formulations of the Thomas model:

AM4. Thomas justified the original scaling on the grounds that most of the mass leaving Antarctica leaves through ice streams. However, as Table 5-1 shows, most ice does not leave through the Ross and Ronne/Filchner Ice Shelves. We doubt that the Thomas model should apply to situations where the ice streams are not blocked by ice shelves. Nevertheless, about 20 percent ($383\ km^3/yr$) of the total does leave the

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[6] The scalar adds one dimension, so we divide volume by area, or area by length.

[7] Thomas scales Ice Stream B results by 47.6, that is, 1810 km^3/yr (which is Thomas's estimate of the current annual Antarctic discharge) divided by 37.9 km^3/yr (the current annual discharge of Ice Stream B). Thus, under the 1 m/yr scenario, Ice Stream B accelerates from 37.9 km^3/yr to 83.63 km^3/yr in the year 2100, which Thomas extrapolates to conclude that the total mass flux from the continent will increase from 1810 km^3/yr to 3994 km^3/yr; *i.e.*, sea level rise accelerates by 6.03 mm/yr.

continent through ice streams feeding the Ross and Ronne/Filchner Ice Shelves. Therefore, model AM4 assumes that the appropriate extrapolation is to assume a coincident acceleration of only the streams that feed the Ross and Ronne/Filchner Ice Shelves. This assumption implies scaling the Ice Stream B results by a factor of 10.1. As Figure 5-7 shows, the reference calving scenario would imply an acceleration of 1.67 mm/yr if the shelves thin 1 m/yr.

This assumption also provides a lower estimate of the amount of melting that is driving the model. Unfortunately, it understates melting by a factor of 2.8.

AM5. The other way of addressing the same problem is to view the Thomas model as showing how mass flux lags (or leads) basal melting. Instead of assuming that all (or some) ice streams accelerate by the same fraction as Ice Stream B, AM5 assumes that the continent-wide ratio of mass flux to basal melting is the same as that calculated in the Thomas model. **S** represents the ratio of continent-wide melting to melting of the hypothetical shelf scaled by Ice Stream B, a factor of approximately 28. Thus, the model is driven by an actual estimate of the continent-wide melt rate.

The propriety of this assumption depends in part on whether one is using the fixed or reference calving scenario. In the fixed calving scenario, we have two offsetting oversimplifications. On the one hand, we effectively assume that capacity of ice streams feeding the relevant ice shelves is $\mathbf{S}_{AM5}$ (*i.e.*, 28) times that of Ice Stream B, whereas it may be only $\mathbf{S}_{AM4}$ (*i.e.*, 10) times that of Ice Stream B (unless streams outside of the Ross and Ronne/Filchner Basins would also respond to shelf melt). On the other hand, this overstatement also applies to the negative feedback caused by adding ice to shelves. Thus, in the fixed-calving scenario, any over- or underestimate of ice-stream capacity has an impact on the speed at which ice-shelf mass (and thus sea level) adjusts to shelf melting, but not on the equilibrium rate of sea level rise toward which the system tends.

For the reference calving scenario, by contrast, the system is not adjusting to an equilibrium. Therefore, any implied over- or understatement of ice-stream capacity will translate all the way through to the projections of the rate of equilibrium sea level rise.

Disaggregating the Thomas Model into Different Ice Streams (AM6)

The preceding discussion highlights the fact that if we merely scale up the results of a two-dimensional model, we must either (1) understate the amount of underlying shelf melting or (2) overstate the amount of ice-stream capacity.

Fortunately, we need not make this Hobbesian choice: Data is available for other ice streams as well, as shown in Table 5-1. As a result, one can employ the Thomas ice-stream model without resorting to continent-wide scaling.

AM6 divides Antarctica into the regions shown in Figure 5-2, using the ice streams summarized in Table 5-1. Several aspects of this approach need explaining. Most importantly, AM6 does not arbitrarily scale up the results reached in one basin; rather, it conservatively assumes no change in processes that are not explicitly modeled.

Ross and Ronne/Filchner. AM6 assumes that the Thomas approach applies only to the Ross and Ronne/Filchner Basins. It allows for several ice streams feeding the Ross and Ronne/Filchner Ice Shelves. In response to thinning of the ice shelf at time t_1, each stream is modeled separately; and its contribution is added to the ice shelf at the end of the period, so that at time t_2, the apparent thinning of the shelf will be equal to the basal melting minus the combined contributions during t_1 of (a) precipitation and (b) all the modeled ice streams. Thus, the impact of having several streams is to increase the speed at which mass flux responds to shelf thinning; but because the flux from each stream builds back the shelf, the long-term impact of extra streams is relatively small. Since all of the major streams (plus a category for "other streams") are included, no scaling is necessary. Thus, with respect to the Ross and Ronne/Filchner Ice Shelves, AM6 considers both the actual area of ice shelf (like AM5) and the existing ice-stream capacity (like AM4).

Amery and Other Shelves. AM6 also has features of AM4 and AM5 in the handling of other shelves. While the former assumes no contribution and the latter assumes that the contribution will respond in proportion to shelf melt, AM6 makes an intermediate assumption: the shelves will melt entirely with no contribution to sea level, after which point melting adds to sea level on a 1:1 basis.

Effectively, this approach assumes that the lack of backpressure exerted by the shelves will enable shelves to thin substantially, but that the area of melt-

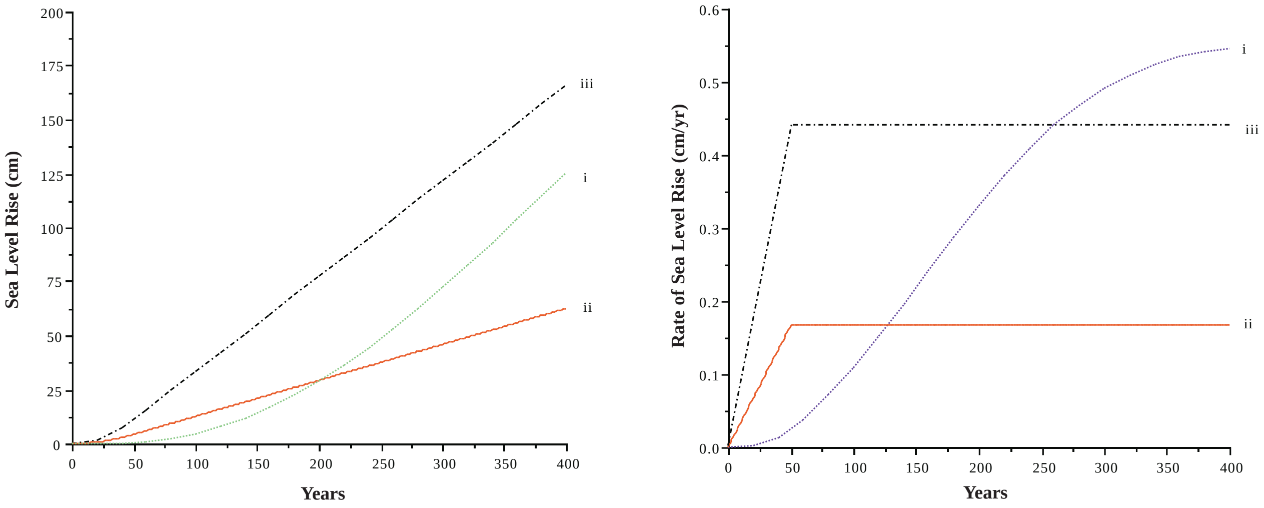

Figure 5-7. Antarctic Contribution to Sea Level According to Model AM4. Same as Figure 5-6 (d) and (e), except based on AM4; *i.e.*, Ice Stream B results scaled by the contribution of ice streams feeding Ross and Ronne-Filchner Ice Shelves.

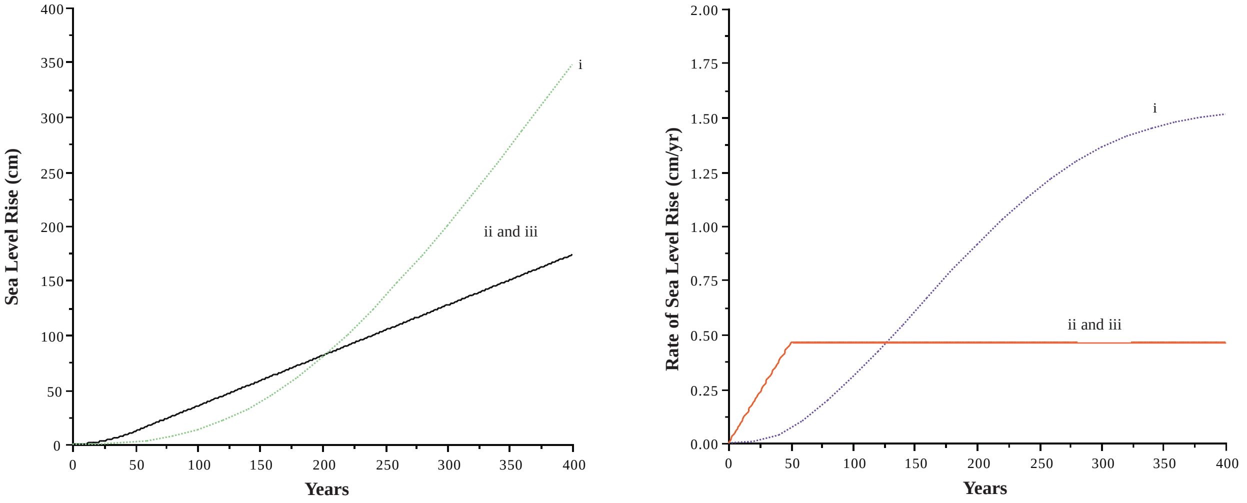

Figure 5-8. Antarctic Contribution to Sea Level According to Model AM5. Same as Figure 5-6 (d) and (e), but for AM5.

ing near the grounding line will retain its configuration. Thus, the shelf does exert backpressure on the ice immediately inland, so that if it thins past a point, enough ice will flow into it to prevent the forming of a vertical wall and commensurate decline in melting (which would require us to explain what happens to the additional heat).

Antarctic Peninsula. The model by Drewry & Morris (1992) suggests that for a 2˚C warming, the total contribution to sea level is only 1 to 2 mm. Because this is not significantly different from zero, we assume that the net contribution from the Antarctic Peninsula is zero (*i.e.*, that ablation and ice sheet flow counterbalance the increase in precipitation over the continent). Future reports should explicitly include the Drewry model, to account for possible ablation from extremely warm scenarios and to uncouple ice flow from precipitation changes.

Adjustment to Antarctic Precipitation if the Area of the Ice Sheet Declines. This adjustment only becomes relevant in the latter years of the extreme scenarios.

If ice shelves or ice sheets in West Antarctica retreat, snow that would otherwise fall on the continent will fall into the sea. The draft assumes that East Antarctica and the Antarctic Peninsula will maintain their current area, but that the areas of the other two regions will decline as their mass declines:

$$\text{Area}_t = \text{Area}_0\ (\text{Volume}_t/\text{Volume}_0)^{P_9}.$$

No studies are available to provide values for P_9. To get a sense of possible values, consider a cube melting along various sides. If the cube melts evenly along the x-y, x-z, and y-z planes, the x-y area (which determines snowfall) declines with the 2/3 power of volume. If the cube melts only along the x-z, y-z, or both planes, then x-y area declines with the 1.0 power. If the cube melts along the x-y and either the x-z or y-z planes, area declines with the 1/3 power.

The draft assumed that P_9 is lognormally distributed with 2σ limits of 1/3 and 2/3. This adjustment is negligible in all but a few runs.

Sensitivity Runs and Selected Simulations

Figure 5-9 compares the four variations of the Thomas model. Scenario A, using the disaggregated AM6, implies a sea level contribution only slightly greater than AM5, mostly because several ice streams would allow a faster response than would a single ice

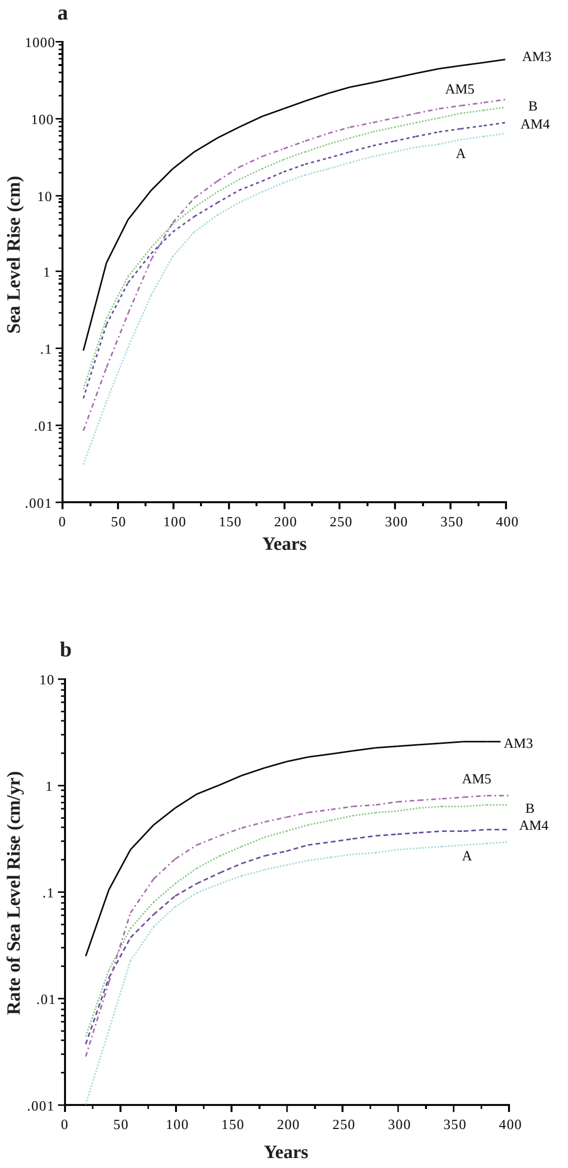

Figure 5-9. Comparison of Alternate Scalings of the Thomas Model. Estimates of (a) total sea level and (b) rate of sea level rise contribution from Antarctica, for the various extrapolations of the Thomas model (AM3, AM4, AM5), as well as our more disaggregated version (A=AM6 with fixed calving, and B=AM6 with Thomas's reference calving). All scenarios assume that the rate of shelf-thinning increases 2 cm/yr^2 for 50 years, after which it remains constant at a rate of 1.17 m/yr (*i.e.*, 1 m/yr greater than the current rate for the Ross Ice Shelf).

stream. The projections are below those for AM3 and AM4, because those formulations (in our view) overextrapolate by assuming that all the ice, or all the ice leaving through the major ice shelves, respond as Ice Stream B would respond if it were the only ice stream feeding the Ross Ice Shelf. The use of Thomas's calving model comes close to doubling the sensitivity of AM6.

Figures 5-10 and 5-11 illustrate the cumulative and annual Antarctic contribution to sea level resulting from the climate forcing scenarios described previously in Table 5-3. The scenario combinations in Figure 5-10b correspond to the scenarios examined in the previous section on shelf-melt rates. The scenarios in the left half of the figure are based on the assumption that global temperatures rise for 100 years and are steady thereafter; those on the right side (other than scenario 3) involve global temperatures rising for 200 years.

As before, scenarios 3 and 4 both keep precipitation fixed, assume that global temperatures rise 4˚C per century, and employ median values for (a) the magnitude and timing of the CDW response to global temperatures; (b) the response of warm intrusion temperature to CDW; and (c) the response of basal shelf melting to warmer water temperatures. The only difference is that global temperatures stabilize after 100 years in scenario 3 and 200 years in scenario 4. Scenario 8 is like scenario 4, except that it also considers the median estimate of increased precipitation; thus, scenario 8 represents our true median scenario. Both scenarios 3 and 4 take about 170 years before climate change can offset the existing negative contribution to sea level rise implied by Bentley's mass balance estimates. Scenario 8 shows a sea level drop of 3.8 cm for the first 100 years and a negative Antarctic contribution for the foreseeable future. *Thus, unlike the previous effort by Thomas—but consistent with previous efforts by IPCC and Huybrechts & Oerlemans—our median scenario shows a negative contribution to sea level from Antarctica.* This is hardly surprising, when one recalls that the shelf-melt rate only increases from the current 0.17 m/yr to 0.42 m/yr in one hundred years and takes two centuries to reach 1 m/yr, which is generally viewed as a threshold for significant ice sheet responses.

Only when we test the high-sensitivity sides of the distributions of our uncertainties do we obtain relatively high shelf thinning. Scenario 5, with the shelf-thinning rate exceeding 1 m/yr after 70 years, provides a positive contribution to sea level after about 90 years; nevertheless, the total contribution after 200 years is only 16 cm. Scenario 10, with its much greater shelf-thinning rates, contributes about 5.6 mm/yr by the 100th year, and about 12 mm/yr after 200 years. This scenario, however, is very unlikely because it would

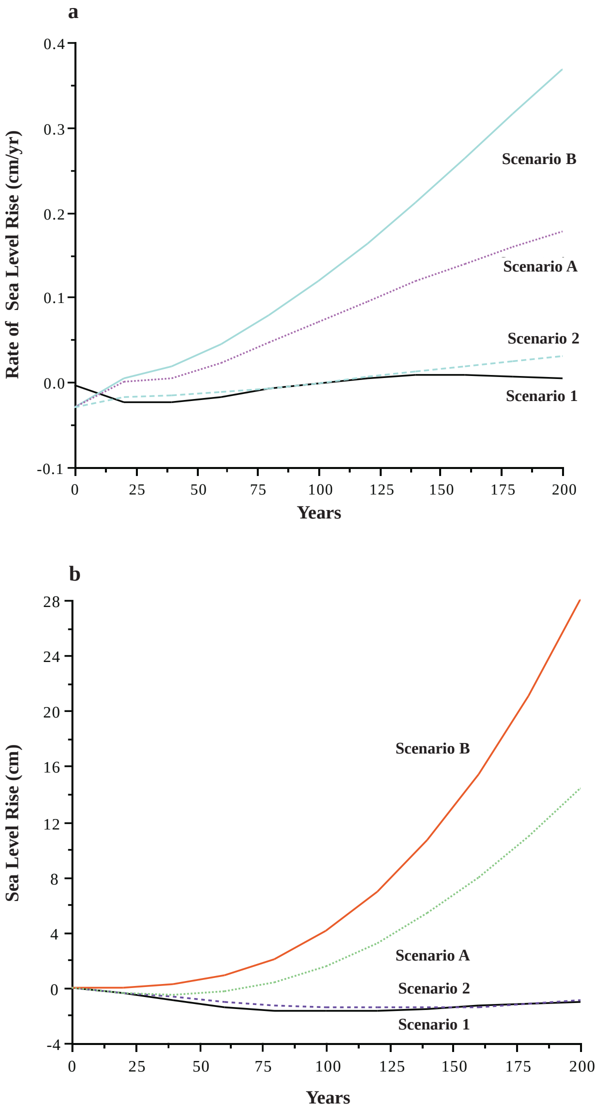

Figure 5-10. Antarctic Contribution to Sea Level According to Model AM6. Total contribution and rate of sea level rise for scenarios A, B, 1, and 2.

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[8] *But see* the comment by Thomas in **Expert Judgment**, *infra*.

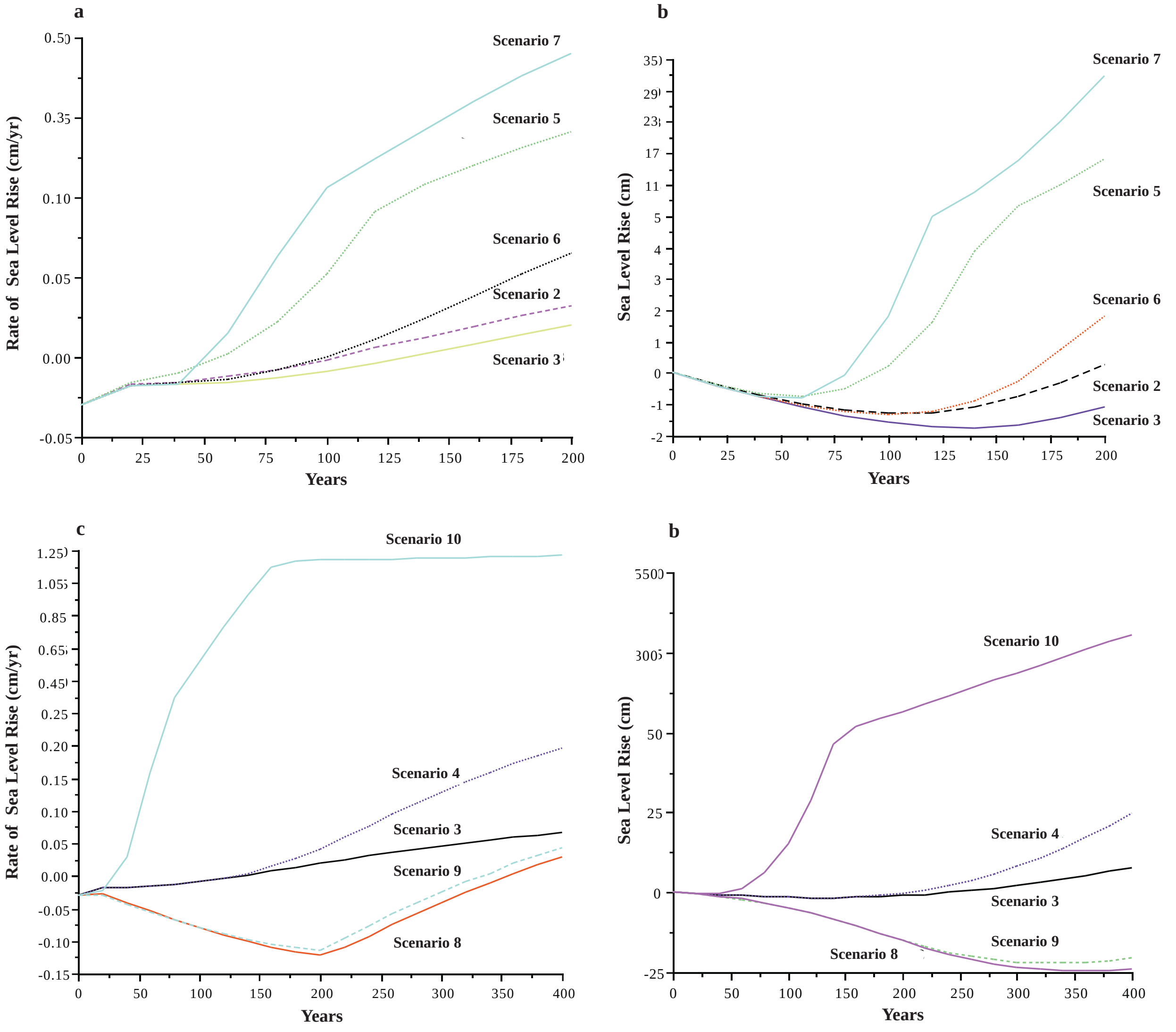

Figure 5-11. Sensitivity Analysis of Model AM6. Cumulative and annual Antarctic contribution to sea level (a and b) for scenarios 2, 3, 5, 6, and 7, and (c and d) for 3, 4, 8, 9, and 10.

require the temperature of the water intruding beneath the ice shelves to warm more than 4˚C by 2100 and almost 9˚C by 2200.[8]

Linearization of the Huybrechts & Oerlemans Model (AM7)

Huybrechts & Oerlemans (1990) estimate that with a 1 m/yr rate of shelf-thinning, sea level rises 2, 3, 7, 8, and 10 cm during each of the next five centuries, respectively. We adopt the simplest way of generalizing these results: the first 100 m of shelf-thinning causes a 2 cm rise, the next 100 m, a 3 cm rise, etc. This assumption oversimplifies the dynamics of their model. Additional runs from those researchers would enable us to determine whether we overstate or understate the likely impact of scenarios with greater melt rates.[9]

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[9] Our simplification effectively assumes that if the rate of basal melting doubles, the response time is cut in half, but that a given shelf-thinning produces a given rise in sea level regardless of its timing. In the short run, this assumption probably overstates sensitivity; a 100 m shelf-thinning over the course of a single year would not cause the full 2 cm rise in that year. In the long run, this assumption may understate the impact. For example, the implication that a rapid 500 m thinning would cause only a 30 cm rise is far more optimistic than Lingle (1985), which suggested that such a thinning could cause an irreversible disintegration of the West Antarctic Ice Sheet.

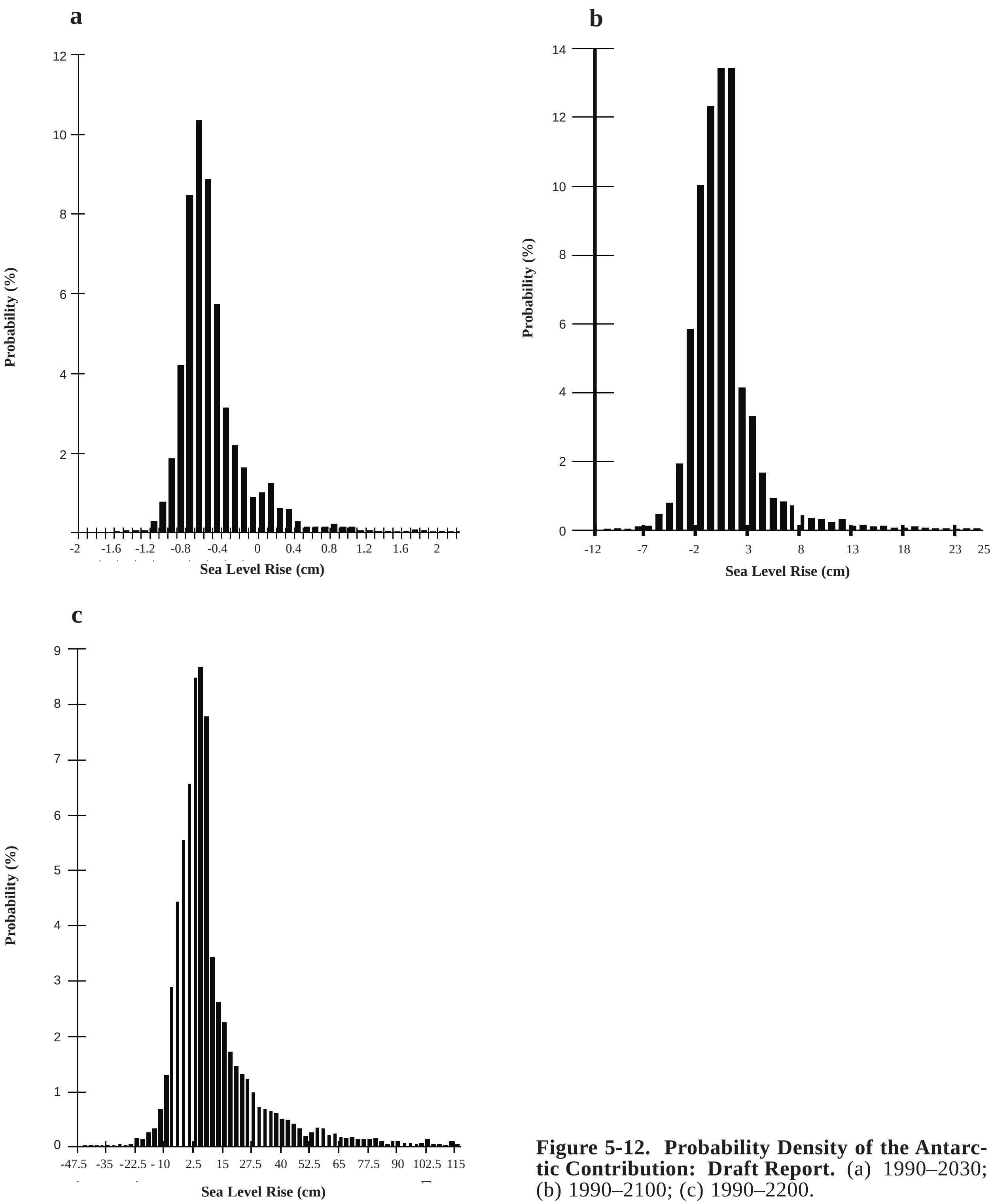

Figure 5-12. Probability Density of the Antarctic Contribution: Draft Report. (a) 1990–2030; (b) 1990–2100; (c) 1990–2200.

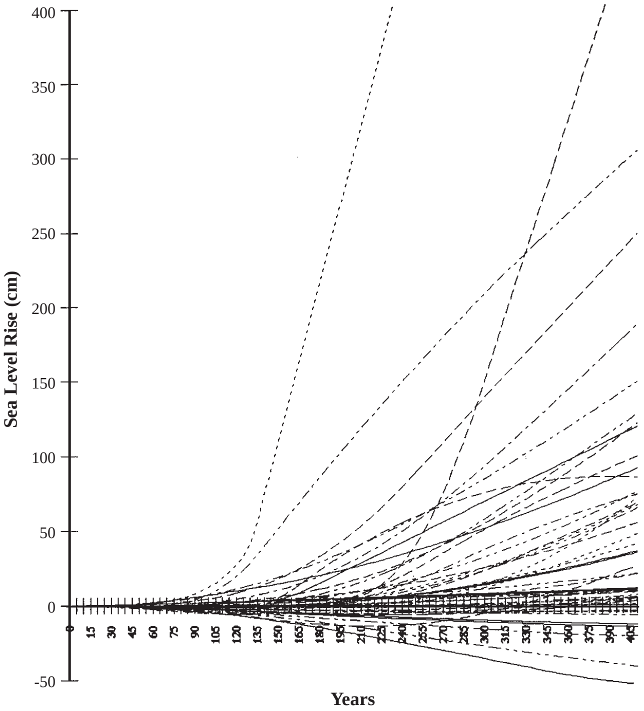

Figure 5-13. Spaghetti Diagram of Antarctic Contribution to Sea Level: Draft Report. Antarctic contribution for selected simulations. See Figure 2-5 and accompanying text for additional explanation.

TABLE 5-4
CUMULATIVE PROBABILITY DISTRIBUTION
FOR ANTARCTIC CONTRIBUTION TO
SEA LEVEL: DRAFT REPORT

Cumulative Probability (%)	2030	2100	2200
1	–1.2	–5.6	–15
5	–.95	–3.6	–8
10	–.86	–2.9	–5
20	–.76	–1.9	–2
30	–.68	–1.6	0
40	–.55	–1.2	2
50	–.15	–1.0	3
60	–.07	0.0	4
70	.02	1.5	5
80	.65	2.1	10
90	.80	2.9	25
95	1.2	5.0	42
97.5	—	8.2	67
99	2.1	16.0	102
99.5	—	21.7	137
Mean	–0.2	0.3	6.1
σ	0.7	4.0	20.3

Draft Results

Figure 5-12 illustrates the draft probability density of the Antarctic contribution; Figure 5-13 illustrates for selected simulations; and Table 5-4 summarizes the draft cumulative probability distribution of the Antarctic contribution to sea level. As expected, the median contribution was negative. There was also a 1 percent chance of a 16 cm contribution through 2100 and a 1 m contribution by the year 2200. Almost all of the high projections resulted, however, from the 500 simulations that used AM3.

Expert Judgment

The nine expert reviewers who provided comments are listed in Table 5-5 (with the exception of one reviewer who preferred to remain anonymous). With the exception of Stan Jacobs and Craig Lingle, all of the reviewers provided probability distributions for at least some of the parameters. Lingle, however, provided scenarios for what the Antarctic contribution might be without a greenhouse warming.

Both Lingle and Jacobs took issue with our assumption that, in the absence of additional climate change, Antarctica would increase its mass and thereby lower sea level 0.1 to 1.1 mm/yr. Indeed, IPCC (1990) estimated that the historic contribution has been between $^{+}$0.5 and $^{-}$0.5 mm/yr. Lingle (1989) developed three baseline scenarios ranging from $^{-}$1.5 cm to $^{+}$16 cm, with a rise of 5 cm most likely for the year 2100. We summarized these projections with a normal distribution with a mean of 0.5 mm/yr and σ limits of $^{-}$0.1 and $^{+}$1.1 mm/yr. These baseline assumptions are invoked 25 percent of the time; the $^{-}$0.1 to $^{-}$1.1 mm/yr range is invoked the rest of the time.[10]

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[10] Neither we nor Lingle were able to devise a reasonable way to incorporate the results of Lingle (1985) into this analysis.

TABLE 5-5
EXPERT REVIEWERS OF CHAPTER 5

Richard Alley	Pennsylvania State University	University Park, PA
Anonymous	University Professor	United States
Robert Bindschadler	Goddard Space Flight Center NASA	Greenbelt, MD
Roger Braithwaite	Geological Survey of Greenland	Copenhagen, Dnmk
Stan Jacobs	Lamont Doherty Earth Observatory Columbia University	Palisades, NY
Craig Lingle	University of Alaska	Fairbanks, AK
Robert Thomas	Greenland Ice Core Project NASA Headquarters	Washington, DC
C.J. van der Veen	Byrd Polar Research Center Ohio State University	Columbus, OH
Jay Zwally	Goddard Space Flight Center NASA	Greenbelt, MD

Note: Wigley & Raper did not review this chapter; but they did provide their own expectations based on previous work, which we employ as the linear model AM1.1.

As discussed in Chapter 1 ("Correlation Between Assumptions"), one-eighth of the simulations reflect Wigley & Raper's suggested assumptions for each of the major contributors to sea level rise. In the case of Antarctica, their assumptions are a slight mod-ification of AM1—the IPCC (1990) assumptions—in that they allow for the possibility that melting would offset some of the increase in precipitation:

$$\frac{d\mathrm{SL}_{\mathrm{Antarctica}}}{dt} = \beta_A \, \Delta T_{\mathrm{Antarctica}}, \qquad \text{AM1.1}$$

where β_A has a median of –0.2 and a standard deviation of 0.135, and $d\mathrm{SL}/dt$ is measured in mm/yr.

Because seven other researchers provided us with process-specific assumptions for Antarctica, each set of assumptions accounts for 1250 simulations. We discuss the comments on ice shelves and ice stream response separately.

Ice Shelf Assumptions

Most of the reviewers focused on our ice stream models, that is, our assumptions regarding how much mass would be transferred from Antarctica to the oceans for a given thinning of the ice shelves; only three provided comments on shelf melting. *The lack of comments does not imply a judgment that our assumptions regarding ice shelf melt are more reliable*. If anything, it indirectly suggests that they are less reliable: The absence of ice shelf data and modeling made it difficult for reviewers to improve on our specific assumptions, so most chose not to comment.

The exceptions were Robert Thomas, Stan Jacobs, and Robert Bindschadler. Although Jacobs was unable to suggest alternative assumptions, his comments provide a suitable caution:

> It is probable that "net melting under the Ross Ice Shelf results from 'warm intrusions' that are currently around 1.4˚C." However, we have learned a few things since 1984, one of which is that the Ross Sea "warm intrusion" is apparently divided into an inflow and outflow, with relatively little net transport of heat beneath the ice. This does not invalidate [the assumption that the rate of melting is based on a] temperature differential [between the temperature of the warm intrusion and the *in situ* freezing point], in part because of an interesting coincidence. That is, the primary deep thermohaline circulation beneath the large ice shelves is now believed to begin with water at the sea surface freezing temperature (approximately –1.9˚C) which is approximately 0.5˚C above the *in situ* freezing point at a depth of about 700 m.

The issue of present-day warm intrusions and how they might change with time is still an open and thorny question. The impact of warm water is best documented beneath the George VI Ice Shelf (Potter and Paren 1985), where the basal melt rate appears to be an order of magnitude higher than beneath the Ross. It is not clear how readily this Bellinghausen Sea type circulation could spread to other regions of the continental shelf. In particular, present circulation beneath the Ross Ice Shelf may be protected by the strong offshore winds that generate large amounts of sea ice and high salinity shelf water in that sector. The winds may not be as strong in the Weddell Sea, but there the Antarctic Peninsula and Weddell Gyre keep the deep water cooler. This makes some of the Jenkins estimates look a bit on the high side to us, at least on the near term.

[The current report assumes] that dilution of the warm intrusion by shelf water is proportional to annual sea ice formation. Maybe so, but there are several problems with that assumption, aside from what's noted above. [The] "dilution" applies only to temperature, whereas the salinity and volume changes may be more important. At low temperatures, salinity exerts the primary control on density and the resulting thermohaline circulation. Further, the "dilution" of interest occurs only over the continental shelf, which occupies <20% of the winter sea ice extent. It might thus be argued that ice cover could change substantially without much of an impact on the shelf circulation. It has also been hypothesized that a warmer and wetter atmosphere will effectively cap vertical heat flux from the deep water, allowing sea ice to grow thicker (Manabe et al., 1991). However, so far the intuition fits the evidence, in that higher air temperatures are negatively correlated with sea ice extent.[11]

Jacobs concludes that our model was an improvement over those assessments that simply assume that the Antarctic contribution is a multiple of thermal expansion (*e.g.*, Hoffman et al. 1983) or of temperature (*e.g.*, IPCC 1990). Nevertheless, his comments show that our assumptions substantially oversimplify the processes that will determine shelf melting.

Robert Thomas suggested specific changes to the model for Ross Ice Shelf melting. The draft assumed that a fixed dilution coefficient A_1 determined the extent to which CDW warming translates into warmer water intruding beneath the ice shelves, holding annual seaice formation constant, and that changes in sea ice result in proportional changes in this dilution. Thomas preferred to remove sea ice from the model and to allow the dilution to change linearly with T_{cdw}:

$$T_{warm} = T_{cdw}/\text{dilution\_factor},$$

where dilution_factor=$6-\Delta T_{cdw}$ for $\Delta T_{cdw}<5$ and 1.0 thereafter in the median scenario, and temperatures are measured with respect to the *in situ* freezing point. Alternatively,

$$T_{warm} = T_{cdw}/(6-\Delta T_{cdw}) \text{ for } \Delta T_{cdw}<5;$$
$$= T_{cdw} \text{ for } \Delta T_{cdw}\geq 5.$$

That is, $T_{warm} = \min\{T_{cdw}, T_{cdw}/(9-T_{cdw})\}$,

where all temperatures are measured with respect to the *in situ* freezing point. Generalizing, Thomas would allow the dilution ratio to fall linearly from its initial value of $(1+A_1)$ to a value of 1 for a warming of A_1°C:

$$T_{warm} = \min\{T_{cdw}, \frac{T_{cdw}}{1+A_1-\Delta T_{cdw}}\}$$

Adjusting for the fact that the initial $T_{warm}=0.5$ when $T_{cdw}=3.0$, we have

$$T_{warm} = \min\{T_{cdw}, \frac{T_{cdw}}{1+A_1-\Delta T_{cdw}} + 0.5 - \frac{3}{1+A_1}\}$$

where all temperatures are expressed in degrees above the *in situ* freezing point of saltwater. This equation is similar to the equation used in the draft, except that (a) the impact of the variable SEAICE on the dilution factor is replaced by a simpler function of temperature and (b) the existence of T_{cdw} in the denominator requires us to explicitly prevent T_{warm} from exceeding T_{cdw}. Because Thomas' functional specification leads T_{warm} to catch up with T_{cdw} more rapidly than our draft assumptions, Thomas employs a narrower range for A_1, retaining our median value of 5 but using 2σ limits of 2.5 and 10.

Perhaps more important, Thomas also models the response to warm intrusion as a quadratic rather than as a linear function of temperature, based on MacAyeal (1984). He assumes that the response becomes linear once the rate of shelf melting exceeds the 3 m/yr that he examined in Thomas (1985). Thus, we have

$$\text{Melt} = 2A_2 T_{warm}^2 + .25(1-2A_2)$$
$$\text{for } T_{warm} < [(2.75+0.5A_2)/2A_2]^{1/2}, \text{ and}$$

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[11] Stan Jacobs, Lamont Doherty Earth Observatory, Columbia University. Letter to James G. Titus. August 12, 1993 (quoting the draft report).

TABLE 5-6
COMPARISON OF SHELF MELT RATES FOR DRAFT AND THOMAS ASSUMPTIONS

Thomas Assumptions				**Draft Assumptions**[a]				
				Fixed Sea Ice		*Median Sea Ice*		
Median Assumptions								
ΔT_{cdw}	T_{cdw}	T_{warm}	melt rate	T_{warm}	melt rate	seaice rate	T_{warm}	melt rate
0	3	0.5	0.25	0.5	0.25	1	0.5	0.25
1	4	0.8	0.64	0.66	0.33	0.85	0.70	0.35
2	5	1.25	1.56	0.83	0.42	0.72	0.97	0.48
2.7	5.7	1.73	3.00	0.95	0.47	0.64	1.22	0.61
3	6	2.00	3.53	1.00	0.5	0.61	1.34	0.66
4	7	3.5	6.53	1.17	0.58	0.52	1.77	0.88
5	8	8.0	15.53	1.33	0.67	0.44	2.29	1.15
6	9	9.0	17.53	1.5	0.75	0.38	2.92	1.46
σ-High Assumption for A_1								
0	3	0.5	0.25	0.50	0.25	1	0.50	0.25
1	4	0.97	0.94	0.91	0.45	0.85	1.07	0.54
1.93	4.93	1.73	3.00	1.28	0.64	0.73	1.69	0.86
2	5	1.81	3.16	1.31	0.66	0.72	1.74	0.87
3	6	3.75	7.05	1.72	0.86	0.61	2.51	1.23
3.55	6.55	6.55	12.64	1.95	0.97	0.56	2.96	1.48
4	7	7	13.53	2.13	1.06	0.52	3.35	1.68
5	8	8	15.53	2.54	1.27	0.44	4.28	2.14
6	9	9	17.53	2.94	1.47	0.37	5.27	2.64

[a] These calculations use the draft assumptions for the shelf-melt parameters. The temperature assumptions are arbitrarily specified. The assumption that sea ice declines 15 percent per degree (C) is the median scenario for the final results; although the simulations base the calculation on ΔT, this table uses ΔT_{cdw} for simplicity.

$$\text{Melt} = 3 + 4A_2(T_{warm} - [(2.75 + 0.5A_2)/2A_2]^{1/2})$$
$$\text{for } T_{warm} \geq [(2.75 + 0.5A_2)/2A_2]^{1/2}.$$

Table 5-6 compares the resulting estimates of shelf-melt rates for both the draft and Thomas assumptions, using the median and σ-high values of A_1. For the median value, the draft did not project the shelf-melt rate to exceed 1 m/yr until T_{cdw} has warmed by over 5˚C[12]; by contrast, the Thomas assumptions suggest that such a rate would occur with a circumpolar ocean warming of about 1.5˚C.[13]

The potential for high rates of shelf melting is further illustrated by the second half of the table. Using the draft σ-high assumption for A_1 implies a shelf-thinning rate exceeding 1 m/yr with a circumpolar ocean warming of about 3˚C; Thomas's σ-high assumptions imply a similar melting rate with a warming of only 1˚C. Moreover, for a 2˚C warming, Thomas's σ-high assumption implies a melt rate of over 3 m/yr. For a warming in excess of 3.5˚C, his σ-high assumption implies melt rates in excess of 10 m/yr!

Do Thomas's assumptions imply unreasonably high rates of ice shelf melt? We think not, especially

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[12] Except for cases where undiluted circumpolar ocean water intrudes beneath the shelves, in which case the shelf-melt rate accelerates immediately to about 1.5 m/yr.

[13] Recall from Chapter 3 that most of the climate modelers proposed median assumptions in which T_{cdw} warms about 1˚C by the year 2100. Schneider's median assumptions, however, implied a warming of about 1.5˚C after the year 2080. Thus, substantial contributions from Antarctica before the year 2100 seem most likely to result in cases where Schneider and Thomas assumptions coincide. Because Hoffert and Rind have greater equilibrium polar amplification factors—albeit with longer lag times—post-2100 contributions will be greatest when Thomas assumptions coincide with either Hoffert or Rind.

in light of the fact that they represent only one-eighth of the simulations employed in this analysis. A shelf-melt rate of 3 m/yr is certainly high, but in the median case, Thomas does not assume that it would occur unless the circumpolar ocean warmed 2 to 4˚C.[14] Comparable rates of shelf-thinning have been observed in areas where the water beneath the ice shelves is 2 to 3˚C warmer than found under the Ross Ice Shelf.

The possibility that the ice shelves might eventually melt by 10 m/yr seems even more extraordinary, since such a rate implies a fortyfold increase in the currently observed rate. But the physical basis is not implausible: A 4˚C warming would imply an eightfold increase in the temperature differential and hence potential melt rate—if the amount of circumpolar ocean water intruding beneath the shelves remained constant; if that water was not diluted by the colder shelf water, its temperature would be 7˚C above the *in situ* freezing point, and thus the differential would be fourteenfold greater than today. Even assuming linearity, a three- to fivefold increase in the amount of water intruding beneath the ice shelves along with a 4˚C warming would appear to have the potential to cause a melt rate of 10 m/yr. The comments of Stan Jacobs highlight the fact that circulation may not increase—it could even decrease.

These high shelf rates are unlikely in the next century, because they require the coincidence of two unlikely events. First, the high half of Thomas's assumptions account for only 8 percent of our simulations; his σ-high assumptions account for about 2 percent. Second, only 15 percent of the simulations involve CDW warming of 2˚C in the next century, and only 4 percent involve a 3.5˚C warming.[15]

Compared with the Thomas assumptions, Robert Bindschadler's proposed revisions were fairly minor. He generally agreed with the assumptions employed by the draft but proposed a minor change to the sensitivity of the Ronne/Filchner Ice Shelf to warmer temperatures of the Weddell Sea. Because the Jenkins estimate of 3.33 m/yr per degree (C) is a more recent estimate, he suggested that this estimate should be the median sensitivity, with the old estimate of 1.91 becoming the lower σ limit.[16]

Ice Sheet Response to Shelf-Thinning

Aside from the aforementioned changes suggested by Thomas, the assumptions proposed by the Antarctic researchers generally conformed to the analytic structure of the draft report. One exception was our melt-only model (AM2). The reviewers were unanimous that this model should simply assume a linear adjustment similar to those employed extensively in Chapter 3. That is,

$$\text{Shelf\_Mass*}(t) = \text{Shelf\_Mass}_0 \, \frac{\text{Sheet\_Mass}(t)}{\text{Sheet\_Mass}_0},$$

$$\Delta\text{Shelf\_Mass}(t) = \frac{\text{Shelf\_Mass*}(t) - \text{Shelf\_Mass}(t-1)}{A_8},$$

where $\mathbf{A}_8$ represents the e-folding time of the response of the ice shelf to net melting; Shelf_Mass* is the equilibrium toward which the mass of the ice shelf is tending at any point in time; and Sheet_Mass is the mass of all Antarctic glacial ice. For small changes in the mass of the ice shelf, the ratio at the right-hand side of the first equation can be ignored. Thus, if melting reduces the ice shelf's mass by one kilogram, AM2 assumes that eventually one kilogram of ice will be transferred to the ice shelf, but that in the first year only $1/\mathbf{A}_8$ kilograms will be transferred.

All but two of the reviewers suggested that the response-time constant $\mathbf{A}_8$ should have a median of 100 years with 2σ limits of 10 and 1000. Zwally suggested that 2σ limits of 50 and 200 would be more appropriate. Thomas suggested a more rapid response time with a median of 10 years and 2σ limits of 1 and 100 years.

Having made this change in the melt-only model, the reviewers unanimously rejected our "fixed calving" assumptions by which we had proposed to force the Thomas model to assume stability. The reasoning was simple enough: the Thomas model was designed to yield an unstable ice stream response. Thus, when reviewers "voted" to use this model, they were voting for an unstable response; when they wanted a stable response, they had the melt-only model AM2. Thomas also suggested that some of the runs should employ the Thomas (1985) "enhanced calving" scenario based on a retreat of the calving front. For a one degree (C) warming in ΔT_{cdw}, all scenarios use reference calving. From that point on, however, the probability of a retreat of the calving front increases linearly with temperature by 10%/˚C. Thus, a 3˚C warming would imply, for example, a 20 percent chance of the Thomas enhanced calving.

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[14] From the Thomas σ-low assumption, not displayed.

[15] *See* Chapter 3, *supra*.

[16] The draft had used both estimates as 2σ limits.

Coincidentally, the combined assessment of the reviewers was fairly similar to the assumptions employed in the draft, as show in Table 5-7. The low-response models AM1 and AM7 received 30 percent of the allocation in the draft and 34.1 percent from the reviewers. The addition of AM1.1, however, brought the total probability of low-response models up to 46.7. In the original draft, 35 percent of the simulations had a stable equilibrium response roughly equal to the total melting (the Thomas models with fixed calving) and 20 percent had a response equal to a fraction of the total melting (the old AM2). The revised version, by contrast, has 32 percent of the simulations based on a stable response roughly equal to total melting (new AM2). Finally, 15 percent of the simulations in the original draft involved an unstable response (the Thomas models with "reference calving"), while 21 percent of the simulations in the current version involve an unstable response.

At the high end of the simulations, the draft used AM3 for 5 percent of the simulations; the reviewers suggested that this scaling of the Thomas model only be used 1 percent of the time. However, Thomas proposed a modification of AM4 with results that are 60 percent as great. Our original AM4 scaled the AM3 results downward by a factor of 20 percent because only 20 percent of the ice leaves through the Ross and Ronne/Filchner Ice Shelves. Thomas reasoned that a more appropriate scaling would be 60 percent, the portion of ice leaving through any form of ice stream; we call this assumption AM4.1. Coincidentally, this assumption gives the same result scalar as AM5.

Figure 5-14 compares the revised versions of AM2 with the various scalings of the Thomas model. The portion of reviewer-suggested simulations involving the highly sensitive, unstable versions (AM3, AM4.1, and AM5) is about half as great as the portion involving AM3 and AM5 in the original draft. Given that (1) all the simulations of the Thomas models involve the assumption of instability, while (2) the draft employed a stable version of the Thomas model 70 percent of the time, *the net impact of the reviewer comments is to expand the uncertainty range concerning the sensitivity of ice streams to ice-shelf melting.*

Final Results

TABLE 5-7
REVIEWER ALLOCATION OF PROBABILITIES BETWEEN THE ALTERNATIVE ANTARCTIC MODELS
(percent)

	Draft Used	Bindschadler	Bentley	Alley	Van der Veen	Zwally	Thomas	Anonymous	Wigley	Total
AM1	10	5	25	10	30	10	0	0	—	10
AM1.1	—	—	—	—	—	—	—	—	100	12.5
AM2	20	60	25	30	30	40	45	25	—	31.9
Thomas	50	20	25	37	10	35	30	25		22.75
AM3	5	0	0	1	0	1	5	1.11	—	1.02
AM4	10	0	0	1	0	24	0	3.98	—	3.65
AM4.1	—	—	—	—	—	—	25	3.98	—	3.65
AM5	10	5	0	5	0	5	0	2.39	—	2.08
AM6	25	15	25	30	10	5	0	13.53	—	12.32
AM7	20	15	25	23	30	15	25	50	—	24.1

NOTE: AM1 = Precipitation only (IPCC).
AM1.1 = Wigley & Raper (1992) model.
AM2 = Precipitation + melt-only model.
AM3, AM4, AM4.1, AM5, and AM6 = Thomas (1985) model.
AM7 = Huybrechts & Oerlemans (1990) model.

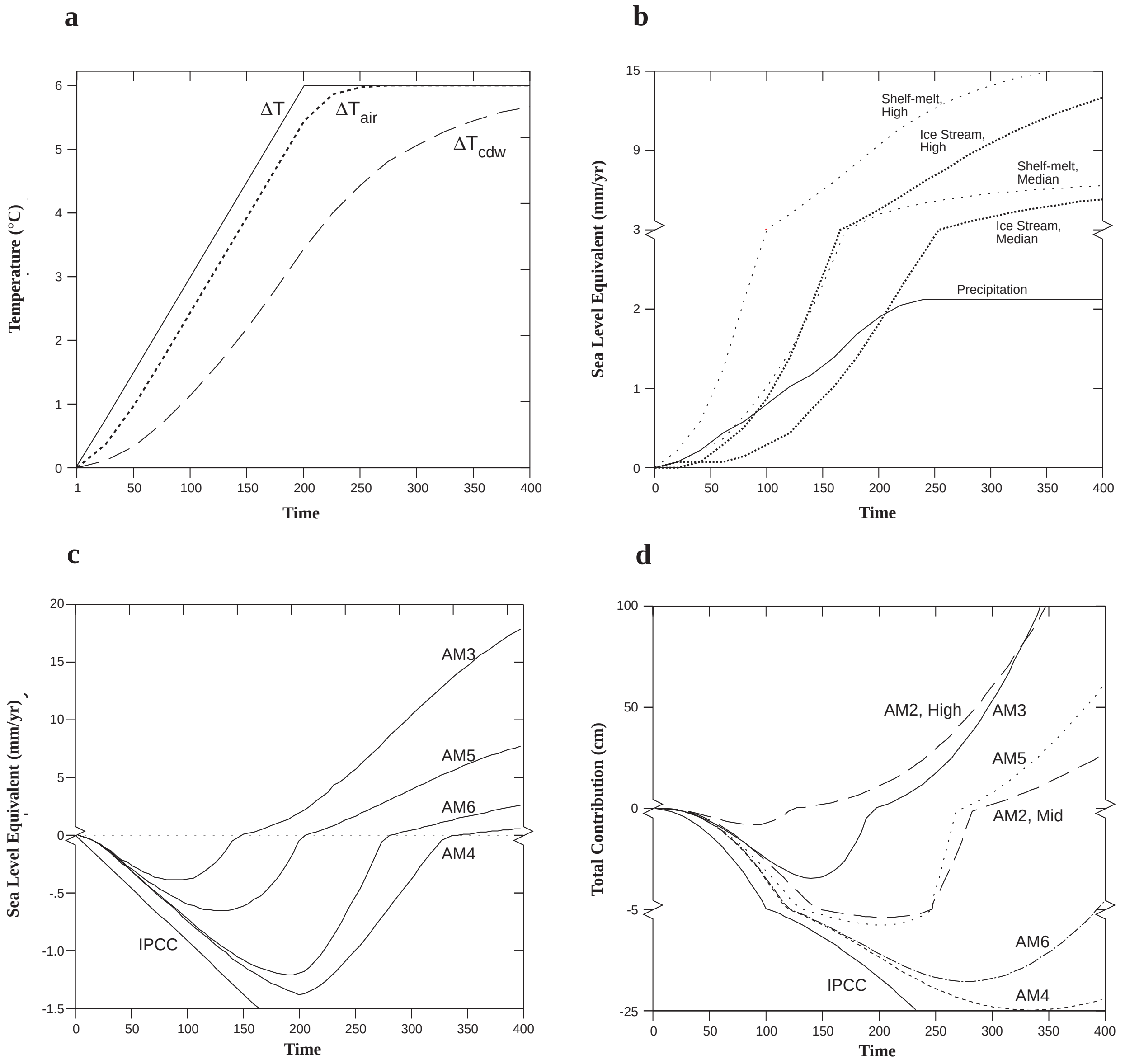

Figure 5-14. Revised Models of Antarctic Contribution. (a) Temperature changes using median response time assumptions. (b) The resulting annual shelf-melting, precipitation, and Antarctic contributions to sea level implied by the stable melt-only model AM2, using median and 2σ-high assumptions for shelf-melt sensitivity, and median assumptions elsewhere. (c) Annual sea level contributions for the unstable models AM3, AM4, AM5, and AM6. The sensitivity of the median assumptions from IPCC (1990) is shown for comparison. (d) Total Antarctic contribution

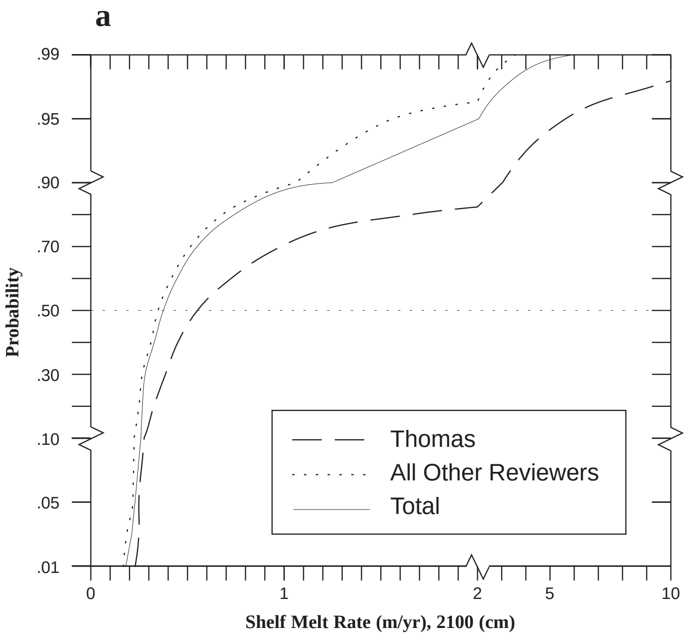

Figure 5-15. Ross Ice Shelf Melt Rates: Cumulative Probability Distribution.

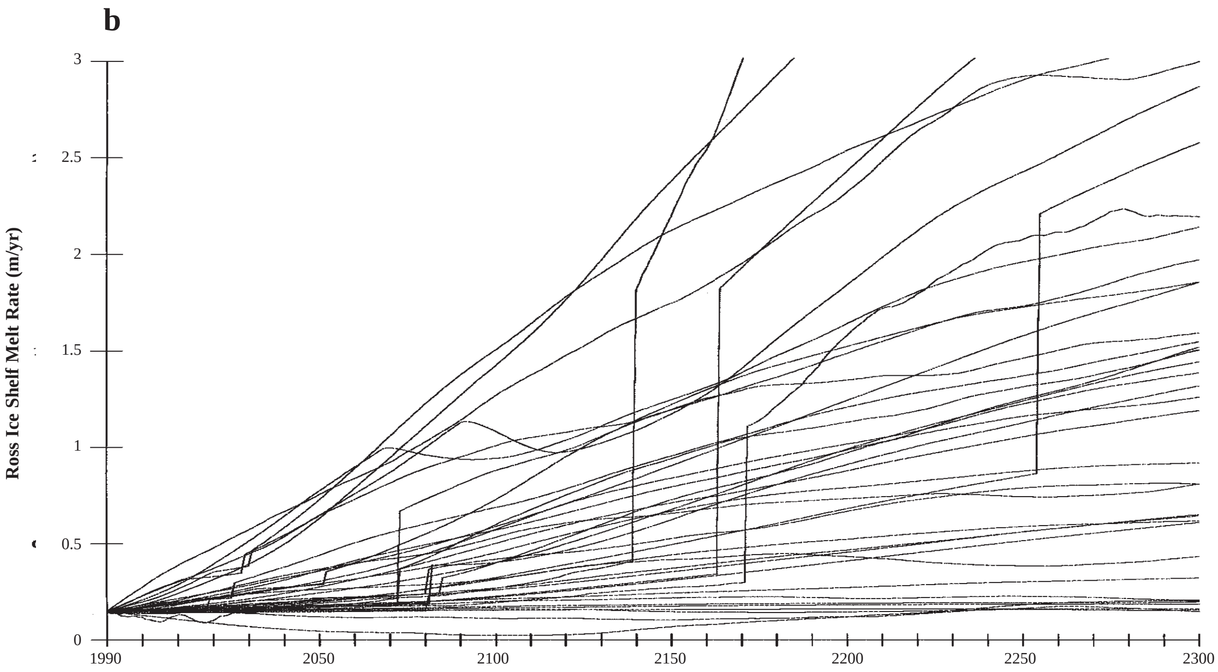

Figure 5-16. Ross Ice Shelf Melt Rates: Selected simulations for the period 1990–2300. See Figure 2-5 and accompanying text for the source of the simulations selected.

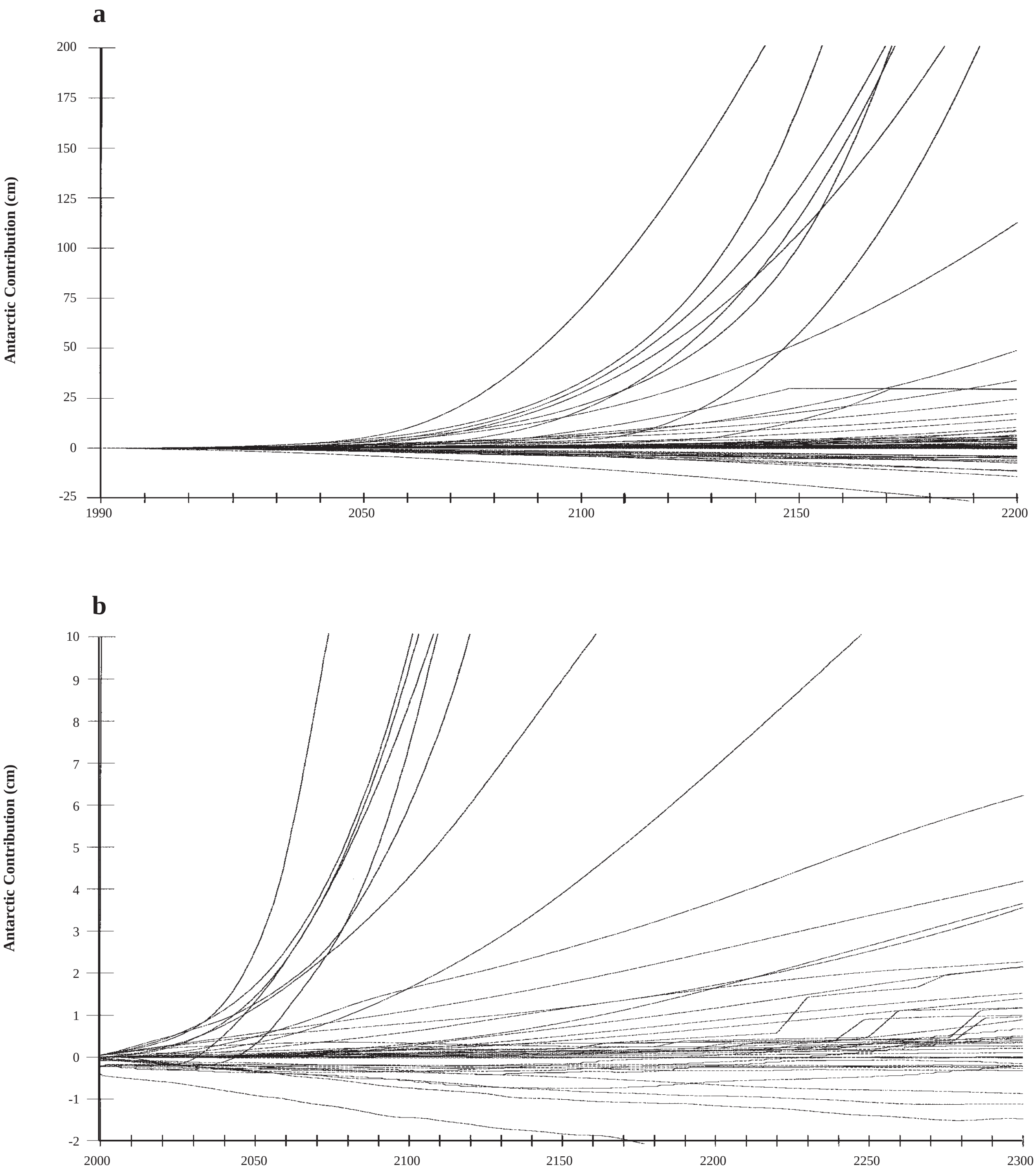

Figure 5-17. **Spaghetti Diagrams for Antarctic Contribution.** (a) Annual and (b) cumulative Antarctic contribution for selected simulations. See Figure 2-5 and accompanying text for explanation of scenarios illustrated.

Figures 5-15 and 5-16 illustrate our estimates of the rate of Ross Ice Shelf melting. Because the circumpolar ocean warms by less than 1˚C in most of the runs, the median shelf-melt rate is less than 0.5 m/yr by 2100; and almost 90 percent of the simulations project melt rates less than 1 m/yr. In the following century, however, shelf-melt rates accelerate as circumpolar temperatures begin to rise at rates comparable to the rate of global warming. In a few cases, shelf-melt rates accelerate rather suddenly due to the possibility of a "switch" in which undiluted circumpolar deep water intrudes beneath the Ross Ice Shelf.

The resulting impact on the Antarctic contribution to sea level is illustrated in Figure 5-17 (*previous page*). For virtually all scenarios, the increased precipitation associated with warmer temperatures dominates at first, both because Antarctic air temperatures (and hence precipitation) are assumed to respond more rapidly than water temperatures (and hence shelf melting), and because the ice streams take another century to respond to shelf melting. Thus, by the year 2050, 67 percent of the scenarios show a net negative sea level contribution; this percentage declines to 62 percent by 2100, and 50 percent by the year 2200 (*see* Table 5-8).

Even though most scenarios show a negative contribution, the analysis suggests that there is a small chance of a very large positive Antarctic contribution. In the upper 10 percent of the scenarios, Antarctica contributes approximately 10 cm during the 21st century, 30 cm during the 22nd century, and 50 cm during the 23rd century. In about 1 percent of the simulations, Antarctica contributes 30–40 cm during the 21st century, 150–200 cm during the 22nd century, and 3–4 m during the 23rd century. Most of the scenarios show an initial negative contribution due to the rapid response of Antarctic precipitation, followed by an eventual positive contribution due to the greater but slower impacts resulting from the ice stream responses to warmer Antarctic ocean temperatures.

Compared with the draft analysis, the reviewers generally had a negligible impact on our median estimate. For the year 2100, the median estimate is a drop of 1.45 cm, barely different from the 1 cm drop projected by the draft analysis (*compare* Table 5-8 *with* Table 5-5). But the reviewer assumptions did increase the uncertainty, compared with the draft analysis. At the low end, the most important contributor was Zwally's (Chapter 3-B) assessment that Antarctic precipitation could, in the extreme case, double with a 4˚C warming. Rind, Schneider, and Hoffert also expanded the low end of the spectrum by suggesting that Antarctic air temperatures might warm by more than we had originally assumed, which would result in more precipitation. These climate reviewers also expanded the high end of the range by suggesting that circumpolar ocean waters are likely to warm 1.0 to 1.5˚C by 2100, compared with the 0.75˚C implied by the draft assumptions.

TABLE 5-8
CUMULATIVE PROBABILITY DISTRIBUTION ANTARCTIC CONTRIBUTION

Cumulative Probability (%)	Contribution Between 1990 and: 2050	2100	2200
0.1[a]	–52.4	–52.2	–135.6
0.5[a]	–32.0	–43.8	–111.9
1.0[a]	–25.7	–36.8	–89.9
2.5[a]	–16.7	–26.8	–56.9
5[a]	–10.9	–18.9	–37.9
10	–6.7	–11.6	–24.6
20	–3.7	–6.8	–13.0
30	–2.4	–4.3	–7.2
40	–1.6	–2.7	–3.3
50	–0.9	–1.4	–0.3
60	–0.4	–0.3	5.4
70	0.2	+1.9	13.8
80	1.9	5.8	24.1
90	4.8	11.3	42.9
95	7.0	16.5	71.6
97.5	8.8	21.3	114.5
99	10.7	30.1	206.4
99.5[a]	13.2	36.6	277.7
99.9[a]	21.2	51.9	455.4
Mean	1.08	–1.1	8.2
σ	0.66	11.1	47.0

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

The glaciology assumptions also increased the uncertainty range. Surprisingly, the Thomas assumptions do not make much of a difference through the year 2100. While Thomas (1985) suggested that a 30 cm contribution was likely, and that a 1–2 m contribution was possible, Thomas's assumptions now imply that the contribution is as likely to be negative as positive and that the chance of a 30 cm contribution is only about 15 percent. Thomas's suggested shelf-melt assumptions have little impact by the year 2100. His lower estimates result primarily because our climatology assumptions imply much less Antarctic warming than was assumed by the 1985 National Academy study to which Thomas had contributed.

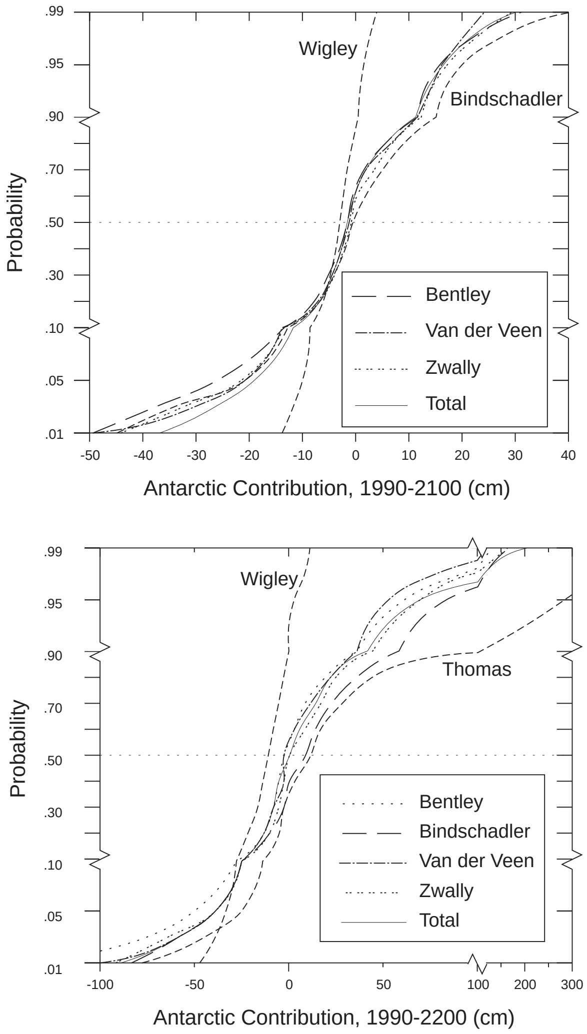

Figure 5-18. **Cumulative Probability Distribution of Antarctic Contribution to Sea Level by Reviewer.** A few curves have been removed for clarity: The distribution implied by the Alley and Anonymous assumptions generally tracked those of Bentley and Van Der Veen, respectively. For the year 2100, the Thomas estimates are close to those of Bindschadler; by 2200, however, they diverge markedly.

Like the draft report, our final results suggest that if Antarctica is going to have a major impact on sea level, it will probably be after the year 2100. Even by the year 2200, the median contribution is negligible. But the reviewers estimate a 10 percent chance of at least a 40 cm contribution, as well as 3 and 1 percent chances that the contribution could exceed 1 and 2 m, respectively. As Figure 5-18 shows, the Thomas assumptions are largely responsible for the upper end of the range. While most reviewers estimate a 2–3 percent chance that the contribution through 2200 will be greater than 1 m, Thomas estimated a 10 percent chance of such a contribution, as well as 2 percent chance that Antarctica could contribute more than 4 m!

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CHAPTER 6

SMALL GLACIERS

Although most of the world's ice is found in Greenland and Antarctica, small glaciers elsewhere contain enough ice to raise sea level approximately half a meter. Because most of the mass of these glaciers is on snow-capped mountains, for our purposes, the terms "mountain glacier," "alpine glacier," and "small glacier" are often used interchangeably.

IPCC (1990) estimated the contribution to sea level from small glaciers with the following equation[1] from Raper et al. (1990):

$$\left|\frac{dz}{dt}\right| = \frac{|\beta|}{\beta} \; \frac{[-z + (z_0 - z)\,|\beta|\,\Delta T]}{\tau}$$

where

z	is sea level contribution (cm),
z_0	is equal to 50 cm (initial ice mass in sea level equivalent),
ΔT	is mean global warming since 1880 (˚C),
β	represents sensitivity of glacial melt to temperature changes, and
τ	is the adjustment time (years).

Note that the equilibrium condition is

$$\frac{z}{z_0} = \beta\,\Delta T/(1 + \beta\,\Delta T),$$

which means that it takes 3.5 times as much warming to raise the sea 30 cm as it does to raise it 15 cm. These diminishing returns will tend to compress the right-hand tail of the distribution for the alpine sea level contribution.

IPCC picked three values for τ: 10, 20, and 30. It then derived 0.45, 0.25, and 0.1 as values for β by fitting the historic temperature trend to Meier's (1984) estimate that the alpine contribution to sea level during the period 1900–1961 was 2.8±1.6 cm. We adopted a similar procedure, except that we use the actual temperature record rather than the modeled values for estimating the historic contribution of small glaciers to sea level. We assume that τ has a lognormal distribution with σ limits of 10 and 30; Figure 6-1 illustrates the resulting distribution of β. The lower half of the figure is based on the recent estimate of Oerlemans

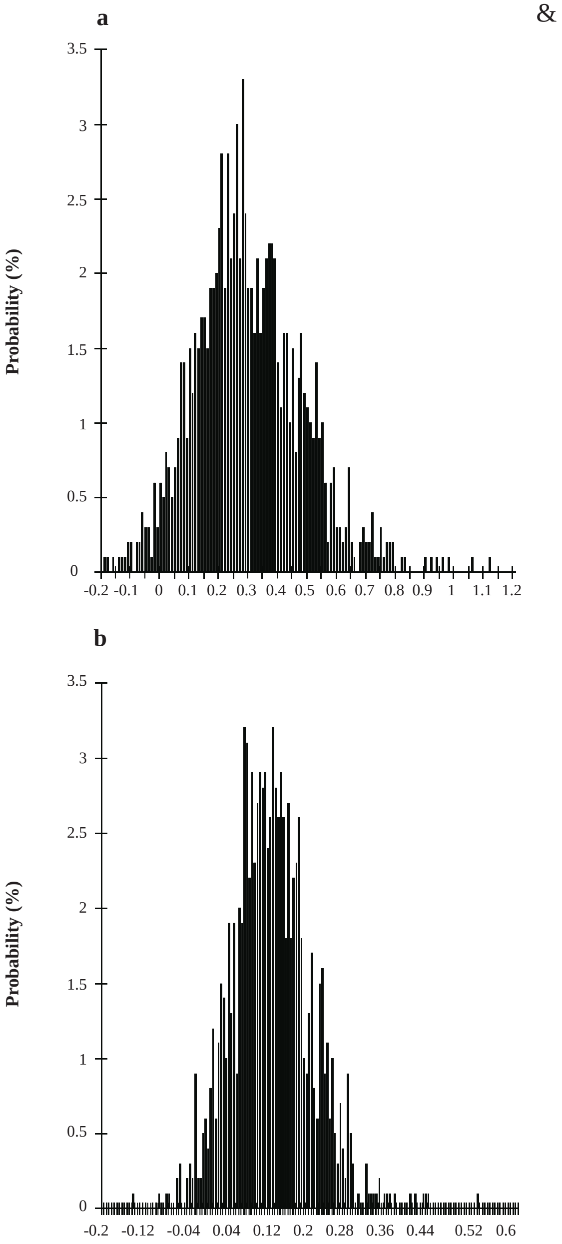

Figure 6-1. Probability Density of Assumed Small-Glacier Sensitivity to Global Warming. Distribution of β based on (a) IPCC/Raper et al. (1990); and (b) scaled by Oerlemans & Fortuin estimate.

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[1] We have added in the absolute value signs so that the model is reasonable for negative values of β.

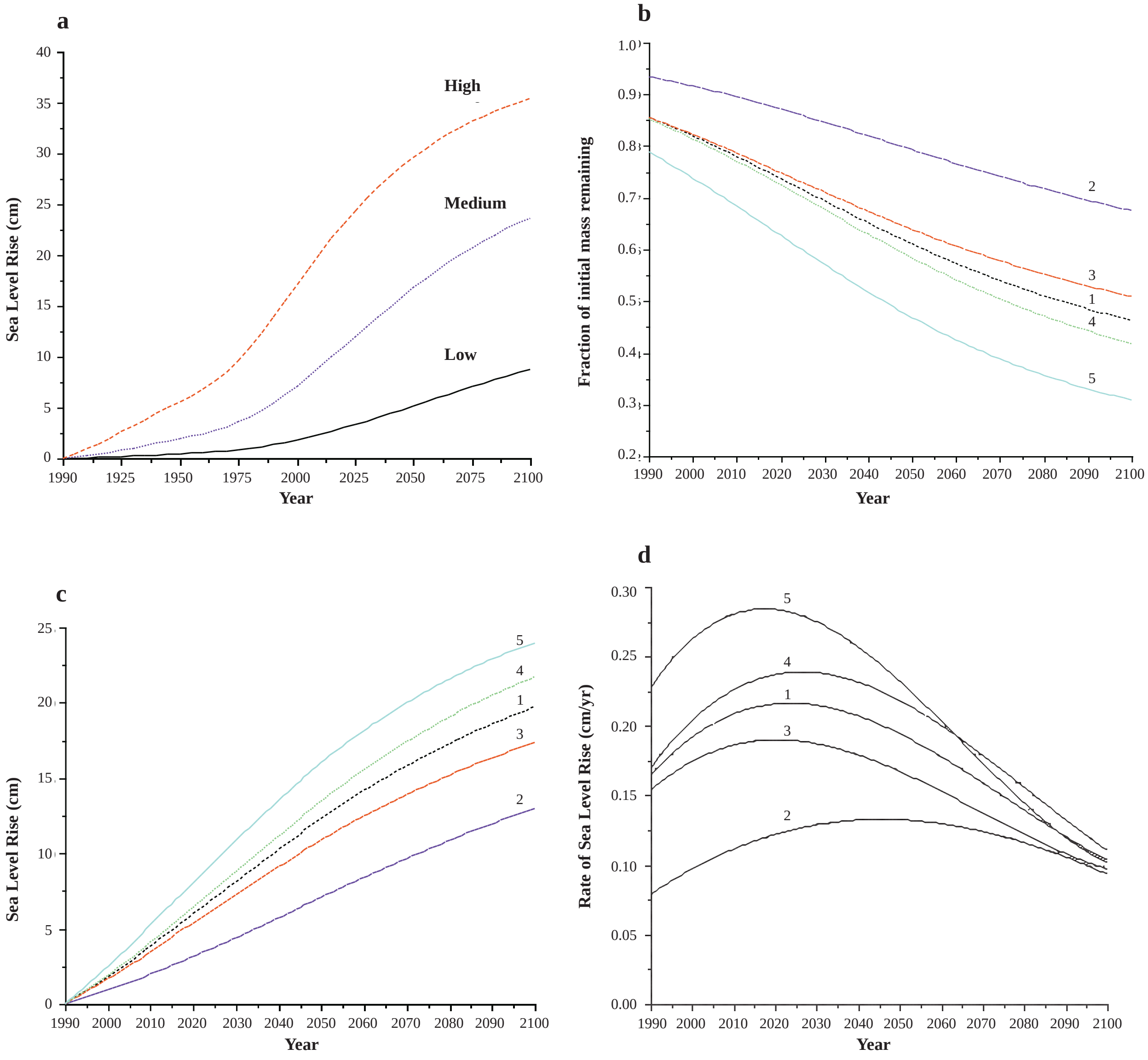

Figure 6-2. Characteristics of the Raper et al. Model of the Small Glacier Contribution. Sensitivity runs using Raper et al. (IPCC) model and IPCC 1990 "Business-as-Usual" forcing, showing (a) IPCC (1990) estimates of the historic and future small glacier contribution; and projections over the period 1990–2100 for (b) remaining mass of world small glaciers (as a fraction of original); (c) contribution to sea level; and (d) rate of sea level contribution. The numbered scenarios in (b), (c), and (d) represent: 1—IPCC (1990) medium scenario (*i.e.*, median ΔT_{2X}, τ and β); 2—same as (1) but using Oerlemans's rather than Meier's estimate of historic small glacier contribution; 3—same as (1) but σ-fast τ; 4—same as (1) but σ-slow τ; 5—same as (4) but $\Delta T_{2X} = 4.5$.

Fortuin (1992) that the small glacier contribution to sea level has been only 1.2 cm.

In the draft, we were uncertain whether to regard this new estimate as an additional piece of information or a replacement for Meier's estimate; as a result, we assumed that both had equal validity. Thus, for 50 percent of the simulations, we derived β on the assumption that Meier's estimates characterize the mean and standard deviation of a normal distribution of the historic contribution to sea level from small glaciers; for the other simulations, we used the Oerlemans & Fortuin estimate for the mean, and imputed a standard deviation of 0.69 cm, the same percentage of the mean as published by Meier.[2]

Figure 6.2a illustrates the IPCC (1990) results. Note that the medium is closer to the high than to the low scenario. This results partly from the peculiar functional form used by the Raper et al. model. Moreover, the high scenario contribution for 1990–2100 is depressed because the IPCC calculations assume that the moun-tain glacier contribution between 1900 and 1990 was about 15 cm (Figure 6-2b), rather than the 4 to 5 cm that one would expect from extrapolating Meier's results for 1900–1960.[3] Thus, IPCC inadvertently compressed the range of future alpine contributions to sea level: the high scenario assumes that in 1990 there was about 10 cm less ice to melt than assumed in the medium scenario; the same argument applies in reverse to the IPCC low scenario.

Draft Results

Figure 6-3 illustrates the estimated probability density for the small glacier contribution to sea level rise. Unlike the distributions of Greenland and Antarctica, which are skewed to the right, this distribution is squeezed on the right-hand side, for the same reasons that explain the IPCC medium scenario being closer to the high than to the low scenario. Given the downward revision implied by the Oerlemans & Fortuin data, it is not surprising that our median estimate for the year 2100 (14 cm) was less than the 18.5 cm estimate of IPCC (1990). Thus, only 10 percent of our simulations exceeded IPCC's 21.5 cm high estimate, while 20 percent were less than IPCC's 8.8 cm low estimate (see Table 6-1).

Note also that about 4 percent of the time there was an increase in the mass of small glaciers and, thus, a negative contribution to sea level. This result stemmed from the fact that Meier's estimate of 2.8±1.6 cm means that, at the 95 percent confidence level, one cannot rule out a negative historic contribution; the functional spec-

TABLE 6-1
DRAFT CUMULATIVE PROBABILITY DISTRIBUTION FOR CONTRIBUTION TO SEA LEVEL FROM SMALL GALCIERS

Cumulative Probability (%)	2030	2100	2200
1.0[a]	–2.4	–7.1	–10.5
5[a]	–0.4	–1.4	1.9
10	1.5	4.4	6.6
20	2.8	7.9	11.3
30	3.8	10.3	14.4
40	4.6	11.9	16.9
50	5.5	14.0	19.3
60	6.6	16.0	21.3
70	7.8	18.0	23.2
80	9.2	19.5	24.8
90	10.9	21.8	26.9
95	11.8	23.3	28.3
99	13.1	25.7	30.5
Mean	5.7	13.4	17.6
σ	3.6	7.1	8.7

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

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[2] Based on the assumption that global temperatures rose linearly by 0.28˚C during the 61-year period, we derived distributions for β with means of 0.23 and 0.125 and standard deviations of 0.14 and 0.077 for the Meier and Fortuin & Oerlemans distributions, respectively.

[3] This happens because Raper et al fit the model to the actual temperature data, but IPCC uses simulated temperatures for 1900–1990; if the model was separately fit for each simulation, the historic projections would more closely correspond to the actual record.

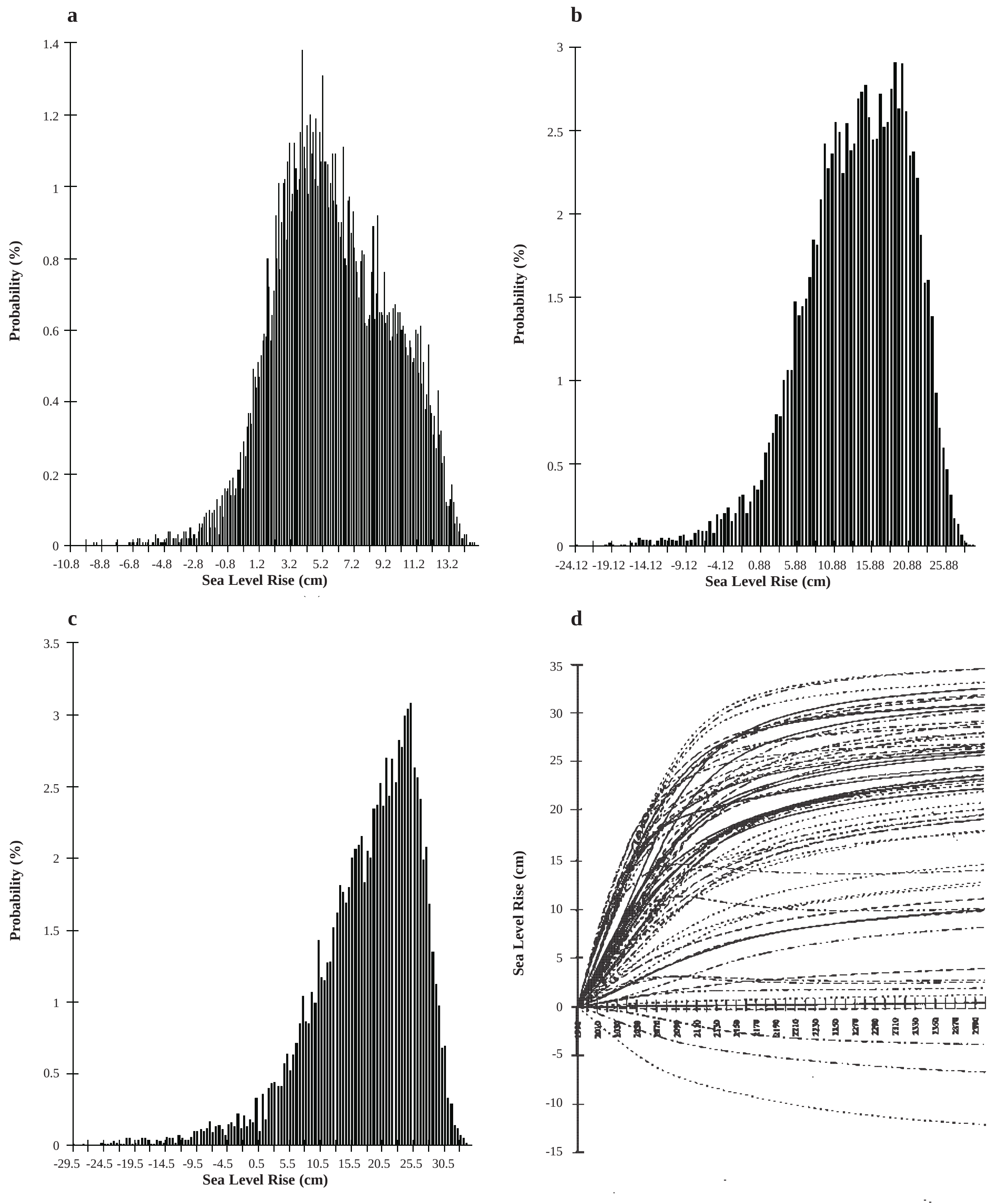

Figure 6-3. Small Glacier Contribution: Draft Report. Probability densities for the periods (a) 1990–2030, (b) 1990–2100, and (c) 1990–2200, along with (d) a spaghetti diagram of cumulative small glacier contributions to sea level: See Figure 2-5 and accompanying text for explanation of the scenarios chosen.

ification employed by the Raper et al. model assumes that such an impact would continue. Although that functional specification has limitations,[4] it seemed reasonable to retain the negative projections in light of the fact that a few researchers believe that increased snowpack is a possible result of global warming.

The spaghetti diagram (Figure 6-3d) shows a few scenarios in which the small glacier contribution to sea level would decline after the year 2075, which implies a negative annual contribution after that year. The declining annual contribution results from the decline in temperatures shown by a few scenarios in the draft analysis (*see* Figure 3-7 and accompanying text).

Changes Made in the Final Version

In the final draft, we base all of the simulations on the Oerlemans & Fortuin estimate. Warrick (1993) suggests that a consensus is emerging among the key IPCC (1990) contributing authors that the next IPCC assessment will "support the Oerlemans & Fortuin downward revision in glacier sensitivity." Deriving β from Oerlemans & Fortuin implies a median of 0.12 with 10 percent of the values greater than 0.22 and 10 percent less than 0.032.

The final version also corrects the IPCC (1990) simulations of past contributions: Regardless of the historic warming estimated in a given simulation, we assume that the historic contribution of small glaciers to sea level was 1.2±0.69 cm.

TABLE 6-2
FINAL CUMULATIVE PROBABILITY
DISTRIBUTION FOR CONTRIBUTION TO
SEA LEVEL FROM SMALL GALCIERS

Cumulative Probability (%)	2050	2100	2200
0.1[a]	–6.6	–10.9	–19.1
0.5[a]	–3.7	–5.7	–9.3
1.0[a]	–2.6	–3.9	–6.5
2.5[a]	–1.2	–1.8	–2.5
5[a]	–0.4	–0.3	–0.3
10	0.4	1.0	1.6
20	1.7	3.3	5.2
30	2.7	5.3	8.1
40	3.7	6.9	10.7
50	4.8	8.7	13.2
60	5.9	10.5	15.7
70	7.2	12.4	18.5
80	9.0	14.8	21.7
90	11.5	18.3	25.8
95	13.8	21.1	29.0
97.5	15.8	23.6	32.8
99	18.0	26.3	34.2
99.5[a]	20.2	27.8	35.6
99.9[a]	26.3	32.2	38.6
Mean	5.4	9.2	13.5
σ	4.5	6.7	9.2

[a] These estimates are included for diagnosis purposes only. Because the focus of the analysis was on the risk of sea level *rise* rather than sea level *drop*, less effort has gone into characterizing the lower end of the distribution.

Final Results

Given these changes, Table 6-2 summarizes the cumulative probability distribution for the small glacier contribution to sea level. The median estimate is one-third lower than in the draft version because of (a) the lower historic glacial sensitivity and (b) the lower temperature estimates.[5] Nevertheless, small glaciers still

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[4] Both the Greenland and the small glacier specifications used in this report impose a mass constraint to prevent the sea level contribution from exceeding the amount of ice that exists. The Greenland specification suffers from the assumption that altitude is the sole reason that some parts contribute more than others; in fact, differences in latitude are also important. A good aspect of that model, however, is that it is capable of assuming that increased precipitation over a given area builds up at first, but that as warmer temperatures expand the ablation zone, that area may begin to lose mass. A consideration of the fraction of precipitation falling as rain would improve this aspect.

By contrast, the mountain glacier equation implicitly assumes a variation in latitude: As temperatures rise, higher latitudes fall within the net annual ablation zone. The model assumes that the equilibrium impact increases at a decreasing rate with temperature, which is consistent with the idea that because there is, for example, less land between 75–80˚N than between 70–75˚N (or for that matter, less land at 3000 m elevation than at 2000 m), each additional degree of warming brings less alpine snow within the net ablation area. The primary problem with the specification is that the equilibrium condition $z/z_0=\beta*\Delta T/(1+\beta*\Delta T)$ appears to have no theoretical or empirical basis. It is hardly self-evident, for example, that it should take 5.44 times as much warming to melt the second 17 cm as it takes to melt the first 17 cm, yet the Raper et al. equation imposes that assumption for all values of β.

[5] Excluding the Balling temperature estimate, our median temperature estimate by the year 2100 is a warming of 2.25˚C, rather than 2.02˚C. This higher warming results in a median mountain glacier contribution of 10 cm.

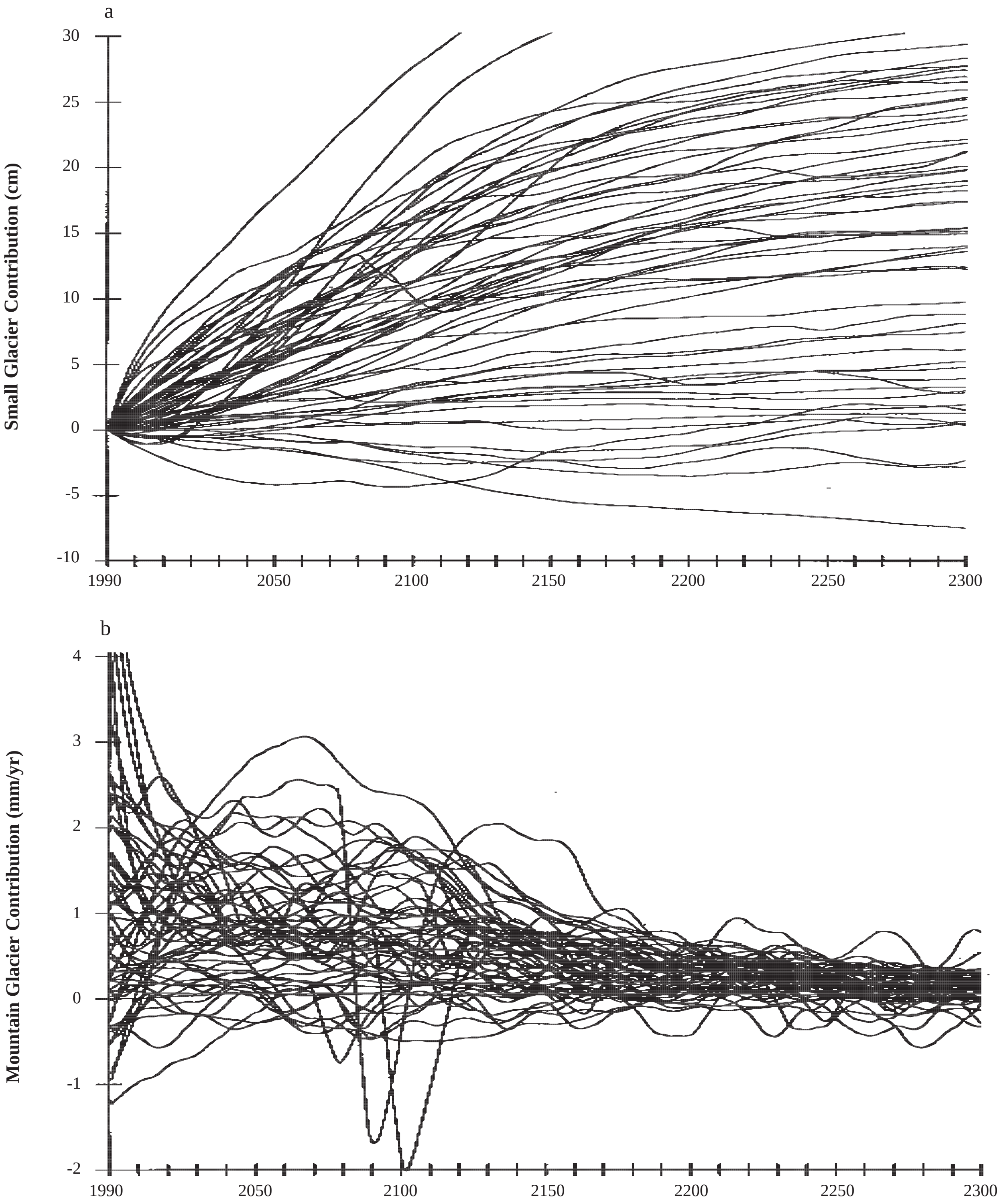

Figure 6-4. Spaghetti Diagrams of the Small Glacier Contribution: Final Results. Selected simulations for (a) cumulative and (b) annual small glacier contribution. See Figure 2-5 and accompanying text for explanation of scenarios selected.

would contribute 0.8 mm/yr—more than four times the historic contribution estimated by Fortuin & Oerlemans.

Unlike the median estimate, the final 1%-high estimate (26.3 cm) is actually higher than the 25.7 cm estimated in the draft report. The higher estimate results primarily from our downward correction of the historic contribution—and thus an upward correction in the current mass of small glaciers—in those scenarios that assume a high degree of global warming.

Figure 6-4 displays spaghetti diagrams for the total and annual contributions of small glaciers to sea level. Unlike other potential contributors to sea level rise, the annual alpine contribution is likely to decline after the next century as the glacial ice available for melting is consumed. In the case of some of the outlier scenarios, where the alpine contribution in the next decade is estimated to be over 4 mm/yr, the current contribution is unlikley to be sustained for more than the next 10–20 years.

The spaghetti diagrams suggest a declining uncertainty in the annual contribution to sea level. In percentage terms, however, the uncertainty does not decline. Even in absolute terms, the decline in uncertainty is an artifact of the model's assumption regarding the relationship between temperature and equilibrium glacial mass.

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Chapter 6

CHAPTER 7

RESULTS

If the experts on whom we relied fairly represent the breadth of scientific opinion, the odds are fifty-fifty that greenhouse gases will raise sea level at least 15 cm by the year 2050, 35 cm by 2100, and 80 cm by 2200.[1] Moreover, there is a one-in-forty chance that changing climate will raise sea level 35 cm by 2050, 80 cm by 2100, and 300 cm by 2200.

For the reader who skipped the chapters outlining our assumptions, we begin by outlining the key results from those chapters. Next, we present our estimates for the total rise in sea level resulting from climate change and compare them with the results of other recent assessments. We then estimate the extent to which emission policies might reduce the risk of sea level rise. We close the chapter with a brief analysis of the extent to which uncertainty might be reduced through a better understanding of some key processes.

Summary of Previous Chapters

We now summarize the highlights of the previous chapters on radiative forcing, global temperatures and thermal expansion, polar temperatures and precipitation, and the contributions to sea level from Greenland, Antarctica, and small glaciers (see Table 7-1).

Radiative Forcing. Our emission projections were based on IPCC (1992) scenarios A through F; and we used the assessment by Wigley & Raper (1992) for calculating the resulting concentrations of both greenhouse gases and sulfate aerosols. As a result, our scenarios for anthropogenic radiative forcing[2] are broadly consistent with other recent assessments.[3] Like those

TABLE 7-1
IMPACT OF GREENHOUSE GASES ON KEY CLIMATIC VARIABLES BY THE YEAR 2100

	mean estimate	Probability that Value Will Not Be Exceeded						
		2.5%	10%	50%	90%	95%	97.5%	99%
Temperature Change (˚C)								
Greenland	3.1	0.0	0.6	2.5	6.3	8.1	10	14
Antarctic Ocean	1.2	0.0	0.16	0.86	2.5	3.3	4.0	5.0
Global Average	2.2	0.0	0.6	2.0	4.0	4.7	5.4	6.3
Sea Level Contribution (cm)								
Thermal Expansion	21	0.6	5.1	20	38	45	50	58
Small Glaciers	9.2	–1.8	1.0	8.7	18	21	24	26
Greenland	4.6	–0.4	0.22	2.9	10	14	19	27
Antarctica	–1.1	–27	–12	–1.5	11	16	21	30
Other Variables								
CO_2 Concentration (ppm)	738	462	511	680	1047	1204	1363	1614
Radiative Forcing (W/m^2)	5.0	2.3	3.0	4.9	7.2	7.8	8.2	8.7
Greenland Precipitation (mm/yr, sea level equivalent)	1.7	1.3	1.4	1.6	2.2	2.6	3.2	4.2
Rate of Melting, Ross Ice Shelf (m/yr)	0.7	0.22	0.25	0.37	1.3	2.1	3.2	6.2

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[1] Because other factors also contribute to sea level, the total rise is likely to be significantly greater, as we see in Chapter 9.

[2] That is, the amount of additional radiation striking the Earth's surface as a result of human modification of the atmosphere.

[3] Our mean estimate of radiative forcing for the year 2100, 5.0 W/m^2, is only slightly less than the medium forcing estimate by Wigley & Raper (1992).

assessments, we generally project smaller anthropogenic changes in forcing than assumed in some of the older assessments.

Our median projection is that, over the period 1990–2100, radiative forcing will increase by 4.9 watts per square meter (W/m^2), which is equivalent to increasing CO$_2$ concentrations from 350 parts per million (ppm) to 770 ppm. By contrast, the IPCC (1990) "Business-As-Usual" scenario projected an increase of 7.5 W/m^2; and IPCC (1992) projected 6.2 W/m^2 for Scenario A.[4] About 1 percent of our simulations have more forcing than the 8.5 W/m^2 IPCC (1992) estimated for Scenario E,[5] while about 20 percent have a forcing less than the 3.5 W/m^2 projected by IPCC (1992) for Scenario C. Our median estimate is that radiative forcing will increase by 4.4 W/m^2 (equivalent to a CO$_2$ doubling) by the year 2089, with a 10 percent probability that the doubling equivalent will occur by 2068.

Although we project less radiative forcing than early IPCC assessments, our assumptions are consistent with the IPCC (1994) report on radiative forcing. That report has adopted scenarios that are much closer to the Wigley & Raper (1992) assumptions on which our scenarios are based. Most important, the IPCC has lowered the projected CO$_2$ concentration from 800 ppm to about 730 ppm for the year 2100. Although IPCC has not yet endorsed a specific estimate of the average global forcing effect of sulfates, it has acknowledged that sulfates offset a large fraction of the historic greenhouse warming.

Global Warming. The reviewer assumptions imply that there is a 90 percent chance that the next century will see more than the 0.5˚C warming experienced in the last century, a 50 percent chance that the Earth will warm more than 2˚C, and a 3 percent chance that our planet will warm 5˚C, which is more than it has warmed since the last ice age. Although a 2˚C warming is most likely by the year 2100, there is a 7 percent chance that it will occur by 2050. Even if emissions are constant after 2100, temperatures are likely to rise about 0.15˚C per decade throughout the 22nd and 23rd centuries.

Thermal Expansion. As global temperatures rise, the various layers of the ocean will warm and expand. Especially in the long run, thermal expansion depends on the extent to which the heat is able to penetrate into the intermediate and deep layers of the ocean. For example, a decline in deepwater formation would slow upwelling, allowing heat to penetrate farther, and thereby increase thermal expansion. Differences in opinions regarding ocean circulation changes led to a 10 percent variation among the reviewers regarding likely expansion. By the year 2100, the most likely expansion is 20 cm, but there is a 2 1/2 percent chance that expansion will exceed 50 cm. Although global temperatures are projected to rise 25 percent less during the 22nd century than in the 21st, thermal expansion is likely to be 20 to 40 percent more, due to the delayed response of expansion to higher temperatures.

Greenland Climate. The likely contribution of Greenland to sea level will depend on the magnitude of increases in precipitation and melting, both of which would increase at higher temperatures. Particularly if the Gulf Stream weakens due to a shutdown in North Atlantic deepwater formation, Greenland may warm less than the global average warming—or perhaps even cool. Nevertheless, most of the reviewers expect Greenland temperatures to eventually warm by more than the global average. Thus, we estimate that there is a 50 percent chance that Greenland will warm at least 2.5˚C between 1990 and 2100, a 25 percent chance of a warming greater than 4˚C, and a 2 1/2 percent chance that the warming will exceed 10˚C. By contrast, Wigley & Raper (1992) projected a best-guess warming of 3.8˚C.

All but one of the reviewers expect Greenland precipitation to increase about 8 percent per degree (C), which is equivalent to a sea level drop of 0.1 mm/yr per degree. In light of the projected warming of Greenland, there is a 50% chance that by 2100 Greenland precipitation will increase 20 percent, and a 5% chance that it will double. At the low end of the spectrum, there is a 10% chance that precipitation will increase by less than 5 percent.

Greenland Contribution. Our median estimate is that Greenland will contribute 2.9 cm to sea level by the year 2100. Our 95 percent confidence range is –0.37 cm to 19 cm. For 2200, we estimate a median contribution of 12 cm, but a 10 percent chance of a 50 cm contribution. At the low end of the range, we estimate a 5 percent chance that Greenland will have a negative

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[4] These estimates are equivalent to increasing CO$_2$ by factors of 3.4 and 2.8, respectively. Note that IPCC (1990) also estimated that radiative forcing increased by about 2.5 W/m^2 through the year 1990, compared with the preindustrial level.

[5] About 20 percent of our simulations, however, have more forcing than the 6.6 W/m^2 estimated by Wigley & Raper (1992) for Scenario E.

contribution to sea level through 2100. Mostly because our temperature estimates are lower, our median is less than the 7.5, cm projected by Wigley & Raper (1992).

Antarctic Climate. Antarctic air temperatures are likely to rise by approximately 2.5˚C in the next century, largely as a result of reduced sea ice. For each degree (C) of warming, Antarctic precipitation is likely to increase approximately 8 percent, equivalent to a 0.4 mm/yr drop in sea level.

Unlike Greenland, Antarctica is colder than freezing even during summer; so warmer *air* temperatures will not cause significant glacial melting. Warmer *water* temperatures, by contrast, could potentially increase melting of the marine-based West Antarctic Ice Sheet and adjacent ice shelves. The reviewers generally agreed, however, that any warming of the circumpolar ocean is likely to lag behind the general increase in global temperatures by at least fifty years, and perhaps by a few centuries. Thus, we estimate that Antarctic ocean temperatures are most likely to warm 0.86˚C by the year 2100. Although a 3˚C warming is likely by 2200, there is only a 6 percent chance that such a warming will occur by 2100.

Antarctic Contribution. Warmer ocean temperatures have about a 50 percent chance of doubling the average rate at which the underside of the Ross Ice Shelf melts, from 0.17 m/yr to 0.35 m/yr, by the year 2100. Although a doubling may seem significant, most previous studies have suggested that the rate of melting would have to increase to at least 1 m/yr to have a significant impact on sea level. The reviewer assumptions imply that there is only about a 10 percent chance of such an increase in the next century. We also estimate that there is a 5 percent chance that by 2100 the Ross Ice Shelf will be melting 2 m/yr, which is similar to the melt rate that prevails today beneath the George VI Ice Shelf.

Even with a large rate of shelf-melting, the Antarctic contribution to sea level may be negligible. Because ice shelves float and hence already displace ocean water, shelf-melting would raise sea level only if it accelerates the rate at which ice streams convey ice toward the oceans. Several models suggest, however, that shelf-melting will not substantially accelerate ice streams—and even the models that project such an acceleration generally suggest a lag of a century or so. Thus, through the year 2100, we estimate a 60 percent chance that the sea level drop caused by increased Antarctic precipitation will more than offset the sea level rise caused by increased ice discharge; this probability declines to 50 percent by 2200.

Our analysis suggests that if Antarctica is going to have a major impact on sea level, it will probably be after the year 2100. Even by 2200, the median contribution is negligible; but the reviewer assumptions also imply a 10 percent chance of a contribution greater than 40 cm, as well as 3 and 1 percent chances that the contribution could exceed 100 and 200 cm, respectively.

Small Glaciers. If all the small glaciers melted, sea level would rise approximately 50 cm. We estimate that a 9 cm contribution through the year 2100 is most likely, with a 5 percent chance that the contribution will be greater than 20 cm.

Total Contribution of Climate Change to Sea Level

The reviewer assumptions imply that there is a 1 percent chance that climate change will raise sea level 42 cm by the year 2050, 104 cm by 2100, and over 4 m by 2200. The most likely (median) contribution, however, is only about one-third as great: 15 cm by 2050, 34 cm by 2100, and 81 cm by 2200. Uncertainty increases over time: the ratio of our 1%-high scenario to our median scenario is 2.8 for 2050, 3.1 for 2100, and 5.1 for 2200. Figure 7-1 illustrates the cumulative probability distribution of the primary contributors to sea level for the year 2100.

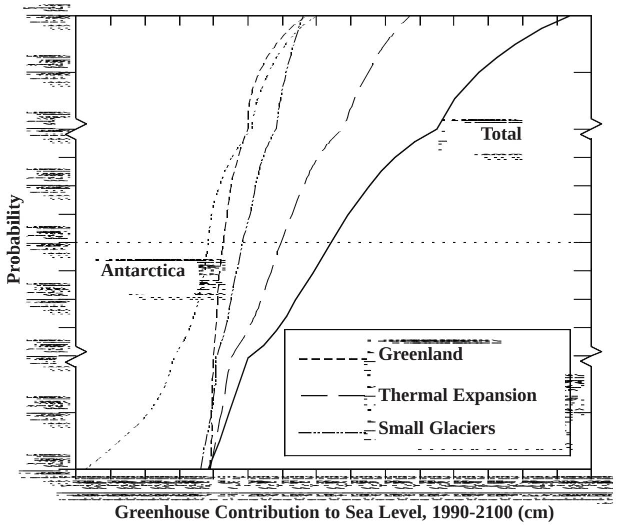

Figure 7-1. Greenhouse Contribution to Sea Level. The cumulative probability distributions show the contribution to sea level from thermal expansion, small glaciers, Greenland, and Antarctica for the period 1990–2100.

TABLE 7-2
YEAR BY WHICH VARIOUS THRESHOLDS ARE EXCEEDED[a]

	Probability that Threshold Will Be Exceeded by a Given Year								
	97.5%	90%	70%	50%	30%	10%	5%	2.5%	1%
THRESHOLD									
Climate Contribution to Sea Level									
> 50 cm	>2200	>2200	>2200	2136	2108	2083	2074	2066	2059
> 1 meter	>2200	>2200	>2200	>2200	2180	2133	2118	2108	2097
Sea Level along U.S. Coast[b]									
> 1 ft	2169	2099	2069	2058	2049	2038	2034	2031	2027
> 3 ft	>2200	>2200	2194	2157	2131	2106	2097	2090	2083
> 5-ft contour on topographic maps	>2200	>2200	>2200	>2200	2180	2141	2127	2117	2107
Other Variables									
ΔForcing > 4.4 W/m^2	>2200	>2200	2103	2089	2064	2068	2066	2064	2062
CO$_2$ > 600 ppm	>2200	>2200	2117	2078	2077	2052	2048	2045	2042
$\Delta T > 1^\circ C$	>2200	>2200	2069	2048	2034	2022	<2020	<2020	<2020
$\Delta T > 2^\circ C$	>2200	>2200	2174	2099	2073	2052	2046	2041	2031

[a] Compared with 1990 levels.

[b] Based on rate of sea level rise at New York City, which typifies the Atlantic and Gulf Coasts of the United States. See Chapter 9 for further details.

(As we discuss in the final chapter, the rise in sea level along most of the U.S. Coast will be higher due to nonclimatic contributors to sea level.) Table 7-2 illustrates the year by which sea level and a few other key variables will exceed particular thresholds. Although a 2°C warming is most likely to occur over the next century, for example, there is a one percent chance that such a warming could occur by the year 2031.

Figures 7-2 and 7-3 illustrate the cumulative and annual contributions of climate change to sea level for selected simulations. By the year 2100, climate change is most likely to add 4 mm/yr to sea level (implying a rate of more than 6 mm/yr along most of the U.S. coast). Moreover, there is a 10 percent chance that climate change will add 1 cm/yr, and a 1 percent chance that it will add 2 cm/yr, by the end of the twenty-first century.

The net effect of the reviewer assumptions is illustrated by Table 7-3, which compares our final reviewer-based estimates with the draft estimates. The final median estimates are approximately one-third lower than estimated in the draft report, primarily because the median estimate of warming over the next century was lowered from 3°C to 2°C. At the high end of the range, by contrast, the final results are only one-fourth lower for the year 2100—and they are actually higher for 2200, primarily because of the potential contribution from Antarctica. At the low end of the range, the final results are much lower than the draft results, for three reasons: (1) one reviewer expects global temperatures to rise only slightly, if at all; (2) another reviewer suggested that polar precipitation is very uncertain and could conceivably increase by 20 percent for a 1°C warming; and (3) the factors that cause a lower median temperature also operate on the low end of the spectrum.

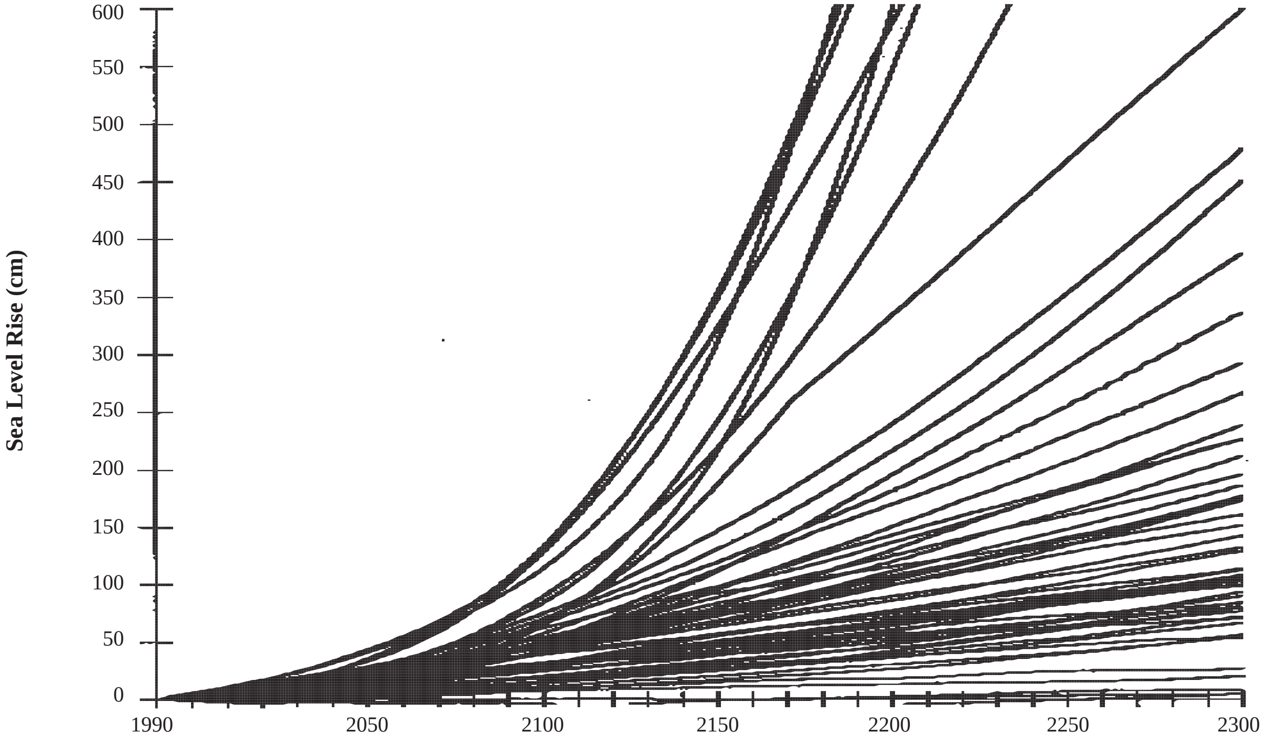

Figure 7-2. Cumulative Contribution of Climate Change to Sea Level: Selected Simulations.

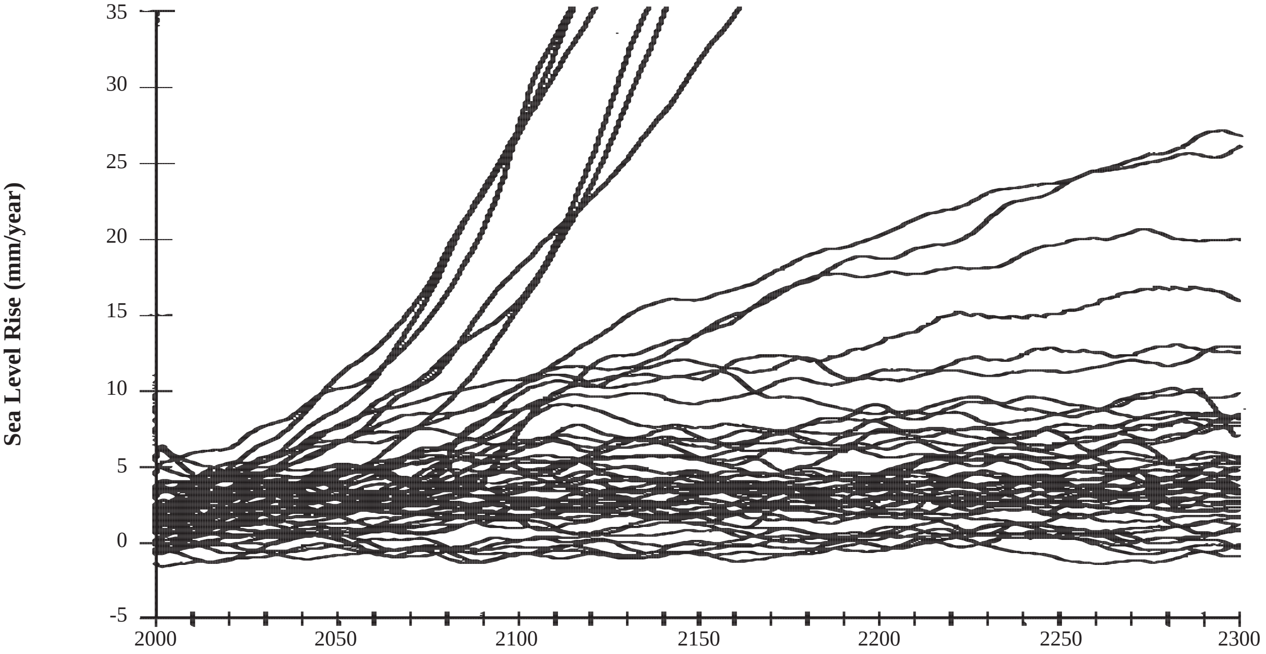

Figure 7-3. Annual Contribution of Climate Change to Sea Level: Selected Simulations. See Figure 2-5 and accompanying text for description of these and other spaghetti diagrams.

TABLE 7-3
CUMULATIVE PROBABILITY DISTRIBUTION OF THE CONTRIBUTION OF CLIMATE CHANGE TO SEA LEVEL RISE

	Draft Results			Final Results			
	Sea Level Rise (cm)			Sea Level Rise (cm)			Rate of Rise (mm/yr)
Cumulative Probability	2030[a]	2100	2200	2050[a]	2100	2200	2100
1[b]	4.1	15	28	-1.2	-1.2	-0.8	-0.36
2.5[b]	—	—	34	0.4	1.7	3.5	0.03
5[b]	6.3	22	43	2.1	4.9	10	0.47
10	7.8	28	55	4.6	10	22	1.05
20	9.7	35	72	8.1	19	39	1.91
30	12	40	84	11	24	53	2.68
40	13	46	100	13	29	67	3.44
50	15	52	112	15	34	81	4.21
60	16	58	128	17	39	96	5.04
70	18	65	148	20	45	115	6.08
80	20	73	180	23	53	143	7.49
90	23	88	228	28	65	196	9.89
95	26	101	280	33	77	254	12.37
97.5	—	—	332	37	88	316	15.41
99	31	131	400	42	104	409	19.34
99.5[b]	—	—	452	46	115	498	23.05
Mean	—	—	—	16	37	99	5.04
σ				9	22	82	4.19

[a] Although the draft provided results for the year 2030, we subsequently decided that the year 2050 would be more useful for the purposes of this chapter. Budget constraints precluded us from recomputing the draft results for 2050.

[b] Included for diagnostic purposes only. Neither the reviewers nor the modeling efforts focused on the risk of a sea level drop. Therefore, the lower end of the uncertainty range is much less reliable than the upper end.

NOTE: Because nonclimatic factors also contribute to sea level rise, these results should not be used to project sea level in specific locations. See Table 9-1 for results better suited for that task.

Because the reviewers represent a cross-section of the scientific community, we have weighted the individual assessments equally.[6] Nevertheless, the variation of reviewer assessments may also be worth considering. Figure 7-4 shows the variation in sea level estimates resulting from the assumptions suggested by the various climate reviewers (see Chapter 3). Even though their estimates for global temperature change were similar, Schneider, Rind, and Hoffert projected much less warming for Greenland and Antarctica than did Manabe or MacCracken. As a result, the Manabe and MacCracken assumptions suggest a 1 percent chance of a 3 m rise by 2200; the Schneider, Rind, and Hoffert assumptions, by contrast, imply a 7 percent chance of a 3 m rise and a 1 percent chance of a 5 m rise over the next two centuries.

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[6] Some Delphic studies have asked the reviewers to assign an appropriate weight to the opinions of each reviewer. We decided not to follow that approach, for reasons explained in Chapter 1. Among those reasons: (a) we would have had to double the number of questions asked of each reviewer; (b) the reviewers' expertise on individual physical processes does not necessarily imply an expertise to assess the merits of other reviewers' opinions; (c) the reviewers already self-selected out of parameters on which they had no expertise; (d) we wanted to keep this analysis "on the record," which would have been impossible if the reviewers had to rate the expertise of other scientists; and (e) we would still have to pick an appropriate weight for each reviewer's opinion of the other opinions. *See* Chapter 1, **Approach**.

TABLE 7-4
CONTRIBUTION OF CLIMATE CHANGE TO SEA LEVEL 1990-2100
COMPARISON BETWEEN IPCC (1990) AND OUR RESULTS

Scenario	Thermal Expansion	Small Glaciers	Greenland	Antarctica	Total
IPCC/low[a]	25.8	7.8	2.9	–7.6	29
1%	–0.8	–3.9	–0.8	–37	–1.2
10%	5.1	1	0.2	–11.7	10.3
IPCC/best[a]	38.7	18.5	11.6	–5.36	64
Median	19.7	8.7	2.9	–1.4	34.1
IPCC/high[a]	58	21.5	27.7	0	107.2
90%	38.1	18.3	10.3	11	65.1
99%	57.5	26.3	27.2	30	104

[a] IPCC results cited here are somewhat different from those of IPCC 1990 because they are with respect to a 1990 base, rather than IPCC's 1985 base. In addition, IPCC (1990) rounded some of its results.

NOTE: Because nonclimatic factors also contribute to sea level rise, these results should not be used to project seal level in specific locations. See Table 9-1 for results better suited for that task.

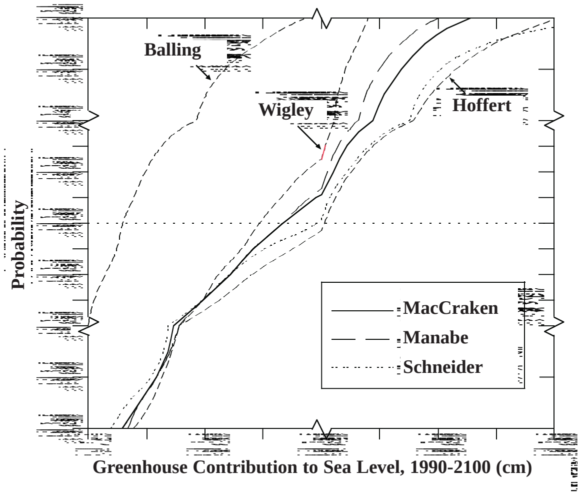

Figure 7-4. Greenhouse Contribution to Sea Level by Climate Reviewer. These cumulative distributions show the greenhouse contribution for the year 2200. Wigley & Raper provided assumptions for Greenland and Antarctica; otherwise, the displayed distributions combine the reviewer's climate assumptions with random samples of the assumptions suggested by the precipitation and Antarctica reviewers.

The assumptions of Wigley & Raper and Balling, by contrast, suggest that the risk of a large rise is much smaller. Because Wigley & Raper assumed a narrower range of possible temperature projections than the other "mainstream" reviewers, their range of sea level projections is also narrower. Finally, Wigley & Raper provided their own assumptions for the ice sheet contribution to sea level—assumptions that suggest lower risk than was suggested by the glacialogy reviewers of Chapters 4 and 5. Their median projection is also somewhat lower because their ocean model assumptions did not imply as much downward penetration of heat as the assumptions favored by the other reviewers. Given Balling's assumption that global temperatures are not sensitive to greenhouse gases, his low projections of the sea level contribution are not surprising. Nevertheless, he allowed for random fluctuations in climate and accepted the other models used in this report. As a result, his relatively optimistic assumptions still imply that there is a 1 percent chance that changing climate will add 90 cm to sea level over the next two centuries.

Comparison with IPCC (1990)

For the last several years, the most widely cited estimates for future sea level rise have been those reported by IPCC (1990). As this report went to press, the IPCC was revising its projections for a report to be released later in 1995. Although we hope that this report satisfies the special information needs of coastal planners and engineers, it seems reasonable to assume that more general assessments of the climate change issue will continue to use IPCC estimates. Therefore, we briefly compare our results with those of IPCC (1990), as well as Wigley & Raper, whose periodic assessments have often provided useful interim indications of the direction in which scientific opinion is headed.

Table 7-4 compares our projections for the year 2100 with those of IPCC (1990). Although our median estimate of 34 cm is fairly consistent[7] with the Wigley & Raper (1992) estimate of 48 cm, it is substantially lower than the IPCC "best-guess" estimate of 64 cm. Our downward revision (compared with IPCC's medium estimate) is primarily driven by the lower temperature estimates, which in turn resulted from lower estimates of radiative forcing (*i.e.*, lower concentrations of greenhouse gases and inclusion of the offsetting effect of sulfate aerosols).

Our draft results, however, show that the median sea level estimate would have been lower than the IPCC (1990) estimate even if our temperature estimates had been as high as those of IPCC (1990). The draft and IPCC (1990) both assumed a warming of about 3˚C over the 1990–2100 period, but the draft projected a sea level contribution of only 51 cm. About half of this downward revision (compared with IPCC) resulted from lower thermal expansion estimates, which stemmed from changes in ocean modeling assumptions.[8] Our nonlinear model of the Greenland contribution, combined with explicitly considering increased precipitation, resulted in a much lower estimate of this ice sheet's sensitivity to a warming of a few degrees (C). Finally, we incorporated recent work suggesting that small glaciers are less sensitive to global temperatures than previously thought.

Although our median projection is a downward revision compared with IPCC (1990), it is more difficult to say whether our estimates of the entire range also constitute a downward revision. The terms "low scenario" and "high scenario" have no precise meaning. The IPCC (1990) high scenario, for example, involved a coincidence of high temperature sensitivity and high values for the sensitivity of Antarctic, Greenland, and small glaciers; but it was based on best-guess estimates of future concentrations and ocean mixing (although those assumptions are both at the high end of the range we use here). Our results, by contrast, do not explicitly include a coincidence of all parameters reaching their "high values," both because we randomly selected the parameter values and because the normal and lognormal distributions do not have fixed upper bounds.

Nevertheless, given the interpretation of "high" and "low" as "worst-case" and "best-case" scenarios, our final results reflect far more uncertainty than the IPCC results. More than 40 percent of our simulations project less sea level rise than IPCC's low scenario of 30 cm by 2100; 15 percent of the simulations suggest that climate change will contribute even less than Wigley & Raper's (1992) estimate of 15 cm. At the upper end of the range, about 0.75 percent of our simulations suggest more sea level rise than IPCC's high scenario (110 cm). Thus, while IPCC's high scenario was 1.7 times its "best-estimate" scenario for the year 2100, approximately 16 percent of our simulations are more than 1.7 times our median estimate; and our 1%-high estimate is 3.1 times our median scenario.

The Implications of Alternative Emission Rates

The preceding results were based on a mix of emission scenarios. To the coastal decisionmaker, future emission rates are but one of many sources of uncertainty and are functionally no different from the various climatic and glacial process parameters. To the climate policymaker, however, emission rates are (in theory) a variable that can be fixed by policy. As a result, climate policymakers may be more interested in the *conditional* probability distribution of sea level rise for a given emissions scenario, and the implications of policies to reduce emissions.

Table 7-5 summarizes the results for a variety of alternative emission scenarios. The left side of the table compares the impacts of IPCC Scenarios A and E. We also examine the potential benefits of freezing emissions in the year 2025 or 2050, rather than 2100. These scenarios use the full distribution of emission sce-

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[7] As discussed in Chapter 9, if one assumes that the historic sea level rise has been 1.8 mm/yr, then our median estimate of the total rise in sea level (including nonclimatic contributors) by the year 2100 is 45 cm.

[8] The most important changes were lower values of the parameter π and a correction in the Wigley & Raper model regarding how expansion was calculated.

TABLE 7-5
IMPLICATIONS OF ALTERNATIVE EMISSIONS SCENARIOS

Assumptions

Emission Scenarios:	E	A	All[a]	All	All	All	All	All	All
Emissions Fixed After:	2100	2100	2100	2050	2025	2100	2100	2050	2025
Climate Sensitivity[b]:	1.0-4.4	1.0-4.4	1.0-4.4	1.0-4.4	1.0-4.4	2.6 fix	4.0 fix	4.0 fix	4.0 fix
Increased Forcing, 1990–2100 (W/m^2)									
median	6.6	5.5	4.9	4.4	4.0	4.9	4.9	4.4	4.0
10%-high	6.6	5.5	7.2	5.8	4.9	7.2	7.2	5.8	4.9
1%-high	6.6	5.5	8.7	7.0	5.9	8.7	8.7	7.0	5.9
Warming, 1990–2100 (˚C)									
median	2.6	2.3	2.0	1.9	1.7	2.4	3.3	3.1	2.9
10%-high	4.5	4.0	4.0	3.6	3.3	3.3	4.8	4.2	3.8
1% high	6.7	6.0	6.3	6.0	5.6	4.4	8.1	6.9	6.3
Warming, 1990–2200 (˚C)									
median	4.9	4.0	3.3	2.9	2.7	4.0	5.8	5.0	4.6
10%-high	9.0	7.4	7.4	5.8	5.2	5.6	8.3	6.6	5.8
1%-high	13.8	11.5	12.8	9.9	9.0	7.4	10.5	8.1	7.1
Sea Level Contribution, 1990–2100 (cm)									
median	40	36	34	33	31	38	53	50	48
10%-high	71	66	65	62	59	53	73	70	67
1%-high	110	103	104	102	101	84	118	113	110
Sea Level Contribution, 1990–2200 (cm)									
median	108	91	81	71	66	97	140	124	114
10%-high	237	200	195	166	152	162	236	205	191
1%-high	447	385	409	357	347	308	455	403	366
Annual Greenhouse Contribution to Sea Level by 2100 (mm/yr)									
median	6.2	4.8	4.2	3.6	3.2	4.9	7.1	5.9	5.3
10%-high	12.0	9.7	9.9	8.2	7.3	8.1	11.7	9.8	8.9
1%-high	21.2	17.8	19.3	17.4	15.3	15.2	22.1	19.5	17.3

[a] The column shows the result for the final analysis discussed throughout this report.

[b] The σ range is 1.0-4.4 rather than 1.5-4.5, due to the downward effect of the Balling assumptions.

narios from the baseline analysis. The third, fourth, and fifth columns in Table 7-5 use a range for the climate's sensitivity to a CO_2 doubling, while the last three columns use the relatively high value of 4.0˚C suggested by many three-dimensional general circulation models.[9]

The results suggest that if emission Scenario E is likely to unfold, the *initial* benefit of emissions policies would be modest. Moving society down to the scenario A trajectory would decrease the median sea level contribution from 40 cm to 36 cm; freezing emissions in the year 2050, which is roughly equivalent to IPCC Scenario D, would reduce the sea level contribution to 33 cm—only 17 percent less than what would occur under Scenario E. Over the next two centuries, however, freezing emissions by 2050 would reduce the expected rise in sea level by 35 percent (71 cm compared with 108 cm).

Using the uncertainty range developed in Chapter 2, freezing emissions by 2050 would only reduce the next century's sea level rise by about 3 percent, compared with freezing emissions in 2100; freezing emissions by 2025 would reduce the rise by about 10 percent. These results do not necessarily mean that stabilizing emissions is not worthwhile, only that the benefits of doing so would accrue over a long period of time. The median *rate* of sea level rise would be one-sixth lower by 2100 if emissions were frozen in 2050, and 25 percent lower if emissions were frozen in 2025. The median cumulative greenhouse contribution to sea level through the year 2200 would be reduced by 12 and 18 percent, respectively, if emissions are frozen in 2050 and 2025; the 10%-high estimates would be reduced by 15 and 25 percent.

Sensitivity Analysis of Variation

Given the large number of parameters used in this analysis, one might reasonably ask: Which of these parameters are superfluous and which contribute significantly to our uncertainty? Although a complete analysis of this question is beyond our current resources, we briefly discuss four of the most important processes: emissions, climate sensitivity, the response of polar temperatures to global temperatures, and the response of ice-shelf melting to changes in Antarctic ocean water temperatures. We fix the parameter(s) controlling these processes at roughly their median values and examine the extent to which uncertainty declines.

As Table 7-6 shows, the climate sensitivity parameter accounts for the most uncertainty, especially at first. For the year 2100, fixing this parameter reduces the standard deviation of sea level rise projections by 35 percent. Fixing the polar-temperature parameters or the ice-shelf-melt parameters, by contrast, each reduces the standard deviation by about 4 percent; and fixing emissions equal to Scenario A reduces the uncertainty by about 0.5 percent. For the year 2200, however, fixing climate sensitivity only reduces the standard deviation by 21 percent, while fixing polar-temperature and ice-shelf-melt sensitivities reduces the standard deviation by 10 and 16 percent, respectively.

The contributions of polar amplification and shelf-melt sensitivity to total uncertainty is greater for the year 2200, primarily because the contributions of Antarctica and Greenland to sea level are likely to be much larger during the 22nd century than during the 21st century. Fixing temperature sensitivity or polar temperature amplification reduces the standard deviation for the Greenland contribution by about one-third. For Antarctica, however, the ice-shelf-melt sensitivity accounts for about half of the uncertainty; polar temperature amplification accounts for about 25 percent of the uncertainty; and climate sensitivity accounts for about 7 percent. The differences are even greater when one focuses on the 1%-high projections: fixing the shelf-melt sensitivity reduces the 1%-high estimate of the Antarctic contribution by more than two-thirds.

Numerical Error of the Monte Carlo Alogorithm

As discussed in Chapter 1, we chose to calculate the probability distribution of future sea level rise using the basic Monte Carlo algorithm. The Latin Hypercube algorithm generally provides more precise estimates of the tails of a distribution for a given number of simulations, but implementing it would have required additional work. We decide that the increased numerical accuracy was not worth the extra effort.

As a rough check to ensure that we had run enough simulations, we divided our sample into eight subsets, representing the first 1250 runs, the second 1250 runs, and so on. For the climate contribution to sea level (1990–2100), the 1%-high generally ranged between 101

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[9] We include the scenario where climate sensitivity is fixed at 2.6˚C here for the reader interested in the resulting temperature projections, which are not displayed in Table 7-6.

TABLE 7-6
ANALYSIS OF VARIANCE: CUMULATIVE PROBABILITY DISTRIBUTION OF SEA LEVEL CONTRIBUTION WHEN CERTAIN PARAMETERS ARE FIXED AT THEIR MEDIAN VALUES

	PARAMETER FIXED				
	None (Baseline)	Emissions	Climate Sensitivity	Polar Temperatures	Ice Shelf Melt Rate
Parameter Set To:		Scenario A	2.6˚C	Median Values	Median Values
Greenland Contribution, 1990–2200 (cm)					
1% low	–2.7	–3.2	2.5	1.5	—
10% low	0.1	1.2	3.7	2.5	—
median	12.0	15.0	14.7	12.8	—
10% high	50.0	53.3	39.8	39.3	—
1% high	150.0	149.1	130.6	105.2	—
mean	21.0	23.3	23.7	18.3	—
σ	29.8	29.4	19.7	19.4	—
Antarctic Contribution, 1990–2200 (cm)					
1% low	–90.0	–88.7	–80.7	–88.3	–92.5
10% low	–25.0	–24.4	–15.4	24.2	–24.1
median	0.0	–0.1	9.7	–0.2	–0.3
10% high	43.0	46.0	47.8	35.7	25.2
1% high	206.0	206.4	152.7	139.0	62.7
mean	8.0	8.9	22.4	6.1	4.2
σ	47.0	45.6	44.0	38.1	23.4
Total Greenhouse Contribution, 1990–2100 (cm)					
1% low	–1.0	–1.0	7.0	–1.0	–1.0
10% low	10.0	12.0	21.0	10.0	9.0
median	34.0	36.0	38.0	33.0	33.0
10% high	65.0	66.0	53.0	62.0	62.0
1% high	104.0	103.0	84.0	102.0	98.0
mean	37.0	39.0	40.0	36.0	36.0
σ	22.3	22.2	14.6	21.5	22.0
Total Greenhouse Contribution, 1990–2200 (cm)					
1% low	–1.0	–1.0	26.0	–1.0	–2.0
10% low	22.0	28.0	5.0	22.0	23.0
median	81.0	91.0	97.0	76.0	77.0
10% high	196.0	200.0	162.0	180.0	171.0
1% high	409.0	385.0	308.0	309.0	293.0
mean	99.0	108.0	111.0	92.0	90.0
σ	82.4	83.9	65.5	73.8	69.2
Annual Greenhouse Contribution by the Year 2100 (mm/yr)					
1% low	–0.36	–0.27	0.48	–0.21	–0.17
10% low	1.05	1.54	2.20	1.05	1.06
median	4.20	4.84	4.90	3.96	4.07
10% high	9.89	9.70	8.10	9.19	9.34
1% high	19.34	17.82	15.21	16.62	16.18
mean	5.04	5.43	5.42	4.69	4.77
σ	4.19	3.79	2.95	3.52	3.71

and 107, with a mean of 104 and a standard deviation of 2.7 cm (*see* Appendix 1). Thus, the standard deviation of our estimate of the 1%-high estimate is 0.99 cm.[10]

For the purposes of this study, a standard numerical error of 1 cm for the 1%-high is acceptable. This result is not surprising, given that the 1%-high estimate represents one hundred observations. Had our intent been to characterize the one-in-a-million risk common in environmental risk assessments, or even the one-in-ten-thousand risk considered in the Dutch flood control system, the use of algorithms that capture the tails of a distribution would have been more important. We determined at the outset, however, that our models and assumptions were not suited for such unlikely risks.

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[10] Recall from elementary statistics that the standard deviation of an estimate of the mean is equal to the standard deviation of a sample, divided by the square root of the sample size. In this case, the “mean” refers to the average value of the 1%-high of various data sets, and the sample size is 8.

CHAPTER 8

PLACING THE RESULTS IN CONTEXT

Revisions of Sea Level Rise Scenarios

Long-range projections of physical, economic, and ecological systems often prove to be wrong, because they involve combinations of assumptions with varying degrees of certainty. Moreover, with a highly visible public policy issue such as climate change, the projections themselves can motivate people to take actions that render early projections obsolete (*e.g.*, projections of a 4˚C global warming could lead people to reduce emissions so that the warming is only 2˚C).

This report and other recent analyses suggest that sea level is likely to rise less than estimated by early reports on the subject (see Table 8-1).[1] The lower estimates have resulted from both a downward revision of future temperatures and an emerging consensus that Antarctica will probably not contribute to sea level in the next one hundred years.

Lower Global Temperatures. In the last decade, estimates of the global warming likely to occur by the year 2100 have been approximately cut in half. The 1983 reports by EPA and the National Academy of Sciences assumed that the radiative forcing equivalent of a CO_2 doubling was likely to occur by 2050. During the mid-1980s, several reports suggested that an effective CO_2 doubling could occur by the 2030s (*see e.g.*, Villach 1985). Thus, the EPA reports released in 1983 projected a warming of 3 to 9˚C by 2100, with CO_2 and other greenhouse gases accounting for equal amounts of warming (Hoffman et al. 1983; Seidel & Keyes 1983). The NAS (1983) report projected a warming of 1 to 5˚C from CO_2 alone and was thus viewed as being consistent with the EPA results (*see e.g.*, Chafee 1986). EPA's 1989 Report to Congress (Smith & Tirpak 1989) was based on similar assumptions, as shown in Table 8-2. For the most part, scenarios of sea level rise for the year 2100 were in the 50 to 200 cm range, with 100 cm being the most likely.

TABLE 8-1
CLIMATE CHANGE CONTRIBUTION
TO SEA LEVEL PROJECTED
BY VARIOUS STUDIES

A. Total Greenhouse Contribution to Sea Level by 2100 (cm)

	Low	Medium	High
EPA (1983)[a]	56	175	345
NAS (1985/1983[b])	50	100	200
NRC (1987)	50	100	150
IPCC (1990)	30	65	110
Wigley & Raper (1992)	15	48	90
This Report[c]	–1	34	104

B. Contribution to Thermal Expansion by 2100 (cm)

	Low	Medium	High
EPA (1983)[a]	28	72	115
NAS (1983)	24	30	36
NRC (1987)	—	—	—
IPCC (1990)	26	39	58
Wigley & Raper (1992)	22	33	44
This Report[c]	–1	20	58

[a] EPA (1983) refers to Hoffman et al. 1983.
[b] Thermal expansion from NAS 1983; glacial contribution from NAS 1985.
[c] Low and High refer to lower and upper 1 percent.

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[1] Unlike some recent assessments by IPCC (1990, 1992) and Wigley & Raper (1992), this report still projects a significant risk that sea level will rise more than one meter by the year 2100; *i.e.*, our downward revision applies more to the "best estimate" than to the high end of the uncertainty range.

TABLE 8-2
GLOBAL WARMING PROJECTED BY VARIOUS STUDIES

A. Warming Over 1990 Levels

Report	2050 Low	2050 Medium	2050 High	2100 Low	2100 Medium	2100 High	CO_2 = 600 ppm Doubling Date
EPA (1983)[a]	0.7	2.4	4.5	2.1	5.0	9.0	2050
NAS (1983)[b]	—	—	—	—	4.5	—	—
NAS (1985)	—	—	—	1.5	3.0	4.5	2085
EPA (1989)[a]	—	3.0	—	—	—	—	2060
IPCC (1990)	1.3	1.6	2.5	2.3	3.7	5.7	2060
IPCC (1992)[c]	1.0	1.4	2.2	1.8	2.8	4.2	2060
Wigley & Raper (1992)[c]	0.8	1.2	1.7	1.7	2.5	3.8	2060
This Report[d]	–0.1	1.0	2.9	–0.1	2.0	6.3	2080

B. Year by Which Temperatures Warm 2˚C or 4˚C

Temperature Report	2˚C Low	2˚C Medium	2˚C High	4˚C Low	4˚C Medium	4˚C High
EPA (1983)[a]	2095	2040	2017	>2100	2085	2040
NAS(1983)[b]	2050	2030	2020	—	2080	—
NAS (1985)		2050		2050	>2100	>2100
EPA(1989)[a]	—	2035	—	—	2060	—
IPCC(1990)	2090	2060	2040	>2100	>2100	2085
IPCC (1992)[c]	2105	2075	2045	>2100	>2100	2095
Wigley & Raper (1992)[c]	>2100	2080	2060	>2100	>2100	>2100
This Report[d]	>2200	2099	2030	>2200	>2200	2065

[a] EPA (1983) refers to Seidel & Keyes (1983); EPA (1989) refers to Smith & Tirpak (1989).
[b] CO_2 only. Analyses based on assumption of 2˚C warming “a few decades into the 21st century” and 3 to 4˚C by 2080.
[c] IPCC (1992) and Wigley & Raper (1992) results use IPCC emissions scenario A.
[d] Low and High refer to upper and lower 1 percent.

Recent reports have gradually lowered the projections of future warming, primarily for three reasons. First, in the mid-1980s the fully halogenated CFCs were perceived as potentially responsible for about one quarter of the expected warming (*Cf. e.g.*, Ramanathan et al. 1985). These CFCs are no longer considered likely to contribute significantly to global warming by the year 2100[2]: The Montreal Protocol phases out their production. Moreover, the direct greenhouse effect from CFCs in the troposphere is partly offset because CFCs deplete stratospheric ozone, which is also a greenhouse gas. Although the partially halogenated HCFCs have not yet been regulated, IPCC has reduced its projections for these gases as well. For example, IPCC (1992) estimated that by the year 2100 the concentration of HCFC-22 will be 1.4 parts per billion, less than half the IPCC (1990) estimate of 3 ppb.[3]

Second, estimates of the concentrations of carbon dioxide have also been revised downward because of both lower emissions and revised carbon cycle models. The EPA studies released in 1983 assumed that CO_2 emissions were most likely to reach 70 gigatons per year by 2100. The IPCC (1992) Scenario A, by contrast, estimates about 20 Gt/yr; and even the high scenario E only projects 35 Gt/yr.[4] Thus, the IPCC (1990) and (1992) reports projected CO_2 concentrations of 825 and 800 ppm, respectively, well below the 1000 ppm projected by the early EPA studies.[5]

Recent revisions in carbon cycle models have also resulted in lower estimates of carbon dioxide concentrations. Wigley (1993) concluded that more carbon may be absorbed by the terrestrial biosphere than previously assumed; he estimated 678 ppm as the most likely scenario for 2100 if emissions follow the trajectory of IPCC (1992) Scenario A. IPCC (1994) applied several alternative carbon cycle models to IPCC Emissions Scenario A; all of the models project a CO_2 concentration between 650 and 725 ppm.[6] Our median estimate is 680 ppm.

Finally, temperature projections have declined because the early studies did not consider the cooling effect of atmospheric sulfates and other aerosols resulting from human activities. Since 1850, aerosols appear to have offset about one-third of the radiative forcing from greenhouse gases.[7] Because aerosols rapidly fall out of the atmosphere while greenhouse gases may accumulate for tens or hundreds of years, the relative contribution of aerosols will probably be less in the next century than it has been in the last century. Nevertheless, as discussed in Chapter 2, the IPCC emissions scenarios imply that sulfates are likely to offset about 8 percent of the increased radiative forcing from greenhouse gases over the period 1990–2100.[8]

In spite of the downward revisions in future temperature projections, one potential downward revision has *not* occurred: climatologists still generally accept the NAS (1979) estimate that, in equilibrium, a CO_2 doubling would raise global temperatures 1.5 to 4.5˚C. The cooling effect of aerosols offers a plausible explanation for why global temperatures have not risen as much as climate models would have suggested.[9] Wigley &

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[2] For example, under IPCC's emissions scenario A, CFC-11 and CFC-12 are expected to contribute 0.2 W/m^2 by the year 2100, about 3 percent of the total radiative forcing from anthropogenic greenhouse gases. Because the current contribution of these two CFCs is about 0.22 W/m^2, IPCC scenario A implies a slight decrease in radiative forcing from CFC-11 and CFC-12. IPCC (1992) at 175.

[3] HCFC-22 is by far the most important partially halogenated chlorofluorocarbon. IPCC (1992) estimates that the radiative forcing due to HCFC-22 will rise from close to zero today to approximately 0.2 W/m^2.

[4] *But see* Energy Modeling Forum (1995). Out of eight models considered, four models project emissions greater than the 26.6 Gt/yr assumed by IPCC's (1992) second highest scenario (F). Two of the models project emissions greater than IPCC's highest scenario (E); and one of the scenarios exceeds 55 Gt by the year 2090. *See Id.* at slide entitled "Modeler's Reference Case, World."

[5] The EPA and IPCC reports all projected concentrations of about 600 ppm for the year 2060. Because of the lags in the various processes, the divergence in assumptions for the post-2060 period has a modest effect on projections of sea level rise for the year 2100.

[6] *But see* Craig & Holmén (1995) (applying four different models for balancing the carbon budget to IPCC emission Scenario A results in CO_2 concentrations of 825, 725, 700, and 690 ppm for 2100).

[7] *See* IPCC (1994) at 167 (The direct radiative forcing from anthropogenic greenhouse gases released since preindustrial times is 2.4 W/m^2 ±15%; the mean direct radiative forcing from sulfates is –0.25 to –0.9 W/m^2; the mean direct radiative forcing from biomass burning is between –0.05 and –0.6 W/m^2).

[8] The IPCC scenarios do not assume that any governmental policies will be implemented to reduce SO_2 emissions, other than those already enacted before 1992. Just as the effects of SO_2 on plants and human health, and eventually acid rain, led the United States and other industrial nations to implement policies to reduce SO_2 emissions, developing nations may also choose to reduce their emissions, in which case the cooling effect of sulfates will be less than implied by the IPCC scenarios.

[9] The extent to which sulfates have offset greenhouse warming can be displayed by comparing world maps showing temperature trends with world maps showing estimated radiative forcing from sulfates. For example, the world map of estimated sulfate forcing, published in IPCC (1994) at 31, shows the greatest sulfate impacts over Europe, China, and the eastern United States. A world map of temperature trends shows that virtually all of the Northern Hemisphere has warmed by more than 1˚C in the last fifty years, except for Europe, China, and the Eastern United States (Kerr 1995 (citing Karl et al. (1995) at Figure 2)). *See also* Mitchell et al. 1995.

Raper (1992) showed that when sulfates are included, the historic change in global temperatures has been consistent with a climate sensitivity of 2.5 to 3.0˚C, which is near the middle of the 1.5 to 4.5˚C range.

The net effect of the various revisions is that the best-guess estimate for global warming by the year 2100 is about 2˚C—half the warming that was expected during the mid-1980s. Thus, even if there were no revisions in our understanding of the impact of global warming on sea level, one might reasonably expect the 50 to 200 cm greenhouse contribution to sea level rise to be cut in half. That appears to have happened: The Wigley & Raper estimate of 48 cm is almost exactly one-half the earlier best-guess estimate of 1 m; and their range of 15 to 90 cm is only slightly below the 25 to 100 cm range that would be expected if the sea level contribution was proportional to warming. Our 1%-high estimate of 1 m also reflects such a revision.

Antarctic Contribution. Changing projections of future temperatures is not the only reason that sea level projections have been revised. Estimates of the likely contribution from Antarctica have also been revised downward. A decade ago, NAS (1985) projected that by 2100, Antarctica could contribute anywhere from –10 to +100 cm, with a contribution in the tens of centimeters most likely. More recent assessments, however, have generally concluded that the initial Antarctic contribution will probably be negative. Since NAS (1985), polar scientists have recognized the possibility that increased snowfall could at least partially offset any positive contribution to sea level from the Antarctic Ice Sheet's response to warmer temperatures. Since IPCC (1990), however, most studies have suggested that the ice sheet's response may be small and thus more than offset by increased precipitation, at least for the next century.[10]

Although a significant positive Antarctic contribution is not likely by 2100, such a contribution is still a risk that must be considered, both for calculating the likely rise by the year 2200 and for examining the 1%-high scenario. In the last fifty years, the Antarctic Peninsula has warmed 2˚C, causing the peninsula alone to contribute approximately 0.5 mm to sea level. (Drewry & Morris 1992). The Wordie and Prince Gustav Ice Shelves have largely disintegrated in the last few decades; around Larsen inlet, the ice shelf has retreated 10 to 15 km. In early 1995, an iceberg with an area of more than 2000 km^2 (the size of Rhode Island) broke away from the Larsen Ice Shelf. Until recently, James Ross Island was connected to the Peninsula by ice shelves; but now it is circumnavigable.

No one has demonstrated that these recent events around the Antarctic Peninsula were caused by global warming, nor that these events are a precursor to a disintegration of any of the other ice shelves. Nevertheless, these events lend some credence to the assumptions provided by the glaciology reviewers (Chapter 5), which generally imply that the NAS (1985) high estimate of a 100 cm contribution from Antarctica still has some validity, albeit for the year 2200 rather than 2100. Our attempts to quantify this risk should not obscure the primary reason for recognizing it: *The processes that determine warming of the circumpolar ocean, the melting of ice shelves, and the speed at which glaciers flow are very poorly understood*. The assessment that Antarctica will not make a major contribution is based on the assumption that the water intruding beneath the ice shelves will warm less than 1˚C in the next century; until there is a consensus among climate modelers on this point, one cannot reasonably rule out the possibility of a significant Antarctic contribution in the next century.

Changes in models of Greenland, mountain glaciers, and thermal expansion have also led to minor downward revisions of the sea level projections. Their combined impact, however, is small compared with the uncertainty regarding Antarctica and global temperatures.

How Should Sea Level Rise Scenarios Be Used?

In the last decade, coastal managers have increasingly incorporated information on sea level rise into decisionmaking. The gradual downward revision has not substantially reduced the use of these scenarios. Possible explanations include: the fact that most decisionmakers did not believe the high scenarios anyway; the existence of tidal gauge measurements—and recent satellite observations—

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[10] The downward revision of the estimated ice sheet response has resulted partly from lower global temperature projections. The NAS (1985) analysis assumed a 4˚C global warming by 2050, whereas a 1.0 to 1.5˚C warming by that date now seems more likely. Although there is some disagreement among glaciologists whether a 4˚C warming would cause ice streams to accelerate, there is a general consensus that a 1˚C warming by 2050 would probably not cause a major impact by 2100.

showing that sea level is rising[11]; an increasing consensus that at least some sea level rise will result from global warming; and increased understanding among coastal scientists, engineers, and policy makers that even a small rise in sea level can have important consequences.

Sea level scenarios have been used to (1) encourage and guide additional research and modeling efforts; (2) justify modifications of engineering designs; (3) alter the land-use planning process to accommodate rising sea level; and (4) develop impact assessments to help national policymakers decide the appropriate level of attention warranted by the global warming issue.

Encouraging Additional Efforts. A draft by Hoffman et al. (1982) was the first effort by EPA or anyone else to estimate future sea level for specific years for the purpose of encouraging coastal decision makers to address rising sea level. A previous analysis by Schneider & Chen (1980) had examined the potential implications of a 5 to 8 m rise in sea level due to a collapse of the West Antarctic Ice Sheet, suggesting that such an occurrence could conceivably occur within several decades. But the purpose of that study was to alert society to the risks of CO_2 emissions, not to motivate coastal officials to change their own policies.

The Hoffman et al. (1982) draft was sent to every U.S. coastal state, as well as one hundred scientists. That draft and the final EPA report quickly spurred three panels of the National Academy of Sciences to consider how to project sea level for specific years. In the NAS Climate Research Board's 1983 report, *Changing Climate*, Roger Revelle estimated that, in the course of a century, Greenland and small glaciers could each add 12 cm to sea level if the Earth warms 3 to 4˚C; he estimated that a 70 cm rise in one hundred years was most likely. Two years later, the NAS Polar Research Board, assisted by the U.S. Department of Energy, provided the first detailed assessment of the potential glacial contribution to sea level (NAS 1985); that report adopted EPA's convention of estimating sea level through the year 2100. Recognizing the superior expertise of the Polar Research Board, EPA impact studies immediately adopted the 50 to 200 cm range implied by the Polar Research Board report,[12] suggesting that a 1 m rise was most likely.

Meanwhile, the National Academy of Engineering's Marine Board commissioned a panel to examine the engineering implications (NRC 1987), assisted by the Army Corps of Engineers. The wide range of uncertainty of the EPA scenarios led the Marine Board panel to recommend that engineers consider scenarios ranging from 50 to 150 cm by the year 2100.

Engineering Design. Rising sea level may sometimes justify designing coastal structures differently than would be appropriate if sea level was stable. In 1985, EPA examined the implications of accelerated sea level rise for the beach at Ocean City, Maryland (Titus 1985). The report noted that while groins *may* curtail erosion due to alongshore transport of sand, they do not curtail erosion due to sea level rise. Therefore, because sea level was already rising and was expected to accelerate, it would be advisable to shift from groins to placing sand onto the beach. That message was presented at dozens of public meetings and private briefings of state and local officials. Shortly thereafter, the State of Maryland decided to shift from groins to beach nourishment (*see* Associated Press (1985)).

The prospect of sea level rise was not the only reason that the state chose to shift strategies. Many geologists doubted that the groins would work anyway; and the U.S. Army Corps of Engineers was already on record as supporting beach nourishment. But sea level rise helped to provide a political environment in which the issue could be reconsidered. First, the issue prompted a series of articles in a Baltimore newspaper, which explained how barrier islands naturally respond to rising sea level, and questioned the state's then-current erosion control strategy. Second, the issue could be viewed as "new information," which made it possible to advocate beach nourishment without impugning the original decision to build groins.

Like many of the policy changes motivated by the accelerated sea level scenarios, the shift to beach nourishment was justified by *current* sea level trends. Thus, the fact that the sea level scenarios were (in retrospect) too high had little or no impact.

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[11] *See* Chapter 9 for a sample of U.S. tide gauge trends. Recent satellite estimates suggest that global sea level rose approximately 4 mm/yr over the last three years (Nerem 1995).

[12] *See* Table 8-1, *supra*. After 1984, no EPA study used the Hoffman et al. (1983) high scenario. A few studies that were initiated before the NAS report but published later made reference to the Hoffman et al. scenarios; but accompanying text generally made it clear that the range of 50–200 cm was to be preferred. The 50–200 cm range was also used in a 1989 report to Congress (Smith & Tirpak 1989) and in EPA-funded studies of Senegal, Nigeria, Venezuela, Argentina, and Uruguay (*e.g.*, IPCC 1995).

More recently, a number of design standards have added an extra 30 to 100 cm to account for future sea level rise. By 1987, California's Bay Area Conservation and Development Commission (BCDC) was requiring an additional one foot of elevation on any newly reclaimed land in San Francisco Bay, based on a scenario of a one-foot rise in fifty years. Perhaps if it had waited for improved scenarios, the BCDC might have chosen to require only an additional nine inches of elevation; but given the long lifetimes of land reclamation projects, it seems just as likely that the Commission would have employed the same standard while citing a longer time horizon. Reclamation in Hong Kong also includes a safety margin for accelerated sea level rise, as do the design of new seawalls in eastern Britain and the Netherlands (Nichols & Leatherman 1995).

Land Use: Planning and Regulation. The early EPA studies helped to motivate two states to alter their land use regulations in the coastal zone. EPA's first case study (Barth & Titus 1984) examined Charleston, South Carolina, and provided maps showing the areas that would be permanently inundated or periodically flooded with various sea-level scenarios ranging from 30 to 350 cm. At a conference presenting the results, an official from the Chamber of Commerce stated that he "wished EPA had studied Savannah [Georgia] instead," fearing that the prospect of sea level rise might scare away business. But businesses do not generally base relocation decisions on potential flooding that might occur in the year 2100, especially in areas that are currently vulnerable to hurricanes.

The State of South Carolina was concerned, however, about its eroding beaches. The State Legislature appointed a "Blue Ribbon Panel," which examined the risks to the shoreline. Motivated in part by EPA's projection that sea level could rise one foot in the next thirty years, the panel recommended that no new structures be allowed within the area most vulnerable to erosion, which it defined as a line landward of the primary dune by a distance equal to forty times the annual erosion rate. The South Carolina Legislature enacted these recommendations in a new Beachfront Management Act.[13]

Shortly thereafter, a developer named Lucas, whose lots were entirely seaward of the setback line, challenged the law as an unconstitutional taking of private property without compensation. In one of the most celebrated cases on property rights, *Lucas v. South Carolina Coastal Council*,[14] the U.S. Supreme Court agreed that he was entitled to compensation. Meanwhile, Hurricane Hugo had prompted the Legislature to slightly revise the law, so that the setback only applied to lots that had room for a house landward of the setback line. People in Lucas' situation are now allowed to build, but subject to a "rolling easement" or "special permit", which requires them to remove their structure if the beach erodes enough to put the house in harm's way.[15]

Did EPA's erroneously high estimate of a one-foot rise in thirty years prompt the Legislature to enact hasty legislation? There is little evidence that this occurred. The forty-year setback is somewhat less stringent than the sixty-year setback in neighboring North Carolina. Moreover, the Beachfront Management Act was passed four years after the EPA case study was published, and only after the extra deliberative step of a Blue Ribbon Panel. Because of the importance of *Lucas*, the Beachfront Management Act has been analyzed by dozens of legal commentators, none of whom has suggested that any flaws in the legislation resulted from unrealistically high sea level scenarios.[16] As with the Ocean City study, the Blue Ribbon Panel's analysis was not precise enough to distinguish between a one-foot rise in thirty years and one foot over sixty years.[17]

Maine's regulations are more closely linked to the sea level rise scenarios: The state's Coastal Sand Dune Rules explicitly presume the mobility of any structures that would interfere with the landward migration of sand dunes or wetlands with a rise in sea level of up to three feet.[18] Considerable technical

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[13] S. C. Code §48-39-250 *et seq.*

[14] 112 S.Ct. 2886, 34 E.R.C. 1897 (1992).

[15] For additional details on the "Takings" implications of policies in response to sea level rise, *see* J.G. Titus, 1994, "Rising Seas, Coastal Erosion, and the Takings Clause" (draft).

[16] *See e.g.*, Richard A. Epstein, "Lucas v. South Carolina Coastal Council: A Tangled Web of Expectations", 45 *Stanford Law Review* 1369, 1377 (1993) ("The Court has provided an effective blueprint for confiscation....").

[17] For a more detailed discussion of the implications of sea level rise for the South Carolina law, *see* J. G. Titus (1994), "Rising Seas, Coastal Erosion, and the Takings Clause" (draft).

[18] "If the shoreline recedes such that the coastal wetland...extends to any part of the structure, including support posts, for a period of six months or more, then the approved structure...shall be removed and the site shall be restored to natural conditions within one year." Coastal Sand Dune Rules. Code Me. R § 355(3)(B)(1) (1987).

discussions took place as the state debated whether to use the EPA or NAS scenarios. This illustrates an information-transfer problem: by the time the regulations were issued in 1987, EPA was recommending the use of the NAS scenarios anyway.

Do the lower scenarios (if accurate) imply that even a three-foot rise was too much to plan for? As discussed in the following chapter, our analysis suggests a 7 percent chance that sea level will rise three feet along the U.S. Atlantic coast by the year 2100, and a better than fifty-fifty chance that such a rise will occur during the next two hundred years. The benefits of this regulation (if the sea does rise three feet) would have to be greater than the cost of the restrictions, which must be borne whether or not the sea rises.

Given the fact that movable structures are allowed in this area, the additional cost of the restriction may be small. The benefits depend both on (1) how soon the shore reaches a house (or the location where it would have been built without the regulation) and (2) the reduction in the cost of moving the structure as a result of having designed it to be moved (or the additional time it takes to reach the structure because it was built farther from the shore).[19] Although evaluating the impact of revised sea level rise scenarios on the regulation is beyond the scope of this report, a recent study by the State of Maine suggests that the regulation has greater benefits than costs even if a 50 cm rise in sea level is most likely (Maine 1995).

Impact Assessments. Finally, sea level scenarios have been used to illustrate the implications of sea level rise for policymakers and members of the general public who need to know whether or not global warming is important, as well as people who are simply curious. Our previous estimate of the cost of a one meter rise in sea level was about twice as great as the cost of a 50 cm rise in sea level (Titus et al. 1991). Both estimates suggest that coastal communities will eventually have to develop a stable mechanism for funding coastal protection. But because the sole use of those national estimates is to gain a rough feel for the issue, not to set an appropriation, there is no practical difference between what must be done today if we expect an eventual cost of $200 billion and what we must do if the cost will only be $100 billion.

Finally, there have and will continue to be strong reasons to consider the one meter sea level rise scenario. In the United States, most maps show the 5 ft contour, which is typically about one meter above high tide. Regardless of which scenario one expects, impact analysis would be much easier if finer-resolution topographic maps were available in coastal areas. Nevertheless, it is wise to analyze a wide variety of possible scenarios.

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[19] The greatest cost savings of the regulation may be institutional cost avoided. Abandoning neighborhoods to an eroding shore is politically problematic. Without an advance understanding that such a retreat is part of the rules of the game, it may be politically infeasible to prohibit property owners from rebuilding; as a result, natural wetlands and beaches may be replaced by bulkheads. *See* Titus (1991).

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CHAPTER 9

HOW TO USE THESE RESULTS TO PROJECT LOCAL SEA LEVEL

The results presented in Chapter 7, like those from previous sea level assessments, only account for the global rise in sea level resulting from global climate change. They include neither the change in global sea level resulting from other factors[1] nor changes in local sea level resulting from land subsidence, compaction, and other factors.

The Approach Employed by Previous Studies

Previous EPA studies on the impacts of sea level rise have assumed that the nonclimate contributors to sea level will remain constant.[2] Based on the assumption that global sea level rose 12 cm over the last century, these studies assumed that the net subsidence at particular locations was 1.2 mm/yr less than the observed rate of relative sea level rise measured by tidal gauges. With that assumption, estimates of local sea level rise were calculated as follows:

$$\text{local}(t) = \text{global}(t) + (\text{trend} - 0.12)\,(t - 1990),$$

where **local(t)** is the rise in sea level by year **t** at a particular location, measured in centimeters; **global(t)** is the global rise in sea level projected by a particular scenario; and **trend** is the current rate of relative sea level rise at the particular location. Because more recent estimates suggest that global sea level may be rising 1.8 mm/yr, some studies have replaced the coefficient 0.12 with 0.18.

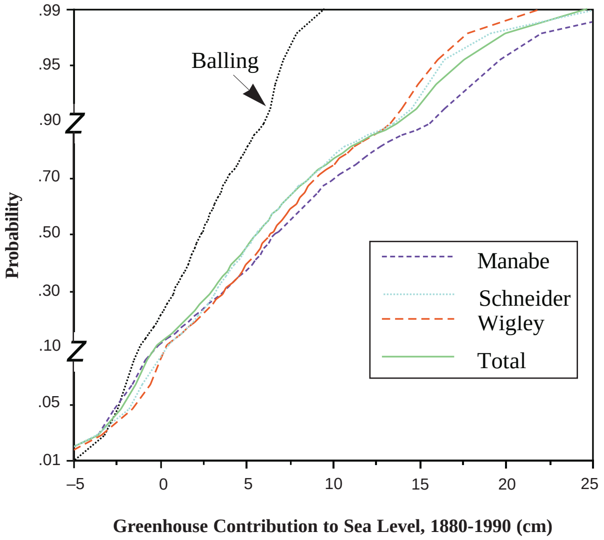

Figure 9-1. Historic Greenhouse Contribution to Sea Level, 1880–1990. The median estimate of the greenhouse contribution (0.5 mm/yr) implied by the reviewer assumptions is well below prevailing estimates of global sea level rise (1 to 2.5 mm/yr). Unless the nongreenhouse contributors are likely to change, it is reasonable to assume that global sea level rise in the next century will also be 0.5 to 2 mm/yr greater than the greenhouse contribution.

Implicit in this procedure was the assumption that in the next century global warming will be the only net contributor to global sea level. Some impact researchers, by contrast, have developed local scenarios simply by adding local trends to the projections of global sea level rise.[3] Implicit in that procedure is the assumption that *none* of the historic sea level rise was caused by global warming. As long as people were investigating the implications of a 1 to 2 m rise in sea level, there was little practical distinction between these two approaches. But with sea level projections on the order of 50 cm, this 12 cm discrepancy is worth resolving.

Which of these assumptions are correct? Probably neither. As Figure 9-1 shows, the reviewer assumptions with which we project future sea level rise imply that sea level rose about 0.5 mm/yr over the last century. This estimate is well below the

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[1] *E.g.,* very long-term (glacial/interglacial) changes in climate, and nonclimatic factors such as groundwater depletion and changes in land use. Although nonclimatic sources have added at most a few centimeters to sea level in the last century (Sahagian et al. 1994), no one has thoroughly assessed the likely future contribution.

[2] This convention started with EPA's first sea level impacts assessment (Barth & Titus 1984) and continued through EPA's final assessment of U.S. impacts (Titus et al. 1991). The approach was endorsed by the National Academy of Engineering (Dean et al. 1987). More recent assessments have subtracted out a slightly higher estimate of global sea level trends.

[3] This procedure is consistent with the approach used by Roger Revelle in NAS (1983). Revelle explicitly added the historic trend of 12 cm to his estimates of thermal expansion, Greenland, and small glacier contributions to sea level.

1.8 mm/yr estimate of total global sea level rise. Thus, it would appear that other factors are adding to sea level. Possible explanations include groundwater depletion (Sahagian et al. 1994), a delayed response to the warming that has taken place since the last ice age, and shifts in ocean basins. It is also possible that tidal gauges cannot measure true global sea level rise because coasts are generally subsiding.[4]

Until we know precisely why our models underpredict historic sea level rise, it seems most reasonable to assume that those factors that we have not modeled will continue. *Because this assessment (like previous IPCC assessments) only examines the sea level rise induced by climate change, the results presented in Chapter 7 should be interpreted as estimating the extent to which climate change will accelerate the rate of sea level rise, compared with what otherwise would occur.*

Recommended Procedure

The most realistic procedure, in our view, is to extrapolate all trends other than those due to global warming. Simply adding historic trends to published projections of sea level rise doublecounts whatever portion of the historic local trend was caused by global warming. We remove this doublecounting by developing a set of normalized projections in which the historic component of the greenhouse contribution has been removed.[5] *The normalized projections estimate the extent to which future sea level rise will exceed what would have happened if current trends simply continued*. Table 9-1 summarizes our normalized results.

Those who require an estimate of sea level rise at a particular location can simply add the normalized projection to the current rate of sea level rise[6]:

$$\text{local}(t) = \text{normalized}(t) + (t - 1990) \times \text{trend}.$$

For example, according to Table 9-2, sea level at New York City has been rising 2.7 mm/yr.[7] This rate is typical of the U.S. Atlantic and Gulf Coasts (Lyles et al. 1988). For the year 2100, the median and 1%-high normalized projections are 25 and 92 cm for the year 2100. Because even current trends would result in a 30 cm rise, the total rise is most likely to be 55 cm (about 2 feet); but it also has a 1 percent chance of exceeding 122 cm (about 4 feet). Similarly, if one assumes that average worldwide sea level has been rising 1.8 mm/yr, then global sea level has a 50 percent chance of rising 45 cm, and a 1 percent chance of rising 112 cm, by the year 2100. (See Figure 9–2.)

Caveats

Scenarios of sea level rise can be put to a variety of uses. In general, individual users know—far better than we—the most appropriate uses for these scenarios. All we can do is convey what we know about their limitations.

Most importantly, our *probability estimates are not based on statistics*. Our estimates simply convey what the probability of various rates of sea level rise would be *if* one is willing to assume that the experts we polled are each equally wise and that their collective

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[4] For example, due to the additional mass placed on the continental shelves from previous sea level rise.

[5] Each normalized projection was calculated as follows:

$$\text{Normalized}_i(t) = \text{global}_i(t) - [\text{model}_i(1990) - \text{model}_i(1880)]\ \frac{t-1990}{110},$$

where $\mathbf{global_i(t)}$ is the greenhouse (and sulfate) contribution to sea level (*i.e.*, the result reported in Chapter 7) between 1990 and the year **t** for the i^{th} simulation; and $\mathbf{model_i}$ represents the historic greenhouse contribution to sea level estimated by the i^{th} simulation between 1765 and a particular year. Thus, the i^{th} normalized projection represents the extent to which the greenhouse contribution by a particular year exceeds the contribution that would be expected by merely extrapolating the estimated historic greenhouse contribution. Assuming that the nongreenhouse contributors remain constant, the normalized projection also represents the extent to which sea level rise will exceed the rise that would be expected from extrapolating the historic rate of rise.

[6] This procedure is not the same as simply adding a historic trend to every element of the probability distribution, since $\mathbf{Model_i}$ will be different for different simulations (*see* Note 5, *supra*). The overall tendency will be for the normalized distribution to have a smaller variance than the greenhouse contribution; for example, a high temperature sensitivity implies that historic thermal expansion was greater than the mean estimate, and hence that the historic nongreenhouse contribution was less than the mean estimate, for a given estimate of total historic sea level rise.

Notwithstanding our concern in Chapter 3, Note 4, the normalized projections are probably improved somewhat by the fact that each model run included a historic simulation. If a particular set of parameters substantially overestimates the historic rate of sea level rise, for example, the net effect of our procedure is to adjust the future projection downward by the amount of the historical overestimate.

[7] The National Ocean Service periodically publishes estimates of the rate of sea level rise for several U.S. cities. As this report went to press, NOS was about to release its new estimates for sea level trends. The new report can be obtained from Steve Lyles, National Ocean Service, SSMC4, Station 7601, 1305 East-West Highway, Silver Spring, MD 20910-3233. Fax: 301-713-4435.

TABLE 9-1
ESTIMATING SEA LEVEL RISE AT A SPECIFIC LOCATION
Normalized Sea Level Projections, Compared with 1990 Levels (cm)

	Sea Level Projection by Year:					
Cumulative Probability	2025	2050	2075	2100	2150	2200
1	–10	–16	–21	–24	–32	–40
5	–3	–4	–5	–6	–7	–8
10	–1	–1	0	1	3	5
20	1	3	6	10	16	23
30	3	6	10	16	26	37
40	4	8	14	20	35	51
50	5	10	17	25	43	64
60	6	13	21	30	53	78
70	8	15	24	36	65	98
80	9	18	29	44	80	125
90	12	23	37	55	106	174
95	14	27	43	66	134	231
97.5	17	31	50	78	167	296
99	19	35	57	92	210	402
Mean	5	11	18	27	51	81
σ	6	10	15	23	47	81

NOTE: To estimate sea level at a particular location, add these estimates to the rise that would occur if current trends were to continue. See Table 9-2 for historic rates of sea level rise. For example, if sea level is currently rising 3 mm/yr, then under current trends, sea level will rise 26 cm between 1990 and 2075. Adding 26 cm to the normalized values in the Table, the median estimate for 2075 is 43 cm, with a 1 percent chance of an 83 cm rise.

TABLE 9-2
HISTORIC RATE OF SEA LEVEL RISE AT VARIOUS LOCATIONS IN THE UNITED STATES
(mm/yr)

Atlantic Coast

Eastport, ME	2.7	Sandy Hook, NJ	4.1	Portsmouth, VA	3.7
Portland, ME	2.2	Atlantic City, NJ	3.9	Wilmington, NC	1.8
Boston, MA	2.9	Philadelphia, PA	2.6	Charleston, SC	3.4
Woods Hole, MA	2.7	Lewes, DE	3.1	Ft. Pulaski, GA	3.0
Newport, RI	2.7	Annapolis, MD	3.6	Fernandina, FL	1.9
New London, CT	2.1	Solomons, Is., MD	3.3	Mayport, FL	2.2
Montauk, NY	1.9	Washington, DC	3.2	Miami Beach, FL	2.3
New York, NY	2.7	Hampton Roads, VA	4.3		

Gulf Coast

Key West	2.2	Grand Isle, LA	10.5	Galveston,TX	6.4
St. Petersburg, FL	2.3	Eugene Island, LA	9.7	Freeport, TX	14.0
Pensacola, FL	2.4	Sabine Pass, TX	13.2	Padre Island, TX	5.1

Pacific Coast

Honolulu, HI	1.6	Los Angeles, CA	0.8	Astoria, OR	–0.3
Hilo, HI	3.6	Santa Monica, CA	1.8	Seattle, WA	2.0
San Diego, CA	2.1	San Francisco, CA	1.3	Neah Bay, WA	–1.1
La Jolla, CA	2.0	Alameda, CA	1.0	Sitka, AK	–2.2
Newport, CA	1.9	Crescent City, CA	–0.6	Juneau, AK	–12.4

wisdom reflects the best available knowledge. In a statistical model, we would conduct an experiment at least several dozen times and determine the variation of outcomes. But within the time horizon of this project, humanity can only conduct the experiment once, which we are doing; so statistical estimates of probability are impossible. Our projections are less like a statistical weather forecast and more like handicapping a horse race.

As with a horse race, our inaccuracy results more from our inability to quantify the relevant factors than from the random fluctuations within the processes whose uncertainties we have described. We have left out some factors; so our uncertainty is probably greater than we estimate it to be.

Finally, this particular exercise, like EPA's 1982–83 report projecting sea level rise (Hoffman et al. 1983), is limited by the fact that the authors are not experts about any of the particular processes that contribute to sea level. Just as the 1983 report was undertaken because no one else was estimating sea level rise for specific years, this report was undertaken because no one was estimating the probability of sea level rise or factoring in the small-but-important risk of a large Antarctic contribution. For the foreseeable future, coastal decisionmakers should view this prospect as a potentially important risk that is poorly understood. Although Antarctica will probably not contribute significantly to sea level in the next century, the glaciology reviewers of this report were unanimous that the research necessary to rule it out simply has not been undertaken. (*See also* Appendix 3.)

The reader should have no illusions about the adequacy of the models used in this or any report projecting future sea level rise. Because a reasonable person cannot confidently be certain that any particular group of experts knows the actual story, we have attempted to incorporate every view that we could obtain. We hope that these estimates of the probability of sea level rise help coastal engineers, planners, and legislators to determine whether and how to prepare for the consequences of a rising sea.

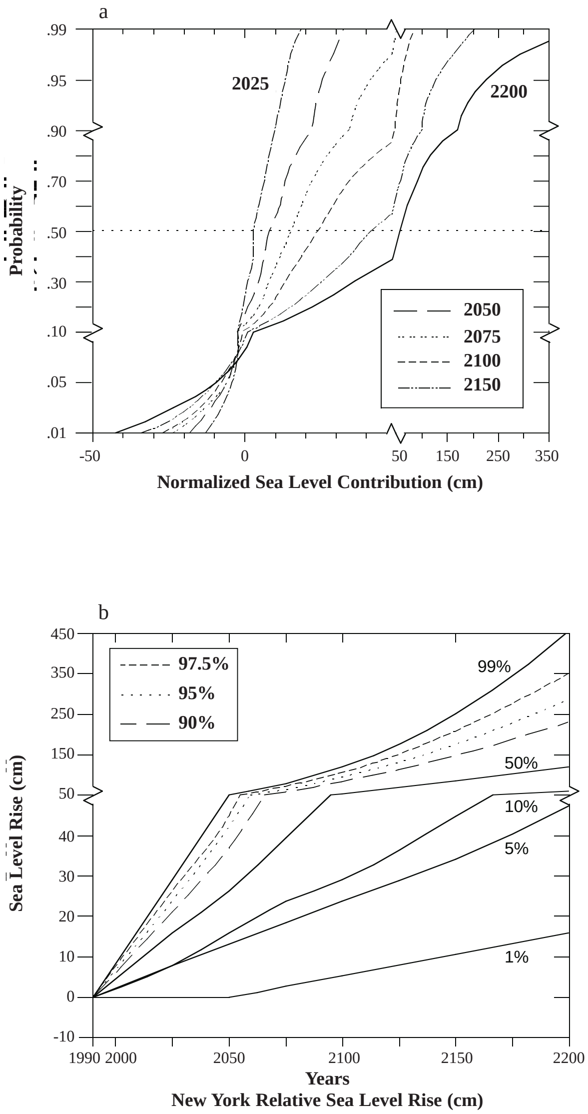

Figure 9-2. Normalized Contribution to Sea Level. By netting out the historic greenhouse contribution, the normalized estimates in (a) represent the projected *acceleration* in sea level compared with historic trends. One can estimate local or global sea level by adding these estimates to trends from tide guages. For example, in (b) these estimates are added to New York's historic trend of 2.7 mm/yr, which typifies the U.S. Atlantic

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APPENDICES

APPENDIX 1

CUMULATIVE PROBABILITY DISTRIBUTIONS

Explanations and Suggested Comparisons

This Appendix presents tables documenting the cumulative probability distributions presented in the body of the report. Due to their repetitious nature, we present explanations and suggested comparisons at the outset, rather than repeating them in each of the relevant tables.

Table 13: Wigley and Raper did not specify parameter values for Circumpolar Deep Water.

Tables 14-17, 19-21, 27-29, 31-37, 41-42, and 45-50: With the exception of Wigley and Raper, all projections include a random cross-section of precipitation and ice sheet parameters.

Tables 22-23: All projections include background probability distribution as modified from the draft based on Jacobs and Lingle comments.

Table 39. This table provides statistics for 8 random subsamples. The 99 percentiles range from 101.5 to 110.2, with a mean of 104.2 and a variance of 8. The variance of the mean of this series (i.e. the average estimate of the 99th percentile) is 8/n, where n is the sample size of 8. Thus, the standard error is approximately 1.0 cm. As a result, additional simulations did not seem worthwhile. Note also that the 99-percentile tails do not appear to vary (in percentage terms) any more than the mean. Therefore, the Latin Hypercube algorithm, with its bias toward better estimates of the tails, would probably be of little use for our purposes. *See also*. **Numerical Error of the Monte Carlo Algorithm**, Chapter 7, *supra*.

Table 40: Compare to Tables 7 and 8.

Table 41: Compare to Table 21.

Table 42: Compare to Table 17.

Table 43: Compare to Tables 28 and 35.

Table 44: Compare to Tables 29 and 37.

Table 45: Compare to Table 30.

Table 46: Compare to Tables 7 and 40.

Table 47: Compare to Tables 8 and 40.

Table 48: Compare to Tables 28 and 43.

Table 49: Compare to Tables 29 and 44.

Table 50: Compare to Tables 30 and 45.

Table 51: The “Fixed Emission 2100” scenario refers to the range of emissions scenarios developed in Chapter 2 and used in Chapter 3 to generate temperatures. The other two scenarios are based on the assumptions that emissions remain constant after the year 2025 and 2050.

Table 52-59: To simplify the necessary comparisons, these tables present results for only one reviewer; arbitrarily, we picked Schneider. Therefore, each of the tables should be compared to the column reporting Schneider values.

Table 52: Compare to Table 7.

Table 53: Compare to Table 8.

Table 54: Compare to Table 17

Table 55: Compare to Table 21

Table 56: Compare to Table 28

Table 57: Compare to Table 29

Table 58: Compare to Table 38

Table 59: The authors regret omitting the breakout by reviewer in Table 30.

A. RESULTS REPORTED IN CHAPTERS 2 THROUGH 9

1. 2100 CO_2 Concentration

Cumulative %	CO_2 (ppm)
0.10	405.28
0.50	426.87
1.00	438.65
2.50	461.90
5.00	481.96
10.00	510.59
20.00	553.50
30.00	591.41
40.00	633.28
50.00	679.52
60.00	728.78
70.00	792.21
80.00	877.97
90.00	1046.68
95.00	1203.56
97.50	1362.93
99.00	1614.16
99.50	1774.73
99.90	2363.46
Median	679.52
Mean	737.98
StdDev	242.19

2. Year by Which CO_2 Concentration Exceeds 600 ppmv

Cumulative %	Year
0.10	2037
0.50	2040
1.00	2042
2.50	2045
5.00	2048
10.00	2052
20.00	2059
30.00	2064
40.00	2070
50.00	2078
60.00	2088
70.00	2103
80.00	2131
90.00	2200
95.00	2200
97.50	2200
99.00	2200
99.50	2200
99.90	2200

3. Forcing: 1990–2100, all Reviewers (W/m^2)

Cumulative %	$\Delta Q_{1990\text{-}2100}$
0.10	1.28
0.50	1.77
1.00	1.94
2.50	2.29
5.00	2.61
10.00	3.02
20.00	3.55
30.00	3.99
40.00	4.41
50.00	4.90
60.00	5.38
70.00	5.83
80.00	6.36
90.00	7.17
95.00	7.76
97.50	8.23
99.00	8.69
99.50	8.99
99.90	9.39
Median	4.90
Mean	4.99
StdDev	1.58

4. Year by Which Forcing Exceeds 4.4, all Reviewers (W/m^2)

Cumulative %	Year
0.10	2059
0.50	2061
1.00	2062
2.50	2064
5.00	2066
10.00	2068
20.00	2073
30.00	2077
40.00	2081
50.00	2089
60.00	2099
70.00	2117
80.00	2151
90.00	>2200
95.00	>2200
97.50	>2200
99.00	>2200
99.50	>2200
99.90	>2200

5. Equilibrium Temperature Change for a Doubling of CO_2, all Reviewers (°C)

Cumulative %	ΔT2x
0.10	0.00
0.50	0.00
1.00	0.00
2.50	0.07
5.00	0.29
10.00	0.62
20.00	1.26
25.36	1.50
30.00	1.68
40.00	2.01
50.00	2.37
60.00	2.75
70.00	3.19
80.00	3.83
86.97	4.50
90.00	4.90
95.00	5.93
97.50	7.21
99.00	8.64
99.50	9.54
99.90	14.31
Median	2.37
Mean	2.66
StdDev	1.81

6. Global Mean Surface Temperature Change by Reviewer, 1990–2050

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-0.44	0.00	0.07	0.08	0.16	0.04	0.04	0.24	-0.36
0.50	-0.36	0.11	0.15	0.23	0.26	0.14	0.14	0.33	-0.21
1.00	-0.32	0.22	0.19	0.27	0.30	0.20	0.22	0.38	-0.13
2.50	-0.24	0.33	0.34	0.33	0.34	0.29	0.31	0.47	0.00
5.00	-0.18	0.42	0.45	0.43	0.41	0.40	0.41	0.57	0.12
10.00	-0.10	0.54	0.58	0.55	0.51	0.55	0.55	0.67	0.31
20.00	0.00	0.70	0.75	0.70	0.68	0.71	0.75	0.83	0.55
30.00	0.07	0.84	0.88	0.85	0.80	0.83	0.88	0.95	0.73
40.00	0.13	0.97	1.01	0.99	0.93	0.99	1.02	1.05	0.88
50.00	0.20	1.11	1.13	1.12	1.04	1.12	1.15	1.16	1.03
60.00	0.26	1.25	1.26	1.27	1.18	1.27	1.34	1.28	1.18
70.00	0.33	1.41	1.43	1.43	1.32	1.43	1.52	1.38	1.35
80.00	0.41	1.65	1.61	1.66	1.49	1.65	1.78	1.53	1.55
90.00	0.52	1.96	1.97	2.01	1.77	1.99	2.23	1.74	1.89
95.00	0.60	2.28	2.29	2.32	1.98	2.26	2.68	1.97	2.19
97.50	0.71	2.61	2.52	2.64	2.14	2.51	3.05	2.23	2.52
99.00	0.79	2.82	2.89	2.89	2.45	2.87	4.60	2.48	2.87
99.50	0.84	3.03	3.00	3.15	2.72	3.15	6.03	2.61	3.15
99.90	0.93	3.20	3.62	3.50	3.05	3.41	9.06	2.85	4.96
Median	0.20	1.11	1.13	1.12	1.04	1.12	1.15	1.16	1.03
Mean	0.21	1.19	1.21	1.21	1.10	1.20	1.33	1.20	1.08
StdDev	0.24	0.57	0.56	0.59	0.48	0.58	0.88	0.43	0.66

7. Global Mean Surface Temperature Change by Reviewer, 1990–2100

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-0.58	0.15	0.20	0.24	0.35	0.27	-0.60	0.25	-0.47
0.50	-0.47	0.33	0.42	0.40	0.50	0.36	0.17	0.63	-0.24
1.00	-0.43	0.41	0.49	0.51	0.58	0.43	0.32	0.73	-0.12
2.50	-0.28	0.66	0.66	0.60	0.70	0.56	0.50	0.88	0.04
5.00	-0.19	0.83	0.85	0.76	0.83	0.72	0.72	1.05	0.26
10.00	-0.09	1.03	1.09	0.99	1.03	1.00	0.99	1.32	0.57
20.00	0.04	1.36	1.41	1.34	1.34	1.34	1.37	1.60	1.05
30.00	0.19	1.70	1.68	1.62	1.63	1.64	1.68	1.86	1.41
40.00	0.27	1.96	1.90	1.91	1.87	1.92	1.96	2.08	1.73
50.00	0.38	2.24	2.19	2.15	2.13	2.23	2.31	2.34	2.02
60.00	0.48	2.54	2.43	2.45	2.40	2.58	2.70	2.64	2.35
70.00	0.59	2.94	2.78	2.81	2.74	2.97	3.16	2.92	2.73
80.00	0.74	3.39	3.29	3.22	3.21	3.46	3.82	3.28	3.22
90.00	0.99	4.11	4.04	4.04	3.82	4.18	4.78	3.80	3.98
95.00	1.19	4.80	4.74	4.89	4.40	5.04	5.74	4.28	4.69
97.50	1.38	5.61	5.31	5.45	4.98	5.71	6.54	4.6	5.41
99.00	1.47	6.31	6.30	6.66	5.55	6.37	7.62	5.16	6.30
99.50	1.64	6.83	6.82	6.91	6.03	6.94	8.67	5.52	6.87
99.90	2.02	7.10	7.62	9.15	6.32	8.07	11.87	5.93	8.67
Median	0.38	2.24	2.19	2.15	2.13	2.23	2.31	2.34	2.02
Mean	0.42	2.45	2.41	2.38	2.31	2.46	2.66	2.47	2.20
StdDev	0.42	1.25	1.21	1.27	1.11	1.32	1.63	0.98	1.37

8. Global Mean Surface Temperature Change by Reviewer, 1990–2200

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-0.91	-0.07	0.22	0.25	0.12	0.31	-0.02	0.40	-0.60
0.50	-0.62	0.33	0.69	0.46	0.57	0.50	0.34	0.73	-0.31
1.00	-0.57	0.46	0.73	0.59	0.75	0.58	0.45	0.94	-0.17
2.50	-0.40	0.79	0.93	0.92	0.98	0.77	0.77	1.21	0.08
5.00	-0.25	1.12	1.23	1.17	1.24	1.01	1.01	1.52	0.37
10.00	-0.10	1.52	1.62	1.52	1.59	1.45	1.43	1.93	0.84
20.00	0.11	2.12	2.18	2.04	2.16	2.11	2.10	2.59	1.59
30.00	0.25	2.72	2.67	2.53	2.69	2.62	2.64	3.02	2.20
40.00	0.41	3.24	3.15	3.00	3.15	3.12	3.22	3.48	2.78
50.00	0.58	3.85	3.62	3.54	3.66	3.64	3.86	3.97	3.34
60.00	0.74	4.41	4.19	4.12	4.24	4.30	4.75	4.50	3.99
70.00	0.94	5.07	4.80	4.92	5.01	5.04	5.67	5.13	4.75
80.00	1.23	6.07	5.95	5.93	5.88	5.97	6.88	5.92	5.76
90.00	1.65	7.64	7.64	7.72	7.66	7.50	9.27	7.18	7.39
95.00	2.02	9.16	9.66	9.37	9.46	9.17	11.32	8.14	9.12
97.50	2.28	10.68	11.07	11.06	10.88	10.99	13.06	8.95	10.87
99.00	2.57	12.12	12.77	13.08	12.93	12.71	15.53	9.80	12.73
99.50	2.78	13.16	13.64	14.52	14.00	13.80	16.81	11.19	14.10
99.90	3.37	14.49	15.36	18.83	14.71	15.80	21.14	12.00	18.48
Median	0.58	3.85	3.62	3.54	3.66	3.64	3.86	3.97	3.34
Mean	0.68	4.27	4.22	4.19	4.23	4.19	4.73	4.29	3.85
StdDev	0.69	2.52	2.56	2.70	2.54	2.56	3.28	2.02	2.74

9. Thermal Expansion by Reviewer, 1990–2050

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-2.79	1.63	0.77	2.00	1.49	1.48	-2.74	2.76	-2.09
0.50	-2.28	2.02	2.18	2.28	2.57	1.77	0.85	3.30	-1.11
1.00	-1.94	2.54	2.62	2.50	2.94	2.06	1.26	3.59	-0.54
2.50	-1.30	3.27	3.31	3.18	3.71	2.78	2.03	4.28	0.19
5.00	-0.92	3.94	4.11	3.74	4.28	3.57	2.86	4.92	1.05
10.00	-0.39	4.96	4.86	4.68	5.29	4.78	3.95	5.81	2.50
20.00	0.21	6.17	6.12	5.94	6.78	6.19	5.19	6.90	4.71
30.00	0.68	7.22	7.47	6.78	7.84	7.37	6.40	7.84	6.18
40.00	1.08	8.47	8.50	7.77	8.93	8.45	7.31	8.58	7.41
50.00	1.53	9.63	9.59	8.84	10.10	9.54	8.34	9.34	8.61
60.00	1.96	10.78	10.81	10.05	11.23	10.62	9.42	10.08	9.78
70.00	2.42	12.03	12.14	11.40	12.56	12.04	10.73	10.96	11.14
80.00	3.03	13.97	13.87	12.68	14.30	13.71	12.78	12.24	12.82
90.00	3.84	16.55	16.78	15.26	17.05	16.77	15.88	14.28	15.56
95.00	4.54	18.77	19.42	18.30	19.02	19.04	18.27	15.77	18.19
97.50	5.27	21.05	21.97	20.26	21.23	21.41	21.76	17.38	20.58
99.00	6.11	23.83	23.88	21.84	24.58	24.03	26.20	18.70	23.19
99.50	6.65	26.11	24.98	22.71	27.55	26.21	30.49	20.78	25.49
99.90	8.23	29.39	30.65	25.48	30.73	29.91	46.87	25.70	31.71
Median	1.53	9.63	9.59	8.84	10.10	9.54	8.34	9.34	8.61
Mean	1.64	10.23	10.36	9.55	10.71	10.20	9.34	9.71	8.97
StdDev	1.69	4.67	4.78	4.29	4.65	4.78	5.78	3.36	5.22

10. Thermal Expansion by Reviewer, 1990–2100

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-4.58	3.09	4.06	3.72	2.85	2.59	-3.90	5.23	-3.42
0.50	-3.42	3.85	5.03	4.49	6.19	3.92	-0.24	6.33	-1.55
1.00	-2.66	4.96	5.70	5.10	7.12	4.66	0.59	7.38	-0.81
2.50	-1.93	6.71	7.42	6.61	8.77	6.25	3.36	8.83	0.57
5.00	-1.25	8.59	9.17	8.06	10.00	8.02	5.27	10.54	2.27
10.00	-0.45	10.82	11.20	9.85	12.02	10.22	7.78	12.36	5.12
20.00	0.67	13.97	14.34	12.80	15.21	13.80	10.90	15.12	10.28
30.00	1.58	16.67	17.16	15.47	18.17	16.87	13.92	17.39	13.82
40.00	2.40	19.21	20.07	17.79	21.06	19.33	16.30	19.02	16.84
50.00	3.19	22.43	22.95	20.21	23.90	22.18	18.83	21.37	19.69
60.00	4.10	24.96	25.69	23.39	26.52	24.96	22.41	23.15	22.86
70.00	5.04	28.38	29.28	26.80	30.05	28.94	25.99	25.85	26.25
80.00	6.66	33.37	34.58	31.34	34.60	32.59	31.04	29.33	30.83
90.00	8.29	39.52	42.07	38.76	41.57	41.47	40.62	33.91	38.11
95.00	10.09	46.14	48.44	44.97	47.26	47.70	47.74	37.53	44.97
97.50	11.71	51.01	53.20	50.01	53.19	53.24	55.41	40.65	50.43
99.00	13.84	56.91	61.23	59.01	60.02	61.74	66.63	45.33	57.53
99.50	15.01	63.80	62.63	64.55	65.35	65.72	70.06	48.43	64.01
99.90	17.89	70.76	69.25	69.49	70.24	75.49	94.04	52.35	73.45
Median	3.19	22.43	22.95	20.21	23.90	22.18	18.83	21.37	19.69
Mean	3.66	23.98	24.82	22.59	25.47	24.15	21.89	22.23	21.10
StdDev	3.51	11.59	12.06	11.52	11.56	12.21	13.71	8.31	12.86

11. Thermal Expansion by Reviewer, 1990–2200

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-7.14	3.29	8.10	2.06	4.72	2.53	-9.45	6.67	-7.10
0.50	-6.48	5.92	11.21	6.73	10.87	6.34	-7.56	10.58	-3.27
1.00	-4.73	7.95	11.60	8.48	13.99	8.46	-4.31	12.60	-1.57
2.50	-3.29	12.49	14.73	11.32	17.08	12.33	-0.18	15.16	0.88
5.00	-1.95	16.14	17.95	14.53	20.42	15.76	5.78	18.77	3.84
10.00	-0.42	20.58	22.88	18.21	24.46	20.66	11.88	22.71	9.92
20.00	1.40	28.89	30.74	26.35	32.57	29.17	20.72	29.76	20.11
30.00	2.93	35.91	39.17	32.61	40.03	36.80	26.84	35.38	28.36
40.00	4.69	42.90	46.01	39.65	47.91	43.78	33.85	40.50	36.07
50.00	6.50	49.08	54.22	46.41	55.13	49.99	40.27	45.20	43.72
60.00	8.38	57.96	62.32	56.93	62.23	59.50	50.20	50.75	52.16
70.00	10.85	66.18	72.46	69.35	73.04	69.12	61.25	57.85	62.26
80.00	13.46	80.13	88.56	82.89	85.02	81.41	78.05	67.47	76.06
90.00	18.39	101.30	110.06	105.57	107.94	104.47	106.72	80.97	98.73
95.00	22.23	121.86	135.93	122.24	125.01	130.06	129.67	93.18	119.34
97.50	26.44	136.76	151.33	139.16	145.24	148.80	151.43	103.17	138.92
99.00	31.24	164.15	170.18	173.97	162.45	179.39	179.23	120.22	163.15
99.50	35.42	175.70	189.70	181.44	178.65	195.42	194.71	125.59	181.44
99.90	42.25	209.72	202.95	235.23	201.13	219.68	217.16	132.26	215.45
Median	6.50	49.08	54.22	46.41	55.13	49.99	40.27	45.20	43.72
Mean	7.88	56.39	61.60	55.92	61.04	58.46	50.97	49.27	50.19
StdDev	7.72	33.04	35.79	35.39	33.16	35.73	39.03	22.97	35.86

12. Greenland Temperature Change by Reviewer, 1990–2100 (°C)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-0.78	0.16	0.20	0.19	0.20	0.43	-0.77	0.32	-0.68
0.50	-0.68	0.46	0.42	0.34	0.25	0.54	0.08	0.71	-0.34
1.00	-0.59	0.59	0.49	0.45	0.31	0.62	0.32	0.91	-0.18
2.50	-0.42	0.92	0.66	0.53	0.39	0.85	0.50	1.16	0.05
5.00	-0.28	1.11	0.85	0.69	0.50	1.08	0.77	1.46	0.33
10.00	-0.12	1.40	1.13	0.91	0.64	1.49	1.02	1.78	0.64
20.00	0.06	1.87	1.69	1.22	0.85	2.12	1.53	2.22	1.09
30.00	0.25	2.31	2.21	1.53	1.07	2.70	1.96	2.63	1.52
40.00	0.38	2.72	2.69	1.82	1.27	3.27	2.43	2.96	1.98
50.00	0.54	3.13	3.37	2.14	1.46	3.79	2.94	3.37	2.47
60.00	0.69	3.58	4.09	2.48	1.70	4.39	3.54	3.73	3.02
70.00	0.86	4.16	5.06	2.92	2.08	5.15	4.36	4.21	3.68
80.00	1.06	4.96	6.96	3.58	2.48	6.28	5.62	4.84	4.58
90.00	1.42	6.09	9.67	4.62	3.28	8.07	7.80	5.83	6.23
95.00	1.79	7.30	12.96	5.80	3.90	9.98	10.45	6.51	8.06
97.50	1.99	8.41	15.88	6.73	4.42	11.30	13.02	7.22	10.32
99.00	2.44	10.16	17.67	8.42	5.34	13.48	16.74	7.99	13.65
99.50	2.61	10.56	17.82	11.64	5.56	14.64	22.06	8.29	16.00
99.90	3.65	11.62	19.12	13.82	7.71	18.00	23.10	9.63	19.12
Median	0.54	3.13	3.37	2.14	1.46	3.79	2.94	3.37	2.47
Mean	0.60	3.51	4.58	2.53	1.74	4.38	3.91	3.59	3.11
StdDev	0.63	1.95	3.80	1.71	1.10	2.75	3.47	1.57	2.69

13. Circumpolar Deepwater Warming by Reviewer, 1990–2100 (°C)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	All
0.10	-0.60	0.05	0.06	0.06	0.03	-0.71	0.17	-0.35
0.50	-0.33	0.07	0.15	0.08	0.10	-0.11	0.27	-0.12
1.00	-0.21	0.10	0.20	0.11	0.14	-0.03	0.31	-0.06
2.50	-0.14	0.12	0.26	0.16	0.17	0.10	0.46	0.00
5.00	-0.08	0.18	0.35	0.19	0.23	0.25	0.57	0.06
10.00	-0.03	0.25	0.44	0.26	0.29	0.47	0.73	0.16
20.00	0.02	0.38	0.59	0.38	0.39	0.83	1.01	0.33
30.00	0.05	0.49	0.71	0.52	0.48	1.08	1.22	0.50
40.00	0.08	0.63	0.84	0.65	0.57	1.29	1.46	0.68
50.00	0.13	0.79	0.99	0.78	0.67	1.52	1.71	0.86
60.00	0.18	0.98	1.15	1.00	0.77	1.79	2.00	1.09
70.00	0.24	1.24	1.39	1.26	0.90	2.14	2.31	1.39
80.00	0.33	1.63	1.68	1.59	1.08	2.58	2.69	1.79
90.00	0.50	2.39	2.25	2.29	1.39	3.36	3.44	2.52
95.00	0.69	3.08	2.81	3.26	1.69	3.95	4.19	3.26
97.50	0.87	3.98	3.40	3.96	1.92	4.33	5.12	3.97
99.00	1.40	5.30	4.23	5.30	2.40	5.09	6.32	4.99
99.50	1.56	5.99	4.87	6.49	2.81	5.74	7.38	5.74
99.90	1.98	6.91	5.45	7.16	3.13	7.30	8.10	7.38
Median	0.13	0.79	0.99	0.78	0.67	1.52	1.71	0.86
Mean	0.19	1.10	1.21	1.12	0.77	1.75	1.95	1.16
StdDev	0.28	1.01	0.83	1.04	0.47	1.14	1.20	1.06

14. Greenland Precipitation by Reviewer, 2100 (cm/yr sea level equivalent)

Cumulative %	Alley	Kuhn	MacCracken	Rind	Schneider	Zwally	All
0.10	0.1301	0.1279	0.1274	0.1147	0.1289	0.1231	0.1278
0.50	0.1322	0.1292	0.1303	0.1304	0.1306	0.1312	0.1305
1.00	0.1325	0.1312	0.1316	0.1314	0.1314	0.1318	0.1318
2.50	0.1331	0.1328	0.1339	0.1330	0.1330	0.1329	0.1330
5.00	0.1334	0.1357	0.1373	0.1359	0.1361	0.1356	0.1343
10.00	0.1340	0.1406	0.1405	0.1398	0.1404	0.1389	0.1366
20.00	0.1351	0.1463	0.1460	0.1465	0.1467	0.1443	0.1417
30.00	0.1364	0.1521	0.1519	0.1522	0.1518	0.1496	0.1466
40.00	0.1377	0.1586	0.1567	0.1568	0.1569	0.1544	0.1522
50.00	0.1397	0.1654	0.1629	0.1627	0.1630	0.1605	0.1583
60.00	0.1422	0.1735	0.1703	0.1692	0.1696	0.1683	0.1656
70.00	0.1453	0.1843	0.1791	0.1788	0.1798	0.1783	0.1748
80.00	0.1511	0.1975	0.1925	0.1951	0.1934	0.1950	0.1894
90.00	0.1626	0.2314	0.2236	0.2241	0.2231	0.2314	0.2192
95.00	0.1777	0.2800	0.2647	0.2570	0.2631	0.2811	0.2590
97.50	0.2003	0.3318	0.3400	0.3126	0.3190	0.3437	0.3196
99.00	0.2607	0.4252	0.4325	0.4077	0.4157	0.5210	0.4217
99.50	0.3153	0.5096	0.4636	0.5046	0.4786	0.6749	0.5208
99.90	1.0348	0.6711	0.6425	0.5544	0.6001	1.2871	0.8940
Median	0.1397	0.1654	0.1629	0.1627	0.1630	0.1605	0.1583
Mean	0.1478	0.1807	0.1777	0.1765	0.1773	0.1809	0.1750
StdDev	0.0442	0.0575	0.0557	0.0498	0.0523	0.0803	0.0589

15. Greenland Contribution to Sea Level, 1990–2050 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-0.64	-0.70	-0.63	-0.69	-0.76	-1.64	-2.69	-1.08	-0.87
0.50	-0.60	-0.06	-0.13	-0.19	-0.41	-0.52	-0.36	-0.39	-0.42
1.00	-0.48	-0.01	-0.08	-0.12	-0.31	-0.31	-0.21	-0.03	-0.31
2.50	-0.38	0.08	0.00	-0.05	-0.19	-0.01	-0.06	0.42	-0.17
5.00	-0.29	0.14	0.08	0.00	-0.12	0.11	0.00	0.72	-0.07
10.00	-0.20	0.22	0.17	0.08	-0.06	0.27	0.11	1.09	0.02
20.00	-0.08	0.41	0.30	0.20	0.01	0.46	0.26	1.59	0.18
30.00	-0.03	0.56	0.42	0.31	0.10	0.72	0.43	1.97	0.31
40.00	0.03	0.73	0.54	0.42	0.17	0.94	0.63	2.32	0.47
50.00	0.09	0.93	0.66	0.55	0.25	1.15	0.83	2.60	0.68
60.00	0.16	1.15	0.81	0.73	0.35	1.43	1.08	2.93	0.95
70.00	0.23	1.38	1.04	0.94	0.47	1.82	1.41	3.30	1.32
80.00	0.32	1.78	1.36	1.22	0.64	2.22	1.94	3.77	1.88
90.00	0.48	2.45	1.88	1.75	0.96	3.19	2.86	4.48	2.83
95.00	0.65	3.20	2.45	2.40	1.34	4.08	3.94	5.10	3.74
97.50	0.85	3.92	3.22	3.12	1.72	4.99	5.56	5.78	4.52
99.00	1.06	4.75	4.10	4.39	2.13	6.49	9.75	6.42	5.73
99.50	1.19	5.66	5.31	4.86	2.63	7.51	12.87	6.84	6.69
99.90	1.64	6.43	12.19	8.34	5.45	12.46	28.51	8.18	12.46
Median	0.09	0.93	0.66	0.55	0.25	1.15	0.83	2.60	0.68
Mean	0.13	1.18	0.91	0.80	0.38	1.50	1.39	2.72	1.13
StdDev	0.30	1.02	0.98	0.89	0.55	1.44	2.99	1.35	1.60

16. Greenland Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-1.40	-2.77	-3.29	-2.39	-2.76	-4.29	-3.98	0.57	-4.19
0.50	-1.31	-0.16	-0.75	-0.67	-1.70	-2.34	-1.63	1.49	-1.26
1.00	-1.12	0.08	-0.06	-0.41	-1.10	-1.24	-1.01	1.74	-0.81
2.50	-0.81	0.42	0.22	-0.11	-0.62	-0.03	-0.15	2.53	-0.37
5.00	-0.56	0.67	0.49	0.12	-0.36	0.58	0.11	3.31	-0.10
10.00	-0.33	1.06	0.85	0.42	-0.13	1.12	0.52	4.21	0.22
20.00	-0.09	1.72	1.43	0.87	0.17	1.92	1.16	5.18	0.77
30.00	0.08	2.31	2.03	1.27	0.47	2.85	1.81	5.98	1.34
40.00	0.25	3.05	2.58	1.67	0.75	3.70	2.56	6.76	2.00
50.00	0.42	3.77	3.37	2.20	1.12	4.69	3.42	7.52	2.87
60.00	0.62	4.53	4.15	2.86	1.47	5.93	4.36	8.24	3.99
70.00	0.88	5.68	5.43	3.74	1.97	7.50	5.69	9.14	5.37
80.00	1.18	7.46	7.55	4.97	2.63	9.60	8.21	10.22	7.30
90.00	1.68	10.31	12.24	7.28	4.06	14.52	13.34	11.90	10.28
95.00	2.34	13.75	18.47	9.92	5.62	19.28	18.99	13.34	13.75
97.50	2.95	18.46	26.56	13.37	7.13	25.62	27.16	14.78	18.56
99.00	4.07	23.41	36.28	18.80	9.20	36.35	43.45	16.66	27.16
99.50	4.51	28.34	51.08	22.23	12.59	43.38	54.87	18.13	36.11
99.90	6.14	40.72	75.57	47.19	21.28	58.74	59.99	19.96	64.94
Median	0.42	3.77	3.37	2.20	1.12	4.69	3.42	7.52	2.87
Mean	0.60	5.03	5.64	3.33	1.64	6.66	5.83	7.80	4.57
StdDev	0.95	4.77	8.35	4.00	2.31	7.25	9.74	3.10	6.28

17. Greenland Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-3.87	-11.23	-9.20	-10.01	-12.21	-22.07	-12.71	4.80	-11.44
0.50	-2.82	-1.09	-5.48	-3.38	-8.62	-10.19	-9.80	6.43	-5.81
1.00	-2.65	0.26	-2.36	-1.91	-6.93	-4.63	-7.20	7.49	-2.69
2.50	-1.82	1.42	0.77	-0.34	-2.51	-0.25	-1.23	8.91	-1.08
5.00	-1.20	2.37	2.11	0.46	-1.42	1.72	0.46	11.19	-0.16
10.00	-0.61	4.18	3.86	1.63	-0.43	4.03	1.87	13.90	0.92
20.00	0.03	6.83	7.03	3.22	0.71	7.26	4.31	16.84	2.90
30.00	0.48	9.24	10.73	4.73	1.91	10.88	6.88	18.92	5.32
40.00	1.02	11.80	14.86	6.51	3.07	15.29	10.17	21.74	8.24
50.00	1.66	15.86	20.63	8.64	4.57	19.78	14.45	24.25	12.28
60.00	2.37	19.91	27.42	11.44	6.18	25.99	19.90	26.77	17.21
70.00	3.20	25.98	41.74	15.14	8.30	33.77	26.24	30.07	23.01
80.00	4.65	35.38	61.10	21.22	11.96	46.38	38.80	33.43	31.21
90.00	6.71	55.86	100.23	36.38	19.83	76.50	68.68	38.96	50.04
95.00	9.14	73.54	134.93	54.03	28.70	105.79	105.33	44.49	76.95
97.50	12.62	107.39	180.65	69.02	38.18	135.58	135.70	48.02	109.91
99.00	17.84	124.31	223.86	93.06	55.32	192.18	184.60	53.22	150.94
99.50	21.82	138.77	239.40	111.11	71.50	195.45	198.79	59.61	190.22
99.90	25.85	148.00	247.76	194.39	94.99	205.66	240.72	64.74	236.97
Median	1.66	15.86	20.63	8.64	4.57	19.78	14.45	24.25	12.28
Mean	2.58	23.99	38.57	15.01	7.74	31.44	26.79	25.47	21.45
StdDev	3.74	25.25	47.28	19.63	11.49	35.50	35.98	10.14	29.76

18. Ross Ice Shelf Melt Rate in the Year 2100 (m/yr)

Cumulative %	Thomas	All Other Reviewers	All Reviewers
0.10	0.020	0.021	0.020
0.50	0.226	0.137	0.139
1.00	0.236	0.178	0.186
2.50	0.247	0.215	0.219
5.00	0.259	0.230	0.233
10.00	0.281	0.245	0.247
20.00	0.327	0.259	0.263
30.00	0.382	0.280	0.289
40.00	0.447	0.311	0.323
50.00	0.549	0.352	0.372
60.00	0.724	0.415	0.443
70.00	0.986	0.515	0.557
80.00	1.690	0.683	0.764
90.00	3.138	1.071	1.252
95.00	5.954	1.586	2.068
97.50	9.769	2.360	3.208
99.00	16.629	3.684	6.203
99.50	22.608	5.101	9.464
99.90	36.955	9.568	19.918
Median	0.549	0.352	0.372
Mean	1.541	0.581	0.718
StdDev	3.331	0.780	1.489

19. Antarctic Contribution to Sea Level by Climate Reviewer, 1990–2050 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-58.58	-49.04	-47.74	-73.70	-42.61	-52.39	-62.04	-6.84	-52.39
0.50	-40.54	-34.02	-27.60	-30.89	-32.63	-44.61	-31.98	-5.66	-34.02
1.00	-35.09	-25.99	-20.38	-23.98	-27.35	-26.83	-26.67	-5.25	-25.70
2.50	-20.03	-17.82	-15.93	-16.34	-19.03	-19.90	-17.53	-4.31	-16.68
5.00	-11.04	-10.87	-11.55	-11.50	-13.76	-13.00	-11.63	-3.83	-10.90
10.00	-7.45	-6.97	-7.07	-6.92	-8.20	-7.99	-7.25	-3.03	-6.66
20.00	-4.02	-3.98	-3.82	-3.84	-4.16	-4.35	-4.04	-2.24	-3.67
30.00	-2.51	-2.50	-2.55	-2.33	-2.73	-2.89	-2.56	-1.64	-2.37
40.00	-1.64	-1.63	-1.64	-1.47	-1.79	-1.84	-1.55	-1.28	-1.55
50.00	-1.04	-0.88	-0.91	-0.85	-1.05	-1.04	-0.72	-0.95	-0.94
60.00	-0.42	-0.30	-0.35	-0.27	-0.55	-0.48	-0.14	-0.69	-0.44
70.00	0.42	0.72	0.62	0.72	0.23	0.48	1.12	-0.46	0.22
80.00	2.30	2.58	2.64	3.00	2.27	2.40	3.15	-0.18	1.93
90.00	5.18	5.21	5.39	5.43	4.83	5.26	5.63	0.18	4.84
95.00	7.12	7.36	7.63	7.05	6.96	7.26	7.97	0.52	6.96
97.50	8.77	9.28	9.12	8.44	8.63	9.44	9.66	0.86	8.77
99.00	10.68	11.70	11.16	10.23	11.61	11.77	11.68	1.37	10.73
99.50	11.76	13.70	14.77	10.68	13.51	13.55	16.63	1.58	13.16
99.90	21.12	27.80	22.48	19.95	16.61	14.85	25.77	2.28	21.23
Median	-1.04	-0.88	-0.91	-0.85	-1.05	-1.04	-0.72	-0.95	-0.94
Mean	-1.64	-1.34	-1.19	-1.25	-1.75	-1.77	-1.19	-1.21	-1.42
StdDev	7.12	6.66	6.14	6.56	6.63	7.18	7.04	1.33	6.35

20. Antarctic Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-28.62	-49.45	-55.89	-55.01	-56.02	-55.02	-50.78	-15.92	-52.18
0.50	-27.03	-45.02	-41.53	-43.99	-48.08	-45.81	-47.90	-14.21	-43.84
1.00	-24.00	-37.29	-36.08	-39.17	-41.17	-42.18	-42.54	-13.66	-36.80
2.50	-20.29	-26.50	-29.02	-29.44	-32.53	-32.25	-28.15	-11.56	-26.83
5.00	-16.60	-18.23	-21.87	-19.89	-25.11	-21.78	-20.23	-10.07	-18.87
10.00	-11.18	-11.53	-13.23	-12.40	-15.02	-15.07	-11.92	-8.38	-11.65
20.00	-6.37	-6.72	-7.10	-6.68	-7.61	-8.22	-6.42	-6.22	-6.78
30.00	-4.15	-4.07	-4.56	-3.68	-4.69	-4.92	-3.55	-4.77	-4.32
40.00	-2.65	-2.34	-2.46	-2.06	-2.82	-2.78	-1.78	-3.76	-2.70
50.00	-1.54	-0.77	-0.99	-0.93	-1.58	-1.43	-0.35	-2.97	-1.45
60.00	-0.35	0.56	0.21	0.54	-0.55	-0.12	1.95	-2.22	-0.33
70.00	1.93	3.47	3.22	3.51	1.72	3.10	5.48	-1.45	1.89
80.00	5.68	6.88	6.67	7.69	5.81	6.80	9.32	-0.67	5.81
90.00	10.72	12.08	11.87	13.06	10.62	12.50	15.77	0.47	11.36
95.00	14.93	16.87	16.29	17.49	15.62	18.33	22.28	1.51	16.47
97.50	18.96	21.98	20.83	21.47	19.85	22.73	27.75	2.43	21.33
99.00	22.66	32.25	31.45	29.80	28.65	33.15	37.19	3.80	30.11
99.50	25.76	48.72	36.20	36.70	34.66	36.21	43.46	4.22	36.58
99.90	33.49	61.00	53.84	70.43	40.58	46.49	53.36	6.13	51.89
Median	-1.54	-0.77	-0.99	-0.93	-1.58	-1.43	-0.35	-2.97	-1.45
Mean	-0.87	-0.37	-1.03	-0.39	-2.02	-1.37	0.77	-3.45	-1.09
StdDev	9.02	11.63	11.70	12.00	11.91	12.42	12.97	3.51	11.09

21. Antarctic Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-129.09	-148.07	-135.00	-135.44	-126.19	-143.55	-131.31	-58.59	-135.63
0.50	-119.02	-113.68	-116.72	-108.46	-115.00	-124.69	-97.63	-52.31	-111.93
1.00	-107.26	-82.27	-96.57	-84.54	-93.78	-100.68	-86.34	-45.12	-89.93
2.50	-59.75	-58.15	-65.38	-51.00	-63.96	-63.54	-55.38	-38.63	-56.86
5.00	-37.54	-35.69	-48.10	-35.63	-46.96	-41.88	-32.42	-33.21	-37.93
10.00	-24.90	-21.55	-27.54	-21.85	-28.80	-25.35	-18.18	-27.87	-24.63
20.00	-12.60	-10.66	-11.73	-10.40	-12.92	-10.25	-7.95	-20.12	-13.02
30.00	-7.35	-5.34	-5.94	-4.26	-6.63	-3.24	-2.39	-15.52	-7.25
40.00	-4.16	-1.58	-1.57	-1.51	-2.98	1.01	1.63	-12.22	-3.26
50.00	-1.93	1.98	2.99	2.29	-0.60	7.29	8.88	-9.57	-0.27
60.00	1.03	9.05	10.73	9.34	3.97	15.80	18.18	-7.18	5.43
70.00	7.78	16.36	19.16	16.86	12.08	24.94	27.04	-4.80	13.78
80.00	15.43	25.60	28.90	26.08	20.70	38.23	44.26	-2.44	24.07
90.00	25.56	40.72	51.96	41.68	34.66	70.09	77.63	1.50	42.88
95.00	35.67	67.38	81.63	64.76	50.71	121.80	124.71	4.73	71.56
97.50	45.71	112.89	120.62	108.60	75.82	188.76	203.09	8.01	114.54
99.00	69.13	206.73	216.99	189.81	114.60	320.09	356.47	11.56	206.38
99.50	79.17	240.09	289.64	286.58	221.73	424.31	486.92	12.47	277.76
99.90	100.44	293.21	326.23	333.38	274.47	536.76	635.87	18.07	455.40
Median	-1.93	1.98	2.99	2.29	-0.60	7.29	8.88	-9.57	-0.27
Mean	-1.03	9.10	10.87	9.86	3.34	20.17	24.74	-11.36	8.21
StdDev	25.98	41.03	47.37	42.91	35.80	64.16	69.09	11.67	46.98

22. Antarctic Contribution to Sea Level by Glaciology Reviewer, 1990–2100 (cm)

Cumulative %	Alley	Anonymous	Bentley	Bindschadler	Thomas	Van der Veen	Zwally
0.10	-58.58	-55.01	-56.93	-59.83	-55.89	-56.72	-59.43
0.50	-52.15	-48.94	-51.45	-47.90	-46.02	-52.41	-48.13
1.00	-42.06	-43.55	-49.20	-44.57	-38.88	-49.29	-43.84
2.50	-32.89	-29.53	-37.41	-34.02	-27.72	-30.17	-32.18
5.00	-22.53	-21.73	-25.77	-20.81	-18.47	-20.65	-21.39
10.00	-14.96	-13.12	-13.46	-12.87	-10.64	-13.62	-13.44
20.00	-8.20	-7.26	-7.81	-6.81	-4.74	-7.18	-6.97
30.00	-5.30	-4.31	-5.19	-3.87	-2.37	-4.31	-4.03
40.00	-3.20	-2.76	-3.12	-1.96	-0.98	-2.57	-2.34
50.00	-1.64	-1.51	-1.74	-0.42	0.26	-1.29	-1.06
60.00	-0.38	-0.38	-0.56	1.79	2.98	-0.20	0.22
70.00	2.31	1.26	1.45	4.97	4.96	1.96	3.23
80.00	6.25	5.78	5.78	9.04	8.63	6.69	6.69
90.00	11.03	10.27	11.56	15.06	14.86	11.51	12.17
95.00	16.21	15.67	15.75	19.86	19.30	16.12	17.18
97.50	20.51	21.72	21.54	26.92	26.83	20.00	22.41
99.00	30.10	30.11	31.12	40.58	40.50	24.02	29.41
99.50	36.52	36.20	34.66	50.66	53.03	32.44	39.76
99.90	61.02	53.37	48.75	78.63	71.04	53.84	54.23
Median	-1.64	-1.51	-1.74	-0.42	0.26	-1.29	-1.06
Mean	-1.95	-1.64	-2.19	0.31	1.33	-1.60	-1.04
StdDev	12.27	11.63	12.72	13.77	12.70	12.04	12.50

23. Antarctic Contribution to Sea Level by Glaciology Reviewer, 1990–2200 (cm)

Cumulative %	Alley	Anonymous	Bentley	Bindschadler	Thomas	Van der Veen	Zwally
0.10	-206.45	-121.36	-179.79	-184.04	-168.28	-143.55	-135.44
0.50	-137.93	-93.33	-143.84	-115.69	-94.33	-123.31	-117.30
1.00	-113.68	-80.94	-111.68	-83.68	-76.97	-99.12	-91.88
2.50	-65.38	-54.19	-73.96	-56.93	-44.05	-56.47	-62.96
5.00	-44.56	-38.52	-48.62	-38.61	-24.81	-39.19	-38.95
10.00	-29.77	-24.65	-26.56	-23.30	-12.97	-25.41	-22.93
20.00	-14.24	-11.27	-14.08	-9.56	-4.23	-12.48	-9.99
30.00	-7.76	-5.49	-8.23	-3.05	-0.37	-6.45	-4.93
40.00	-3.21	-2.05	-4.21	1.47	4.81	-3.07	-1.80
50.00	0.51	0.90	-1.33	8.75	12.32	-0.76	2.08
60.00	6.38	6.32	2.92	15.85	19.27	3.95	8.81
70.00	13.73	13.01	10.64	23.03	28.17	12.61	17.35
80.00	23.98	20.60	20.85	35.88	45.08	21.88	27.28
90.00	38.33	37.30	36.40	58.21	104.12	36.86	45.47
95.00	59.54	57.58	61.11	83.80	227.41	55.49	69.60
97.50	86.59	84.63	91.96	117.67	339.93	78.14	98.01
99.00	128.90	149.06	131.16	167.58	589.34	120.62	165.16
99.50	199.56	181.81	164.38	207.52	675.42	152.53	219.59
99.90	256.96	210.65	239.23	274.81	693.72	234.62	286.58
Median	0.51	0.90	-1.33	8.75	12.32	-0.76	2.08
Mean	4.02	5.69	2.68	14.21	38.36	4.09	9.16
StdDev	39.25	34.20	38.27	42.25	100.36	34.04	40.84

24. Small Glacier Contribution to Sea Level by Climate Reviewer, 1990–2050 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-5.56	-6.08	-9.13	-6.98	-4.54	-6.32	-10.44	-9.88	-6.58
0.50	-4.17	-4.18	-3.88	-3.12	-3.26	-3.34	-4.07	-2.99	-3.72
1.00	-3.31	-2.49	-2.05	-2.40	-2.26	-1.84	-2.26	-2.09	-2.55
2.50	-2.50	-0.73	-0.83	-0.94	-0.78	-0.78	-0.94	-0.90	-1.23
5.00	-1.40	0.23	0.18	0.21	0.20	0.27	0.23	0.19	-0.36
10.00	-0.79	1.09	1.10	1.19	1.01	1.07	0.99	1.18	0.41
20.00	-0.26	2.34	2.44	2.37	2.18	2.24	2.40	2.57	1.65
30.00	0.11	3.35	3.64	3.26	3.23	3.36	3.57	3.66	2.69
40.00	0.53	4.28	4.47	4.30	4.07	4.41	4.61	4.76	3.73
50.00	0.94	5.20	5.38	5.29	4.99	5.45	5.67	5.84	4.76
60.00	1.49	6.25	6.45	6.45	6.15	6.64	6.77	6.72	5.92
70.00	2.01	7.56	7.94	7.78	7.38	7.88	8.38	7.95	7.20
80.00	2.68	9.26	9.69	9.61	8.83	9.37	10.17	9.43	8.97
90.00	3.81	11.97	12.21	12.29	11.11	11.86	13.17	11.77	11.52
95.00	4.85	14.54	13.93	14.64	13.10	13.68	15.69	13.53	13.76
97.50	5.70	16.36	15.73	16.38	14.71	15.58	18.39	16.84	17.96
99.50	7.35	20.44	19.37	20.83	17.50	19.56	26.92	18.31	20.16
99.90	9.26	22.93	22.84	26.26	19.05	21.10	32.49	21.42	26.26
Median	0.94	5.20	5.38	5.29	4.99	5.45	5.67	5.84	4.76
Mean	1.22	5.93	6.09	6.07	5.61	5.99	6.51	6.12	5.44
StdDev	1.97	4.37	4.38	4.53	4.00	4.28	5.11	4.16	4.49

25. Small Glacier Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-5.72	-8.54	-14.43	-12.30	-8.65	-12.72	-11.25	-10.91	-10.92
0.50	-4.90	-7.34	-6.46	-5.64	-5.36	-5.73	-6.76	-5.70	-5.72
1.00	-3.78	-4.22	-3.60	-4.31	-4.62	-3.90	-3.89	-4.10	-3.94
2.50	-2.10	-1.53	-1.44	-1.70	-1.54	-1.04	-1.81	-1.73	-1.76
5.00	-1.48	0.59	0.69	0.53	0.60	0.66	0.63	0.70	-0.32
10.00	-0.68	2.34	2.50	2.40	2.44	2.37	2.51	2.92	1.03
20.00	0.01	4.68	4.83	4.69	4.60	4.85	4.64	5.40	3.34
30.00	0.48	6.56	6.68	6.28	6.11	6.62	6.67	6.94	5.25
40.00	1.11	8.13	8.16	7.94	7.95	8.09	8.30	8.73	6.92
50.00	1.73	9.82	9.47	9.47	9.42	9.70	10.14	10.28	8.73
60.00	2.48	11.47	11.31	11.27	10.93	11.32	12.06	11.74	10.55
70.00	3.39	13.16	13.21	12.76	12.71	12.98	14.10	13.63	12.43
80.00	4.36	15.38	15.14	15.41	14.86	15.70	17.06	15.66	14.82
90.00	6.23	19.22	18.43	18.92	17.78	19.04	20.44	18.49	18.31
95.00	7.53	21.72	20.83	21.70	20.50	21.95	23.75	20.90	21.09
97.50	9.00	23.85	23.17	24.40	22.37	24.14	26.13	22.59	23.57
99.00	10.61	26.81	25.94	27.28	24.77	26.17	29.54	24.87	26.31
99.50	11.26	28.55	27.77	28.91	27.23	27.53	32.34	27.04	27.83
99.90	13.11	31.27	31.37	33.20	29.87	28.90	33.61	27.83	32.18
Median	1.73	9.82	9.47	9.47	9.42	9.70	10.14	10.28	8.73
Mean	2.23	10.19	10.11	10.07	9.72	10.21	10.82	10.45	9.23
StdDev	2.84	6.50	6.36	6.57	6.10	6.50	7.22	6.17	6.71

26. Small Glacier Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-7.17	-14.08	-23.18	-21.49	-15.32	-19.14	-18.06	-20.17	-19.14
0.50	-4.71	-11.28	-10.29	-8.08	-9.92	-10.50	-11.19	-9.26	-9.28
1.00	-3.90	-7.50	-6.40	-7.01	-8.65	-6.68	-7.34	-7.29	-6.53
2.50	-2.47	-2.39	-2.52	-3.25	-2.89	-2.03	-2.43	-3.16	-2.54
5.00	-1.61	0.93	1.22	0.92	1.06	1.09	1.14	1.40	-0.26
10.00	-0.62	3.95	3.99	3.90	4.02	3.77	3.68	4.69	1.63
20.00	0.12	7.50	7.70	7.32	7.46	7.20	7.26	8.28	5.15
30.00	0.86	10.20	10.31	9.89	9.61	10.14	10.13	10.79	8.11
40.00	1.70	12.46	12.47	11.78	12.50	12.29	12.70	13.00	10.73
50.00	2.66	14.90	14.61	14.03	14.66	14.63	15.21	15.37	13.25
60.00	3.78	17.60	16.70	16.35	16.90	16.67	17.53	17.63	15.75
70.00	5.08	19.82	19.49	18.87	18.96	19.09	20.64	20.33	18.47
80.00	6.80	22.65	22.09	21.72	22.22	22.04	24.09	22.87	21.68
90.00	9.51	26.32	26.19	26.93	25.52	26.16	28.41	26.05	25.82
95.00	11.83	29.08	28.80	29.82	29.16	29.76	31.80	28.55	28.98
97.50	14.15	31.08	31.79	32.89	32.03	31.87	33.58	30.01	31.75
99.00	15.72	33.94	33.99	35.23	34.24	34.14	35.79	32.49	34.17
99.50	17.17	35.45	35.66	37.96	35.77	34.91	37.90	34.53	35.63
99.90	19.87	38.28	38.68	39.20	38.41	36.31	39.05	37.85	38.61
Median	2.66	14.90	14.61	14.03	14.66	14.63	15.21	15.37	13.25
Mean	3.59	14.91	14.74	14.56	14.61	14.68	15.50	15.26	13.48
StdDev	4.21	8.81	8.73	8.95	8.70	8.72	9.62	8.52	9.23

27. Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2050 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-7.40	2.37	1.01	1.92	1.83	1.28	0.55	2.53	-5.20
0.50	-5.89	2.90	2.53	3.21	3.20	2.52	2.05	3.39	-2.52
1.00	-4.39	3.75	3.41	3.82	3.80	3.12	3.48	4.24	-1.19
2.50	-3.19	5.12	4.94	5.31	4.93	4.62	4.36	6.18	0.43
5.00	-2.14	6.26	6.16	6.51	6.15	6.25	5.53	7.57	2.09
10.00	-0.95	8.09	8.09	7.79	7.85	7.95	7.22	9.05	4.61
20.00	0.43	10.50	10.56	10.06	10.40	10.48	10.14	11.34	8.11
30.00	1.40	12.54	12.28	11.85	12.16	12.80	12.09	13.11	10.60
40.00	2.24	14.63	14.46	13.64	13.90	14.99	13.84	14.75	12.74
50.00	3.02	16.43	16.84	15.36	16.02	17.08	16.06	16.29	14.94
60.00	4.06	18.84	18.98	17.52	18.31	19.38	18.48	18.22	17.19
70.00	5.13	21.48	21.28	20.21	20.78	22.07	21.38	20.29	19.90
80.00	6.57	24.92	24.34	23.81	23.53	24.70	25.10	22.96	23.24
90.00	8.71	30.62	29.85	27.98	27.97	30.06	30.70	26.79	28.17
95.00	10.16	34.82	34.53	33.39	32.57	34.29	35.94	30.11	32.80
97.50	11.96	38.59	37.88	38.08	35.57	38.64	41.52	34.02	36.94
99.00	14.05	43.47	42.55	41.75	41.80	43.16	52.54	36.31	42.26
99.50	16.78	46.49	45.99	44.81	45.81	45.83	57.99	37.97	46.43
99.90	21.60	49.49	59.04	55.46	56.52	53.18	80.20	48.37	60.75
Median	3.02	16.43	16.84	15.36	16.02	17.08	16.06	16.29	14.94
Mean	3.54	18.08	17.90	17.06	17.25	18.22	18.01	17.34	15.93
StdDev	3.90	8.79	8.69	8.38	8.19	8.78	10.01	7.06	9.41

28. Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-8.60	4.83	5.98	3.77	4.13	4.17	0.99	6.25	-6.43
0.50	-6.96	6.82	7.46	6.50	8.75	5.71	4.03	9.69	-3.06
1.00	-6.34	8.69	8.95	8.74	9.80	6.99	7.00	11.32	-1.24
2.50	-4.35	12.02	11.74	12.00	12.61	11.35	9.27	14.86	1.71
5.00	-2.40	15.09	14.73	14.33	14.74	14.19	12.61	17.36	4.86
10.00	-0.57	18.44	18.98	17.41	18.16	18.25	17.08	20.72	10.35
20.00	1.78	24.47	24.37	22.66	23.16	24.90	22.57	24.99	18.55
30.00	3.49	29.66	29.27	27.00	27.61	29.90	27.37	28.67	24.14
40.00	5.10	34.03	33.76	31.11	31.81	34.62	32.13	31.82	29.23
50.00	6.96	38.57	39.06	34.86	36.07	39.81	37.70	35.47	34.08
60.00	8.94	43.72	43.96	39.65	40.70	45.13	43.68	39.31	39.34
70.00	11.05	51.20	49.65	45.78	45.83	51.32	50.54	43.05	45.22
80.00	14.40	58.13	56.93	53.45	52.44	59.90	60.86	48.64	53.08
90.00	18.85	69.84	71.81	64.86	62.65	72.10	76.31	55.87	65.08
95.00	22.72	82.99	84.05	75.94	71.21	85.10	87.52	61.07	77.23
97.50	26.85	95.05	95.52	86.18	81.32	98.16	101.58	68.23	88.25
99.00	32.15	107.06	113.19	104.23	92.03	110.62	118.24	75.92	104.01
99.50	38.07	116.66	131.19	112.42	104.83	122.28	135.23	78.92	114.58
99.90	60.01	131.51	186.09	130.81	122.68	171.37	157.18	87.63	151.64
Median	6.96	38.57	39.06	34.86	36.07	39.81	37.70	35.47	34.08
Mean	8.34	42.27	42.59	38.80	38.88	43.42	42.59	37.04	36.74
StdDev	8.34	21.05	22.48	19.67	18.14	22.71	24.34	13.85	22.34

29. Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-12.63	4.25	-6.46	1.76	-3.35	7.93	-0.13	10.32	-10.23
0.50	-11.35	12.43	9.68	13.23	15.33	10.93	6.12	13.48	-4.77
1.00	-9.45	13.69	15.62	15.28	18.79	14.28	10.96	20.81	-0.82
2.50	-6.45	23.52	22.32	21.57	23.54	22.53	18.45	26.16	3.48
5.00	-3.21	30.01	29.67	28.85	30.54	32.08	26.10	32.58	10.35
10.00	0.28	39.57	39.76	36.01	38.70	40.64	34.59	39.09	22.06
20.00	3.85	53.13	57.49	48.62	50.11	60.57	49.92	48.50	39.30
30.00	7.68	66.69	71.88	61.10	60.27	75.87	62.52	57.49	53.19
40.00	11.58	81.10	87.87	71.86	71.47	91.34	76.85	65.34	66.61
50.00	15.83	93.99	105.27	84.24	83.94	107.76	97.19	74.59	80.60
60.00	20.53	111.47	125.52	97.44	95.02	126.67	115.04	82.64	96.28
70.00	26.06	130.93	150.58	118.64	110.96	148.70	144.17	93.37	115.79
80.00	33.30	155.00	189.60	144.03	129.28	185.87	182.17	107.09	142.94
90.00	47.39	203.22	258.16	187.07	163.65	251.31	250.99	123.13	195.70
95.00	59.08	256.27	331.03	236.12	199.33	321.23	304.86	142.48	254.16
97.50	73.09	311.29	395.84	277.53	235.99	393.93	383.57	160.06	315.97
99.00	92.85	379.53	502.49	354.39	302.71	548.35	540.44	180.43	409.59
99.50	105.82	467.31	568.02	484.99	337.48	601.56	587.61	184.77	497.77
99.90	125.99	526.21	608.11	549.11	434.75	732.86	724.72	203.49	641.96
Median	15.83	93.99	105.27	84.24	83.94	107.76	97.19	74.59	80.60
Mean	20.28	111.89	131.66	102.04	94.74	132.05	124.05	78.63	99.42
StdDev	20.42	74.73	97.50	70.96	57.07	98.27	100.67	34.24	82.41

30. Annual Greenhouse Contribution to Sea Level in 2100, all Reviewers (mm/year)

Cumulative %	Rate (mm/yr)
0.10	-1.21
0.50	-0.57
1.00	-0.36
2.50	0.03
5.00	0.47
10.00	1.05
20.00	1.91
30.00	2.68
40.00	3.44
50.00	4.21
60.00	5.04
70.00	6.08
80.00	7.49
90.00	9.89
95.00	12.37
97.50	15.41
99.00	19.34
99.50	23.05
99.90	33.63
Median	4.21
Mean	5.04
StdDev	4.19

31. Historic Greenhouse Contribution to Sea Level by Climate Reviewer, 1880–1990 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-6.80	-11.42	-15.09	-12.12	-11.37	-9.42	-12.49	-10.80	-12.09
0.50	-5.49	-9.20	-10.90	-7.81	-8.23	-7.73	-9.23	-7.99	-8.19
1.00	-4.86	-6.40	-7.59	-6.23	-6.56	-6.45	-6.75	-6.07	-6.42
2.50	-3.44	-3.91	-5.03	-4.09	-4.02	-4.42	-4.14	-3.64	-4.05
5.00	-2.46	-2.13	-2.50	-1.76	-2.67	-2.65	-1.74	-1.54	-2.29
10.00	-1.33	-0.32	-0.60	0.15	-0.33	-0.28	0.22	0.23	-0.41
20.00	-0.10	2.11	1.74	2.22	1.81	1.95	2.08	2.23	1.58
30.00	0.84	3.68	3.39	3.77	3.66	3.61	3.25	3.71	3.02
40.00	1.68	4.95	4.82	5.03	5.44	4.79	4.45	5.16	4.28
50.00	2.37	6.35	6.15	6.25	6.65	6.30	5.60	6.41	5.59
60.00	3.10	7.75	7.86	7.40	8.36	7.75	6.93	7.72	6.94
70.00	3.93	9.30	9.78	8.84	10.21	9.49	8.65	9.14	8.61
80.00	4.96	11.35	11.89	11.09	12.49	11.61	10.43	11.07	10.78
90.00	6.13	15.03	15.85	13.81	15.88	15.84	13.89	13.62	14.30
95.00	7.16	18.47	18.79	17.15	19.67	19.91	16.43	16.06	17.59
97.50	8.23	21.64	20.79	20.52	22.42	23.19	19.64	18.12	20.59
99.00	9.53	25.01	25.47	24.34	28.55	27.26	25.52	22.10	24.69
99.50	11.13	27.48	27.56	27.04	31.07	30.92	32.77	24.80	28.29
99.90	14.33	31.61	34.17	38.16	36.02	31.22	38.01	25.65	35.46
Median	2.37	6.35	6.15	6.25	6.65	6.30	5.60	6.41	5.59
Mean	2.42	6.96	6.94	6.78	7.41	7.10	6.43	6.70	6.34
StdDev	3.03	6.28	6.64	6.02	6.84	6.68	6.09	5.52	6.18

32. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2025 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-31.79	-20.71	-12.80	-13.63	-16.31	-25.32	-15.88	-3.69	-24.30
0.50	-24.44	-13.39	-7.86	-11.91	-12.37	-17.83	-12.84	-1.01	-13.20
1.00	-20.19	-9.75	-6.74	-8.95	-10.43	-11.02	-10.79	0.29	-10.37
2.50	-10.68	-5.45	-3.82	-3.96	-5.91	-6.72	-5.76	1.21	-5.83
5.00	-6.36	-2.31	-1.94	-1.64	-2.96	-2.23	-2.77	2.05	-3.19
10.00	-4.53	0.05	0.08	0.03	-0.67	0.11	-0.21	2.94	-1.05
20.00	-2.48	1.96	1.99	1.81	1.57	1.98	1.80	3.89	1.10
30.00	-1.48	3.42	3.46	3.05	2.91	3.14	3.01	4.95	2.57
40.00	-0.78	4.66	4.57	4.21	4.20	4.37	4.31	5.88	3.85
50.00	0.00	5.58	5.72	5.41	5.36	5.57	5.64	6.76	5.06
60.00	0.65	6.84	6.94	6.53	6.46	6.63	7.04	7.69	6.29
70.00	1.51	8.33	8.46	8.06	7.60	8.27	8.59	8.77	7.69
80.00	2.52	9.83	10.25	9.79	9.25	10.18	10.18	10.16	9.47
90.00	4.00	12.73	12.74	12.32	11.91	12.57	13.18	12.39	12.04
95.00	5.34	14.93	15.03	14.34	14.00	15.06	15.52	14.17	14.42
97.50	6.46	17.32	17.46	17.51	15.90	16.93	18.47	16.05	16.56
99.00	8.18	19.87	20.22	19.66	18.64	19.63	21.33	18.30	19.34
99.50	9.22	20.47	21.25	21.14	19.89	21.13	23.42	19.77	20.97
99.90	10.55	24.68	27.12	26.62	21.96	27.26	27.78	22.03	26.99
Median	0.00	5.58	5.72	5.41	5.36	5.57	5.64	6.76	5.06
Mean	-0.40	5.88	6.11	5.75	5.35	5.75	5.96	7.23	5.21
StdDev	4.49	5.51	5.35	5.31	5.27	5.72	5.84	3.83	5.64

33. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2050 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-52.57	-33.41	-23.74	-22.08	-25.52	-40.37	-24.30	-0.80	-40.37
0.50	-40.99	-25.04	-14.44	-18.12	-19.21	-27.75	-23.51	0.89	-23.39
1.00	-33.66	-15.25	-10.51	-13.87	-16.73	-17.39	-15.30	2.02	-16.10
2.50	-17.67	-6.73	-5.64	-6.19	-8.31	-9.94	-7.07	4.06	-8.91
5.00	-10.99	-2.00	-1.77	-1.94	-3.39	-1.91	-2.77	5.20	-4.23
10.00	-7.02	1.35	1.51	1.57	0.76	1.50	1.00	6.60	-0.73
20.00	-3.92	4.99	5.11	4.60	4.25	4.96	4.58	8.40	3.18
30.00	-2.05	7.49	7.55	7.01	6.74	7.36	7.06	9.94	5.97
40.00	-0.79	10.04	9.64	9.19	8.74	9.49	9.16	11.55	8.31
50.00	0.37	11.90	11.67	10.84	10.77	11.60	11.52	12.98	10.39
60.00	1.53	13.83	13.93	12.88	12.95	13.79	13.91	14.44	12.65
70.00	3.13	16.23	16.43	15.77	15.28	16.64	16.54	16.26	15.14
80.00	4.91	19.56	19.68	18.69	17.93	19.63	19.81	18.28	18.12
90.00	7.40	24.76	23.96	23.48	21.85	24.94	25.40	21.85	22.78
95.00	9.81	28.96	27.88	27.26	25.93	28.56	29.79	24.95	26.84
97.50	12.03	32.07	32.26	31.52	28.69	31.47	34.76	26.83	30.56
99.00	13.72	35.11	37.53	34.54	33.27	35.63	44.73	30.77	34.77
99.50	16.87	37.78	43.38	36.24	36.97	38.34	54.68	32.97	38.23
99.90	23.68	41.67	49.94	41.39	40.88	53.69	61.18	36.10	52.63
Median	0.37	11.90	11.67	10.84	10.77	11.60	11.52	12.98	10.39
Mean	-0.18	12.18	12.31	11.58	10.92	12.03	12.38	13.62	10.60
StdDev	7.69	9.74	9.42	9.19	9.10	10.11	10.73	6.03	10.00

34. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2075 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-53.99	-45.58	-33.26	-28.66	-31.64	-50.39	-32.53	-1.56	-48.37
0.50	-48.37	-33.06	-20.42	-20.27	-24.39	-36.63	-24.02	2.25	-29.64
1.00	-45.88	-20.78	-13.65	-17.05	-20.44	-23.96	-16.01	3.43	-20.76
2.50	-24.23	-8.76	-6.25	-7.55	-10.22	-9.63	-6.53	6.43	-11.06
5.00	-15.06	-1.11	-0.33	-1.47	-1.99	-1.12	-1.55	8.94	-5.06
10.00	-9.35	3.86	3.75	3.91	2.70	3.99	2.80	11.01	0.00
20.00	-5.29	9.28	9.34	8.49	8.09	8.99	8.40	13.67	6.08
30.00	-2.37	13.18	13.04	11.80	11.54	12.49	11.95	15.85	10.32
40.00	-0.68	16.46	16.18	15.00	14.86	16.21	15.11	18.29	13.83
50.00	0.98	19.70	18.98	17.50	17.79	19.49	18.87	20.45	17.10
60.00	2.69	23.09	22.86	20.76	21.22	23.25	22.57	22.65	20.52
70.00	5.33	27.17	27.07	25.30	24.43	27.17	26.99	25.30	24.42
80.00	7.71	32.03	31.47	30.66	28.29	32.37	32.90	28.64	29.35
90.00	11.23	39.45	38.48	36.80	35.11	40.32	41.93	32.77	36.51
95.00	15.22	46.39	46.35	43.35	40.52	46.90	50.04	37.66	43.32
97.50	18.06	51.73	53.05	50.03	46.57	51.51	56.49	41.20	49.71
99.00	21.23	57.23	61.27	53.63	53.01	57.68	71.48	45.98	56.49
99.50	23.80	62.51	69.35	58.09	56.49	64.08	79.55	48.29	64.08
99.90	25.66	71.48	82.54	67.33	64.43	82.88	90.39	50.55	80.14
Median	0.98	19.70	18.98	17.50	17.79	19.49	18.87	20.45	17.10
Mean	0.47	20.50	20.57	19.10	18.17	20.47	20.82	21.36	17.68
StdDev	10.45	15.12	14.66	13.94	13.61	15.66	16.53	8.83	15.30

35. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-67.32	-62.83	-34.21	-30.28	-36.29	-44.81	-38.58	-2.15	-57.66
0.50	-59.92	-37.09	-24.33	-21.60	-30.56	-31.29	-19.79	2.95	-33.83
1.00	-48.59	-24.61	-16.07	-17.46	-24.31	-27.45	-16.10	4.27	-24.31
2.50	-30.96	-10.21	-5.37	-7.56	-11.36	-10.27	-7.96	9.13	-13.11
5.00	-19.33	0.01	1.06	-0.74	-1.26	-0.60	-1.01	12.68	-5.80
10.00	-12.02	6.91	6.68	5.61	5.49	6.93	6.00	15.10	0.92
20.00	-6.25	14.72	14.79	13.12	12.33	14.42	13.23	19.03	9.52
30.00	-2.73	19.84	19.77	17.45	17.27	19.62	18.27	22.45	15.58
40.00	-0.18	24.68	24.60	22.07	22.02	24.19	23.09	25.63	20.36
50.00	1.79	29.44	29.33	25.70	26.46	30.40	28.20	28.82	25.09
60.00	4.63	34.81	34.68	30.55	30.63	35.01	33.96	32.11	30.25
70.00	7.94	41.13	40.59	37.88	35.78	41.88	41.63	36.16	36.33
80.00	11.22	48.28	48.43	45.59	42.18	49.18	50.18	40.79	43.99
90.00	17.29	59.76	60.76	56.90	51.51	61.86	64.64	47.36	54.94
95.00	21.44	70.72	73.30	64.31	60.40	72.38	78.77	53.04	66.13
97.50	26.33	80.84	87.15	75.43	70.46	85.11	91.34	58.45	77.76
99.00	29.84	91.85	101.13	89.28	77.63	98.05	103.75	63.41	91.85
99.50	33.36	106.09	117.28	102.92	83.96	105.35	109.75	65.88	102.62
99.90	37.45	114.01	171.91	113.28	92.71	111.47	123.77	70.85	122.53
Median	1.79	29.44	29.33	25.70	26.46	30.40	28.20	28.82	25.09
Mean	1.72	31.45	32.38	28.82	27.28	31.98	32.21	30.20	27.00
StdDev	13.40	22.54	23.46	20.85	19.42	23.13	24.42	12.72	22.62

36. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2150 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-76.31	-51.70	-46.04	-33.17	-49.45	-55.06	-51.74	-4.88	-55.06
0.50	-61.92	-37.26	-37.70	-28.81	-39.48	-46.04	-42.79	2.53	-43.72
1.00	-51.38	-30.61	-20.91	-21.21	-30.46	-34.02	-20.79	4.91	-32.30
2.50	-39.67	-11.92	-4.74	-9.97	-12.73	-12.75	-5.45	12.29	-17.20
5.00	-26.88	1.28	2.58	-0.46	-0.19	2.53	1.55	17.22	-6.94
10.00	-17.25	12.63	14.05	10.23	9.86	14.27	10.04	21.73	3.02
20.00	-8.42	25.08	26.02	21.59	21.01	25.87	22.11	28.81	16.16
30.00	-3.28	33.40	35.68	30.03	30.30	35.62	32.69	34.50	26.26
40.00	0.41	43.26	44.39	37.83	37.15	45.18	40.59	39.87	34.94
50.00	4.47	52.35	55.02	45.72	44.71	56.06	49.96	46.10	43.41
60.00	8.37	62.88	64.73	54.42	52.22	66.15	62.44	51.01	52.86
70.00	14.03	74.05	79.54	67.10	62.70	78.89	76.99	58.38	65.14
80.00	19.24	88.23	97.74	82.44	74.11	96.25	100.87	68.18	80.27
90.00	29.52	112.20	134.56	109.06	92.86	126.02	132.65	79.79	106.43
95.00	37.85	137.33	170.00	129.02	113.98	157.94	165.19	91.49	134.03
97.50	45.87	172.12	208.04	157.87	130.31	191.66	204.05	100.32	167.68
99.00	53.95	199.91	244.81	190.63	162.16	237.31	258.06	110.50	209.68
99.50	63.79	251.06	272.13	217.64	177.56	311.97	295.95	113.34	250.84
99.90	69.55	282.43	343.67	308.46	258.94	381.32	515.84	122.44	342.20
Median	4.47	52.35	55.02	45.72	44.71	56.06	49.96	46.10	43.41
Mean	4.89	58.81	65.82	53.61	48.68	64.49	64.00	48.55	51.10
StdDev	19.77	44.76	53.12	42.46	36.35	52.24	57.56	22.76	46.99

37. Normalized Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
0.10	-84.75	-59.94	-53.65	-47.00	-65.08	-60.30	-64.37	-9.20	-68.91
0.50	-69.99	-43.30	-38.57	-36.58	-51.03	-57.34	-45.58	0.02	-51.95
1.00	-61.69	-39.42	-29.52	-25.74	-39.23	-39.82	-27.93	6.38	-40.13
2.50	-51.31	-16.01	-6.34	-9.82	-18.89	-12.83	-5.87	14.24	-21.44
5.00	-34.58	2.86	4.67	-0.28	-0.54	6.02	2.81	20.83	-8.40
10.00	-22.34	17.95	20.44	14.14	13.92	22.23	15.26	28.07	4.78
20.00	-10.51	35.40	39.30	29.96	30.53	41.41	32.34	36.75	23.28
30.00	-3.61	48.38	55.02	42.92	41.85	56.27	47.05	45.23	37.31
40.00	1.19	61.90	70.07	55.05	53.96	71.08	61.35	53.42	50.52
50.00	6.58	76.34	86.23	67.54	63.19	87.83	77.56	60.86	63.67
60.00	12.43	93.68	105.47	81.37	75.21	106.67	96.99	68.84	78.30
70.00	19.64	113.24	136.74	101.59	90.92	129.45	124.79	79.01	98.14
80.00	27.47	136.74	168.82	125.28	109.64	163.49	163.51	92.91	124.79
90.00	42.02	182.64	236.06	171.10	138.52	227.52	225.08	110.52	174.42
95.00	56.31	227.57	312.25	214.07	172.07	296.36	289.69	128.29	230.39
97.50	68.27	288.04	390.40	264.64	211.86	370.80	368.34	142.13	295.91
99.00	81.17	353.79	480.37	332.04	263.12	537.48	534.01	156.07	401.57
99.50	88.56	445.40	519.86	447.65	331.54	559.78	559.61	164.33	481.87
99.90	104.12	542.37	591.61	550.16	427.53	672.03	679.95	172.98	587.01
Median	6.58	76.34	86.23	67.54	63.19	87.83	77.56	60.86	63.67
Mean	8.24	91.73	111.99	83.01	72.74	110.40	104.30	65.63	81.01
StdDev	27.25	76.58	97.38	71.84	58.47	97.49	99.11	32.83	81.49

38. Year by Which U.S. Sea Level is Likely to Inundate 1-Foot, 3-Foot, and NGVD Contours

Cumulative %	Year US Sea Level rises 1ft (relative to 1990)	Year US Sea Level rises 3ft (relative to 1990)	Year US Sea Level rises to NGVD 5ft contour
0.10	2019	2065	2086
0.50	2025	2078	2101
1.00	2027	2083	2107
2.50	2031	2090	2117
5.00	2034	2097	2127
10.00	2038	2106	2141
20.00	2044	2119	2162
30.00	2049	2131	2180
40.00	2053	2144	>2200
50.00	2058	2157	>2200
60.00	2062	2173	>2200
70.00	2069	2194	>2200
80.00	2079	>2200	>2200
90.00	2099	>2200	>2200
95.00	2127	>2200	>2200
97.50	2169	>2200	>2200
99.00	>2200	>2200	>2200

Note: NGVD is the National Geodetic Vertical Datum, which is approximately equal to mean sea level for the year 1929. Because sea level has been rising, the 5-foot (NGVD) contour on U.S. topographic maps is generally only about 4.5 feet above sea level. These calculations assume that sea level is rising 2.7 mm/yr relative to the U.S. coast.

39. Greenhouse Contribution to Sea Level Rise for eight random subsamples (cm): 1990-2100

Cumulative %	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	All
1.00	-1.36	-0.57	-2.02	-2.89	0.44	-1.23	-2.29	-0.08	-1.24
2.50	2.66	1.83	0.50	0.50	3.77	1.77	0.91	3.57	1.71
5.00	5.37	4.63	3.14	3.69	6.99	5.00	3.94	6.92	4.86
10.00	11.17	9.59	9.27	8.15	13.51	10.73	9.87	12.03	10.35
20.00	19.31	17.99	17.32	16.37	20.03	19.11	18.39	18.96	18.55
30.00	24.86	23.68	23.64	22.22	25.06	23.86	24.38	24.24	24.13
40.00	29.31	28.80	29.00	28.31	30.03	29.29	29.65	28.86	29.23
50.00	35.17	33.78	33.54	32.70	34.46	34.06	34.47	33.95	34.08
60.00	40.56	39.41	38.26	38.66	39.79	38.93	39.75	38.85	39.34
70.00	46.95	45.30	44.01	44.57	46.06	45.84	45.62	44.48	45.22
80.00	54.22	53.36	52.43	51.96	54.17	53.95	53.51	51.21	53.08
90.00	65.46	64.86	63.81	65.55	67.29	67.17	64.53	62.99	65.08
95.00	76.56	74.14	74.49	78.90	79.65	79.04	77.31	74.72	77.23
97.50	89.15	86.19	86.41	95.05	87.27	87.94	92.01	86.46	88.26
99.00	104.08	107.04	103.90	110.22	101.54	103.68	106.72	102.74	104.23
Median	35.17	33.78	33.54	32.70	34.46	34.06	34.47	33.95	34.08
Mean	37.65	36.51	35.78	35.95	37.76	37.21	36.90	36.42	36.77
StdDev	22.84	22.79	22.45	23.72	21.57	22.83	22.76	21.12	22.53

Standard Error of 1% high: 0.99cm

The 10,000 simulations were randomly divide into eight sets of mutually exclusive sub-samples. Thus each column represents 1250 simulations. *See* **Numerical Error of the Monte Carlo Algorithm**, in Chapter 7, *supra*.

B. RESULTS FROM SENSITIVITY ANALYSIS USING IPCC EMISSIONS SCENARIO A

40. Global Warming

Cumulative %	1990-2100 °C	1990-2200 °C
0.10	-0.460	-0.580
0.50	-0.240	-0.260
1.00	-0.110	-0.120
2.50	0.070	0.140
5.00	0.310	0.510
10.00	0.700	1.180
20.00	1.300	2.260
30.00	1.670	2.910
40.00	1.980	3.460
50.00	2.270	3.980
60.00	2.560	4.550
70.00	2.900	5.210
80.00	3.320	6.060
90.00	3.980	7.420
95.00	4.650	8.680
97.50	5.290	9.960
99.00	5.980	11.520
99.50	6.530	12.430
99.90	8.680	16.230
Median	2.270	3.980
Mean	2.349	4.236
StdDev	1.315	2.471

41. Antarctic Contribution to Sea Level, 1990–2200 by Climate Reviewer (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-91.50	-91.58	-116.53	-93.50	-87.20	-111.37	-62.09	-45.18	-88.73
2.50	-61.61	-69.05	-72.93	-65.70	-58.97	-63.59	-47.39	-38.61	-58.83
5.00	-39.90	-42.57	-50.29	-39.03	-39.75	-45.72	-31.08	-34.02	-39.01
10.00	-23.12	-23.55	-28.85	-22.40	-24.18	-25.61	-17.01	-28.30	-24.46
20.00	-12.07	-11.08	-12.84	-11.16	-12.22	-10.66	-6.61	-21.36	-13.38
30.00	-7.13	-5.32	-5.75	-5.90	-6.19	-3.06	-2.14	-16.93	-7.46
40.00	-4.21	-1.69	-1.40	-1.97	-2.34	1.34	2.08	-13.47	-3.36
50.00	-1.85	1.81	2.87	1.40	0.28	8.02	9.71	-10.97	-0.13
60.00	1.26	8.81	10.24	8.42	6.34	15.90	18.98	-8.49	5.84
70.00	7.59	16.15	19.46	15.97	13.35	24.95	29.80	-5.65	13.73
80.00	14.01	25.99	29.95	24.89	21.85	40.18	44.44	-2.71	24.51
90.00	24.14	47.80	53.93	45.58	36.66	72.77	79.79	1.58	46.02
95.00	33.36	72.45	90.37	72.00	52.98	127.97	140.97	5.14	74.34
97.50	49.00	103.61	126.61	114.86	72.00	182.40	213.09	8.96	119.72
99.00	67.35	187.54	221.14	175.70	125.56	325.91	330.67	13.42	206.38
Median	-1.85	1.81	2.87	1.40	0.28	8.02	9.71	-10.97	-0.13
Mean	-0.92	9.74	10.70	9.51	4.99	21.54	27.46	-12.17	8.86
StdDev	25.73	39.71	48.06	42.87	35.56	64.22	62.87	10.92	45.62

42. Greenland Contribution to Sea Level, 1990–2200 by Climate Reviewer (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-2.51	0.81	-1.08	-2.99	-5.82	-5.58	-6.84	11.47	-3.18
2.50	-1.84	2.32	1.21	-0.44	-3.18	-0.54	-1.09	13.44	-1.12
5.00	-1.16	3.75	3.13	0.54	-1.62	2.60	0.69	14.87	-0.13
10.00	-0.48	5.62	5.71	2.02	-0.48	5.66	2.63	17.00	1.20
20.00	0.19	8.25	9.94	4.19	0.93	9.70	5.93	20.06	3.70
30.00	0.68	11.29	14.27	6.16	2.43	13.63	8.61	22.24	6.67
40.00	1.29	14.91	19.68	8.01	3.73	17.31	12.12	23.96	10.18
50.00	1.91	18.93	25.86	10.59	5.34	22.47	16.79	26.11	14.96
60.00	2.48	24.04	35.31	13.96	7.44	29.81	22.25	28.27	20.22
70.00	3.52	29.57	50.05	18.01	9.57	38.49	29.41	31.09	25.87
80.00	4.82	38.35	70.60	24.11	13.41	53.07	43.64	34.63	34.40
90.00	7.24	55.99	105.08	37.06	20.29	81.59	70.08	39.51	53.28
95.00	9.39	80.46	132.83	51.04	29.53	106.16	100.62	42.78	83.28
97.50	12.78	103.45	166.73	67.50	37.47	135.33	133.35	45.28	112.85
99.00	15.20	142.37	199.32	113.56	56.15	175.90	184.22	52.95	149.12
Median	1.91	18.93	25.86	10.59	5.34	22.47	16.79	26.11	14.96
Mean	2.72	26.64	41.82	16.70	8.50	34.43	28.13	27.32	23.28
StdDev	3.47	24.87	46.45	19.51	11.13	34.73	34.99	8.79	29.41

43. Contribution to Sea Level by 1990-2100 (cm)

Cumulative %	Greenhouse Contribution	Normalized Contribution
0.10	-5.930	-62.900
0.50	-2.960	-38.780
1.00	-1.280	-25.100
2.50	2.040	-11.520
5.00	5.480	-4.760
10.00	11.860	2.220
20.00	20.730	11.380
30.00	26.420	17.710
40.00	31.560	23.070
50.00	36.310	27.770
60.00	41.400	32.650
70.00	47.610	38.120
80.00	54.990	45.310
90.00	66.160	55.730
95.00	76.730	66.590
97.50	88.880	77.830
99.00	102.880	90.750
99.50	116.020	104.990
99.90	157.190	147.680
Median	36.310	27.770
Mean	38.542	28.735
StdDev	22.219	23.019

44. Contribution to Sea Level by 2200 (cm)

Cumulative %	Greenhouse Contribution	Normalized Contribution
0.10	-12.460	-69.670
0.50	-4.730	-64.390
1.00	-0.590	-41.480
2.50	4.600	-17.190
5.00	12.470	-3.960
10.00	28.050	11.640
20.00	49.950	32.480
30.00	65.050	48.160
40.00	77.540	61.800
50.00	91.040	74.680
60.00	106.700	88.850
70.00	125.730	106.920
80.00	152.910	133.240
90.00	200.230	178.500
95.00	253.610	232.700
97.50	307.870	284.120
99.00	385.290	374.610
99.50	500.670	468.630
99.90	650.440	781.240
Median	91.040	74.680
Mean	107.871	89.142
StdDev	83.857	83.309

45. Annual Greenhouse Contribution to Sea Level by Climate Reviewer in the year 2100 (mm/yr)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-0.82	1.47	1.40	1.30	1.49	1.43	0.93	1.69	-0.27
2.50	-0.61	1.87	1.77	1.75	1.91	1.80	1.51	2.01	0.22
5.00	-0.41	2.26	2.24	2.01	2.31	2.23	1.93	2.35	0.75
10.00	-0.12	2.78	2.87	2.55	2.73	2.89	2.43	2.74	1.54
20.00	0.23	3.57	3.77	3.21	3.38	3.71	3.24	3.44	2.67
30.00	0.54	4.23	4.49	3.80	3.86	4.50	3.90	3.87	3.50
40.00	0.78	4.93	5.32	4.50	4.43	5.08	4.63	4.27	4.17
50.00	1.00	5.67	6.16	5.03	4.97	5.86	5.42	4.57	4.84
60.00	1.24	6.40	6.99	5.77	5.64	6.71	6.29	4.99	5.60
70.00	1.52	7.37	7.99	6.73	6.33	7.95	7.40	5.51	6.49
80.00	1.97	8.48	9.51	7.75	7.28	9.40	8.79	6.12	7.70
90.00	2.62	10.25	12.13	9.28	8.66	11.50	11.29	6.92	9.70
95.00	3.18	12.45	15.06	11.26	9.83	13.46	14.39	7.62	11.83
97.50	3.88	14.90	17.46	13.36	11.25	16.10	16.77	8.38	14.29
99.00	4.72	17.82	21.06	16.80	13.88	20.82	22.63	9.18	17.82
Median	1.00	5.67	6.16	5.03	4.97	5.86	5.42	4.57	4.84
Mean	1.16	6.27	6.98	5.71	5.43	6.80	6.36	4.77	5.43
StdDev	1.14	3.42	4.20	3.36	2.49	4.33	4.56	1.60	3.79

C. RESULTS FROM SENSITIVITY ANALYSIS USING IPCC SCENARIO E

46. Global Warming by Climate Reviewer, 1990–2100 (°C)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-0.42	0.97	0.97	0.92	0.94	0.79	0.73	1.38	-0.09
2.50	-0.27	1.12	1.14	1.09	1.06	1.04	1.06	1.56	0.10
5.00	-0.18	1.31	1.30	1.28	1.27	1.26	1.27	1.77	0.37
10.00	-0.05	1.55	1.56	1.49	1.53	1.51	1.59	1.95	0.82
20.00	0.10	1.91	1.91	1.88	1.85	1.92	1.98	2.28	1.53
30.00	0.25	2.20	2.19	2.20	2.14	2.26	2.29	2.52	1.96
40.00	0.37	2.56	2.45	2.46	2.43	2.55	2.62	2.74	2.31
50.00	0.50	2.89	2.69	2.75	2.72	2.83	2.95	2.96	2.63
60.00	0.61	3.21	3.00	3.00	3.03	3.17	3.31	3.18	2.96
70.00	0.74	3.56	3.33	3.39	3.36	3.56	3.80	3.46	3.31
80.00	0.91	4.03	3.80	3.86	3.78	4.11	4.37	3.76	3.79
90.00	1.12	4.85	4.45	4.64	4.42	4.88	5.46	4.27	4.54
95.00	1.32	5.66	5.23	5.35	4.95	5.60	6.30	4.72	5.26
97.50	1.47	6.22	5.87	5.99	5.40	6.16	6.88	5.18	5.97
99.00	1.60	6.87	6.74	6.70	6.15	6.84	8.87	5.57	6.72
Median	0.50	2.89	2.69	2.75	2.72	2.83	2.95	2.96	2.63
Mean	0.52	3.05	2.91	2.94	2.86	3.05	3.30	3.05	2.71
StdDev	0.45	1.30	1.21	1.26	1.15	1.34	1.81	0.91	1.49

47. Global Warming by Climate Reviewer, 1990–2200 (°C)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-0.53	1.66	1.72	1.63	1.64	1.53	1.44	2.67	-0.09
2.50	-0.34	1.96	2.01	2.04	1.89	1.94	1.94	2.95	0.20
5.00	-0.22	2.31	2.33	2.32	2.30	2.26	2.32	3.27	0.62
10.00	-0.01	2.84	2.78	2.76	2.75	2.68	2.85	3.64	1.44
20.00	0.20	3.47	3.34	3.44	3.43	3.43	3.49	4.25	2.78
30.00	0.39	4.05	3.90	3.94	3.99	4.05	4.21	4.67	3.55
40.00	0.62	4.66	4.35	4.57	4.59	4.66	4.86	5.10	4.23
50.00	0.83	5.33	4.98	5.19	5.18	5.24	5.42	5.54	4.86
60.00	1.05	6.03	5.64	5.87	5.95	5.80	6.19	5.97	5.54
70.00	1.29	6.86	6.42	6.69	6.70	6.59	7.19	6.52	6.36
80.00	1.54	7.72	7.49	7.76	7.76	7.51	8.38	7.17	7.36
90.00	1.91	9.54	9.09	9.39	9.49	9.24	10.25	8.24	8.97
95.00	2.17	10.97	10.24	11.03	11.11	10.46	12.12	9.06	10.42
97.50	2.46	12.38	11.79	12.27	12.30	11.88	13.72	9.78	11.95
99.00	2.69	14.15	13.91	14.23	13.65	12.96	16.07	10.82	13.72
Median	0.83	5.33	4.98	5.19	5.18	5.24	5.42	5.54	4.86
Mean	0.89	5.80	5.53	5.71	5.74	5.63	6.11	5.76	5.15
StdDev	0.75	2.70	2.60	2.71	2.75	2.57	3.09	1.78	2.95

48. Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2100 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-5.61	13.25	12.51	11.84	14.09	11.70	11.74	16.05	-0.99
2.50	-3.90	16.58	15.81	15.47	17.34	15.70	14.63	19.54	2.37
5.00	-2.21	19.86	19.83	19.39	19.00	19.35	18.21	22.44	6.15
10.00	-0.25	23.64	23.66	22.90	22.84	23.71	22.00	26.47	13.31
20.00	2.38	30.38	30.03	27.64	28.72	29.98	28.40	30.79	23.30
30.00	4.38	35.30	34.66	32.66	33.52	35.15	33.26	34.86	29.58
40.00	6.20	39.69	39.68	37.60	37.88	40.63	38.30	37.93	35.00
50.00	8.06	44.90	45.64	41.42	41.92	46.01	43.68	41.27	40.05
60.00	10.32	50.60	51.19	46.39	46.93	51.78	49.53	44.62	45.46
70.00	12.67	56.87	57.74	52.60	52.92	58.19	56.67	49.10	51.95
80.00	15.78	65.19	65.39	59.77	59.10	68.40	66.11	54.04	59.77
90.00	20.57	76.82	78.89	69.74	68.36	80.34	79.95	61.99	71.41
95.00	24.61	88.73	90.99	79.54	76.50	91.37	92.81	67.66	82.48
97.50	28.21	100.48	104.95	93.03	86.73	101.20	106.35	72.01	95.10
99.00	33.60	118.40	118.65	108.52	102.30	121.74	124.41	78.81	109.88
Median	8.06	44.90	45.64	41.42	41.92	46.01	43.68	41.27	40.05
Mean	9.39	48.53	49.13	44.87	44.65	49.63	48.50	42.75	42.18
StdDev	8.65	21.67	23.49	20.23	18.59	23.39	25.87	13.72	23.79

49. Greenhouse Contribution to Sea Level by Climate Reviewer, 1990–2200 (cm)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-8.67	32.40	22.59	32.01	34.06	29.78	27.06	40.49	-0.60
2.50	-5.42	43.35	39.77	40.30	41.70	39.55	36.64	46.63	5.34
5.00	-2.04	49.40	47.84	47.17	48.17	48.55	46.06	53.50	14.87
10.00	1.21	62.22	66.81	57.86	57.23	66.15	57.89	61.43	32.79
20.00	5.94	78.00	88.11	74.35	72.37	85.58	75.13	72.32	59.56
30.00	10.91	93.67	109.70	88.27	83.54	100.64	91.23	82.16	77.44
40.00	15.57	109.41	131.68	100.94	95.61	118.23	110.25	89.17	92.54
50.00	20.32	126.84	154.71	115.58	108.78	141.36	126.84	96.95	108.37
60.00	26.37	143.81	178.64	132.00	122.79	161.97	148.44	104.73	126.52
70.00	31.93	167.55	205.08	152.17	138.85	195.87	174.85	113.90	149.02
80.00	38.98	196.57	249.08	175.32	158.74	228.89	216.48	126.52	181.83
90.00	51.61	242.18	317.11	215.59	197.21	287.00	284.68	145.29	237.34
95.00	65.06	295.55	370.09	270.32	232.10	354.23	342.70	159.70	297.46
97.50	78.43	348.57	430.31	333.60	263.60	421.85	424.52	177.99	357.57
99.00	102.08	453.22	529.82	405.23	338.84	561.67	578.21	193.48	447.37
Median	20.32	126.84	154.71	115.58	108.78	141.36	126.84	96.95	108.37
Mean	24.41	144.68	174.50	132.10	120.76	165.47	155.27	100.73	127.24
StdDev	22.41	87.60	109.00	81.14	64.22	114.42	112.69	32.74	96.00

50. Annual Greenhouse Contribution to Sea Level by Climate Reviewer in the year 2100 (mm/yr)

Cumulative %	Balling	Bretherton	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley	All
1.00	-0.74	2.12	2.11	1.91	2.14	1.95	1.37	2.46	-0.20
2.50	-0.57	2.55	2.50	2.39	2.63	2.38	2.08	2.89	0.30
5.00	-0.36	3.05	3.05	2.86	3.06	2.96	2.59	3.29	0.97
10.00	-0.03	3.70	3.90	3.40	3.60	3.80	3.28	3.81	2.01
20.00	0.33	4.59	4.98	4.28	4.45	4.82	4.24	4.56	3.55
30.00	0.69	5.46	5.90	5.07	5.05	5.75	5.09	5.16	4.57
40.00	1.01	6.29	6.87	5.75	5.71	6.52	5.94	5.57	5.41
50.00	1.28	7.13	7.85	6.44	6.35	7.44	6.95	5.95	6.20
60.00	1.55	8.00	8.93	7.39	7.10	8.44	7.96	6.44	7.11
70.00	1.87	9.23	10.25	8.34	7.97	9.82	9.30	7.05	8.17
80.00	2.41	10.44	12.17	9.64	9.05	11.59	10.81	7.70	9.59
90.00	3.14	12.53	15.20	11.30	10.66	14.12	13.97	8.61	11.95
95.00	3.73	14.95	18.54	13.42	12.18	16.26	17.07	9.53	14.46
97.50	4.38	17.67	21.61	15.61	13.60	19.15	20.28	10.30	17.27
99.00	5.24	20.53	24.97	19.40	16.21	24.59	26.65	11.10	21.18
Median	1.28	7.13	7.85	6.44	6.35	7.44	6.95	5.95	6.20
Mean	1.43	7.83	8.87	7.18	6.85	8.42	7.95	6.15	6.84
StdDev	1.29	3.95	5.04	3.80	2.92	4.91	6.34	1.87	4.64

D. RESULTS FROM SENSITIVITY ANALYSIS USING ALTERNATIVE EMISSIONS POLICIES AND/OR FIXING PARTICULAR PARAMETERS (using Schneider values for Climate coefficients)

51. Forcing, 1990–2100 (W/m^2)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	Fixed Emiss. 2100
1.00	2.51	2.25	1.82
2.50	2.71	2.55	2.25
5.00	2.91	2.83	2.67
10.00	3.12	3.09	3.05
20.00	3.40	3.47	3.56
30.00	3.57	3.77	3.99
40.00	3.78	4.02	4.36
50.00	3.98	4.37	4.91
60.00	4.17	4.69	5.41
70.00	4.37	4.96	5.87
80.00	4.59	5.30	6.37
90.00	4.86	5.77	7.16
95.00	5.13	6.09	7.71
97.50	5.43	6.56	8.29
99.00	5.87	7.06	8.91
Median	3.98	4.37	4.91
Mean	3.99	4.40	5.00
StdDev	0.69	1.03	1.58

52. Global Warming, 1990–2100 (°C)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Emiss. 2100
1.00	0.26	0.25	0.85	0.89	0.70	0.65	0.32
2.50	0.50	0.49	1.06	1.34	1.37	1.38	0.50
5.00	0.70	0.71	1.24	1.66	1.64	1.69	0.72
10.00	0.89	0.94	1.47	2.05	1.93	2.01	0.99
20.00	1.21	1.28	1.75	2.46	2.25	2.35	1.37
30.00	1.45	1.55	1.97	2.77	2.48	2.60	1.68
40.00	1.71	1.83	2.20	3.04	2.66	2.85	1.96
50.00	1.97	2.12	2.39	3.33	2.86	3.07	2.31
60.00	2.25	2.43	2.59	3.59	3.07	3.30	2.70
70.00	2.62	2.89	2.81	3.93	3.27	3.57	3.16
80.00	3.15	3.45	3.10	4.37	3.61	3.90	3.82
90.00	3.96	4.35	3.56	5.13	4.11	4.53	4.78
95.00	4.87	5.32	3.90	5.63	4.81	5.15	5.74
97.50	5.39	5.99	4.34	6.63	5.74	6.21	6.54
99.00	6.79	7.27	4.92	9.21	7.12	7.83	7.62
Median	1.97	2.12	2.39	3.33	2.86	3.07	2.31
Mean	2.28	2.47	2.46	3.52	3.01	3.23	2.66
StdDev	1.62	1.75	0.85	1.66	1.25	1.38	1.63

53. Global Warming, 1990–2200 (°C)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Emiss. 2100
1.00	0.50	0.50	0.82	1.22	1.96	1.81	0.45
2.50	0.86	0.88	1.39	1.71	2.41	2.37	0.77
5.00	1.09	1.10	1.74	2.53	2.82	2.79	1.01
10.00	1.43	1.49	2.12	3.07	3.17	3.24	1.43
20.00	1.87	1.99	2.70	3.98	3.67	3.83	2.10
30.00	2.24	2.40	3.15	4.65	4.01	4.26	2.64
40.00	2.64	2.81	3.60	5.25	4.32	4.64	3.22
50.00	3.09	3.33	4.00	5.85	4.59	5.02	3.86
60.00	3.51	3.87	4.44	6.45	4.88	5.35	4.75
70.00	4.19	4.64	4.88	7.07	5.17	5.76	5.67
80.00	5.25	5.80	5.42	7.90	5.62	6.24	6.88
90.00	6.49	7.21	6.20	9.06	6.18	7.09	9.27
95.00	7.88	8.84	6.88	10.03	6.72	7.66	11.32
97.50	8.88	10.00	7.41	10.80	7.20	8.09	13.06
99.00	10.95	12.04	8.18	11.66	7.75	8.93	15.53
Median	3.09	3.33	4.00	5.85	4.59	5.02	3.86
Mean	3.60	3.95	4.10	5.96	4.65	5.09	4.73
StdDev	2.22	2.50	1.59	2.30	1.29	1.58	3.28

54. Greenland Contribution to Sea Level, 1990–2200 (cm)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Polar Amplification	Fixed Shelf Melt
1.00	-3.10	-4.88	-2.97	-11.36	-3.90	-5.24	-1.25	-7.20
2.50	-0.51	-0.89	-0.54	-2.18	-0.94	-1.01	1.02	-1.23
5.00	0.46	0.40	0.92	0.72	1.07	1.14	2.38	0.46
10.00	1.72	1.85	2.58	3.52	3.42	3.54	3.71	1.87
20.00	3.80	4.03	5.47	8.28	7.46	7.97	6.08	4.31
30.00	5.98	6.39	8.34	12.95	11.11	11.78	8.51	6.88
40.00	8.28	9.08	11.44	17.79	14.83	15.80	11.37	10.17
50.00	11.48	12.45	14.73	23.29	18.38	19.70	15.06	14.45
60.00	15.17	16.94	19.20	30.05	24.12	25.91	19.17	19.90
70.00	20.12	22.30	24.43	40.55	31.35	34.11	25.00	26.24
80.00	29.79	32.52	33.97	58.62	42.73	47.73	34.40	38.80
90.00	50.23	57.75	50.79	85.49	63.09	72.90	53.05	68.68
95.00	72.89	85.35	73.77	114.99	89.34	98.13	78.69	105.33
97.50	99.18	110.41	103.23	155.30	118.29	133.75	100.98	135.70
99.00	152.78	163.42	156.88	204.99	177.22	192.69	128.44	184.60
Median	11.48	12.45	14.73	23.29	18.38	19.70	15.06	14.45
Mean	20.33	21.98	23.68	35.94	28.35	31.08	22.87	26.79
StdDev	26.91	30.17	23.85	35.63	29.12	31.94	23.48	35.98

55. Antarctic Contribution to Sea Level, 1990–2200 (cm)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Polar Amplification	Fixed Shelf Melt
1.00	-85.66	-85.32	-86.36	-86.42	-86.40	-86.41	-86.32	-89.06
2.50	-54.92	-54.86	-52.54	-52.60	-50.69	-50.56	-55.00	-59.40
5.00	-32.45	-32.37	-32.19	-32.03	-30.49	-31.11	-32.50	-34.17
10.00	-18.27	-18.34	-18.21	-17.09	-16.44	-16.41	-19.47	-17.64
20.00	-8.36	-8.16	-7.76	-6.25	-7.08	-6.84	-9.27	-7.10
30.00	-2.70	-2.52	-2.22	-0.79	-1.04	-0.89	-3.27	-2.06
40.00	1.12	1.47	2.47	7.03	5.08	5.97	0.42	2.49
50.00	8.03	8.36	9.72	15.91	14.16	15.00	7.19	8.85
60.00	16.75	17.29	17.64	25.18	22.33	23.22	15.58	17.17
70.00	24.56	25.37	26.46	34.96	32.07	34.03	24.16	25.15
80.00	39.21	40.82	40.41	58.15	51.99	54.48	36.67	35.10
90.00	67.56	71.70	70.39	108.79	96.15	101.33	64.42	49.46
95.00	112.47	117.74	113.00	161.15	145.50	152.59	99.90	68.14
97.50	160.00	165.92	153.85	259.87	237.64	245.56	158.73	85.80
99.00	312.73	320.75	250.21	432.36	360.28	367.75	241.42	114.74
Median	8.03	8.36	9.72	15.91	14.16	15.00	7.19	8.85
Mean	21.22	22.86	22.39	36.45	31.41	33.44	18.49	12.77
StdDev	63.53	67.88	64.75	91.53	82.45	86.13	56.11	34.36

56. Greenhouse Contribution to Sea Level, 1990–2100 (cm)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Polar Amplification	Fixed Shelf Melt
1.00	6.19	6.10	11.44	17.43	17.39	17.70	6.75	7.50
2.50	8.96	9.16	15.86	22.74	22.05	22.26	9.28	9.61
5.00	11.93	12.28	18.91	26.65	25.99	26.65	12.45	12.63
10.00	15.68	16.40	22.99	32.84	30.89	31.84	16.56	16.03
20.00	20.94	21.84	27.28	38.56	36.02	37.39	22.16	22.09
30.00	25.20	26.34	30.84	43.12	40.51	41.92	26.28	27.10
40.00	29.69	30.85	34.42	47.92	43.95	45.98	31.09	31.73
50.00	34.23	36.20	37.87	52.52	47.57	50.28	36.20	36.93
60.00	39.69	41.83	41.09	56.26	51.02	53.72	42.50	41.61
70.00	46.23	48.30	44.19	60.83	55.42	58.13	48.24	48.64
80.00	55.17	57.86	48.98	66.45	61.36	63.96	57.86	57.79
90.00	69.05	72.90	56.28	77.82	71.36	74.57	71.34	71.95
95.00	80.92	84.02	65.69	87.91	81.01	84.75	82.18	84.53
97.50	94.33	98.25	73.29	101.69	94.64	98.78	95.94	96.44
99.00	114.67	116.39	91.37	127.37	119.32	122.55	115.84	111.48
Median	34.23	36.20	37.87	52.52	47.57	50.28	36.20	36.93
Mean	39.38	41.17	39.47	55.05	50.35	52.98	40.99	41.23
StdDev	24.21	24.71	15.93	27.79	21.21	26.47	23.43	23.54

57. Greenhouse Contribution to Sea Level, 1990–2200 (cm)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	$\Delta T_{2x}=2.6$	$\Delta T_{2x}=4.0$	Fix Emiss.2025 and $\Delta T_{2x}=4.0$	Fix Emiss.2050 and $\Delta T_{2x}=4.0$	Fixed Polar Amplification	Fixed Shelf Melt
1.00	12.31	11.27	21.61	29.59	38.24	36.79	10.35	8.76
2.50	19.10	18.63	30.43	48.64	48.66	50.59	16.41	19.61
5.00	25.28	25.66	38.43	57.84	55.94	57.26	23.99	26.63
10.00	33.92	34.20	46.84	69.26	68.40	70.97	33.74	34.45
20.00	45.81	48.02	60.26	88.23	81.84	84.97	47.30	48.28
30.00	55.34	57.88	72.55	105.75	92.43	98.10	60.68	62.87
40.00	68.60	71.79	83.82	122.52	102.17	110.58	73.37	76.96
50.00	79.10	85.13	96.57	140.37	113.93	124.05	91.42	92.67
60.00	94.39	100.48	108.57	158.21	125.92	137.23	109.17	109.67
70.00	114.66	126.41	123.00	178.84	142.41	153.63	134.13	131.95
80.00	144.06	156.05	142.65	210.27	167.13	179.21	169.31	167.54
90.00	194.98	212.99	184.40	268.68	216.99	233.43	230.99	218.39
95.00	242.92	252.97	235.53	341.12	278.49	291.52	274.72	265.20
97.50	301.47	318.53	296.95	412.93	332.70	372.00	339.43	309.72
99.00	458.03	470.70	381.07	563.71	453.67	499.95	405.36	384.61
Median	79.10	85.13	96.57	140.37	113.93	124.05	91.42	92.67
Mean	101.92	109.67	111.58	162.15	134.52	144.51	114.58	111.77
StdDev	87.91	96.10	80.14	115.73	96.09	104.72	90.19	84.50

58. Year by which Climate Contribution to Sea Level Exceeds 50 cm

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	$\Delta T_{2x}=2.6$	$\Delta T_{2x}=4.0$	Fix Emiss.2025 and $\Delta T_{2x}=4.0$	Fix Emiss.2050 and $\Delta T_{2x}=4.0$	Fixed Polar Amplification	Fixed Shelf Melt
1.00	2048	2048	2066	2052	2052	2052	2049	2050
2.50	2059	2059	2077	2061	2061	2061	2061	2060
5.00	2068	2067	2084	2067	2068	2068	2069	2069
10.00	2077	2076	2092	2074	2075	2074	2078	2078
20.00	2092	2089	2102	2081	2084	2082	2090	2090
30.00	2108	2103	2109	2087	2092	2089	2103	2102
40.00	2121	2116	2116	2092	2098	2095	2113	2114
50.00	2139	2131	2123	2097	2105	2100	2128	2127
60.00	2157	2148	2134	2103	2112	2107	2146	2143
70.00	2184	2177	2149	2113	2121	2116	2171	2168
80.00	>2200	>2200	2171	2124	2133	2128	>2200	>2200
90.00	>2200	>2200	>2200	2146	2155	2149	>2200	>2200
95.00	>2200	>2200	>2200	2177	2179	2174	>2200	>2200
97.50	>2200	>2200	>2200	>2200	>2200	2198	>2200	>2200
99.00	>2200	>2200	>2200	>2200	>2200	>2200	>2200	>2200
Median	2139	2131	2123	2097	2105	2100	2128	2127

59. Annual Greenhouse Contribution to Sea Level in the year 2100 (mm/yr)

Cumulative %	Fixed Emiss. 2025	Fixed Emiss. 2050	ΔT_{2x}=2.6	ΔT_{2x}=4.0	Fix Emiss.2025 and ΔT_{2x}=4.0	Fix Emiss.2050 and ΔT_{2x}=4.0	Fixed Polar Amplification	Fixed Shelf Melt
1.00	0.25	0.09	0.19	0.57	0.13	0.42	0.15	0.19
2.50	0.58	0.55	0.98	1.39	1.34	1.21	0.38	0.55
5.00	0.93	0.99	1.45	2.18	2.04	2.06	0.76	0.99
10.00	1.29	1.42	2.02	3.05	2.79	2.90	1.48	1.50
20.00	1.90	2.04	2.93	4.28	3.67	3.92	2.25	2.29
30.00	2.48	2.72	3.65	5.14	4.21	4.58	3.01	3.07
40.00	3.07	3.39	4.24	6.10	4.75	5.24	3.75	3.88
50.00	3.76	4.17	4.90	7.13	5.30	5.90	4.59	4.72
60.00	4.48	4.99	5.58	7.95	5.98	6.61	5.60	5.69
70.00	5.42	5.98	6.40	9.16	6.62	7.47	6.97	6.89
80.00	6.58	7.37	7.35	10.57	7.84	8.80	8.58	8.44
90.00	8.90	10.05	8.99	13.03	9.88	10.88	11.27	11.45
95.00	11.30	12.56	10.81	16.74	12.68	13.94	13.58	13.93
97.50	14.05	15.92	13.36	19.30	15.68	17.16	16.18	16.60
99.00	18.86	21.45	17.79	25.80	20.25	22.94	20.41	19.86
Median	3.76	4.17	4.90	7.13	5.30	5.90	4.59	4.72
Mean	4.64	5.13	5.42	8.03	6.13	6.78	5.62	5.69
StdDev	4.20	4.45	3.89	7.67	4.90	7.46	4.65	4.89

APPENDIX 2

1. Historic Contribution (1890–1990) from Various Sources According to IPCC (1990) (cm) (unreported result)

	Low	Best Estimate	High
Thermal Expansion	4.47	6.57	9.64
Small Glaciers	1.35	5.43	13.85
Greenland	0.26	1.17	2.69
Antarctica	-5.20	-0.52	0
Total	.88	12.65	26.18

Note: These results were not published in IPCC 1990. They were calculated using the Wigley & Raper (1992) version of the gas cycle and ocean models.

APPENDIX 3

MISCELLANEOUS INFORMATION CONCERNING ANTARCTIC ICE SHEET RESEARCH

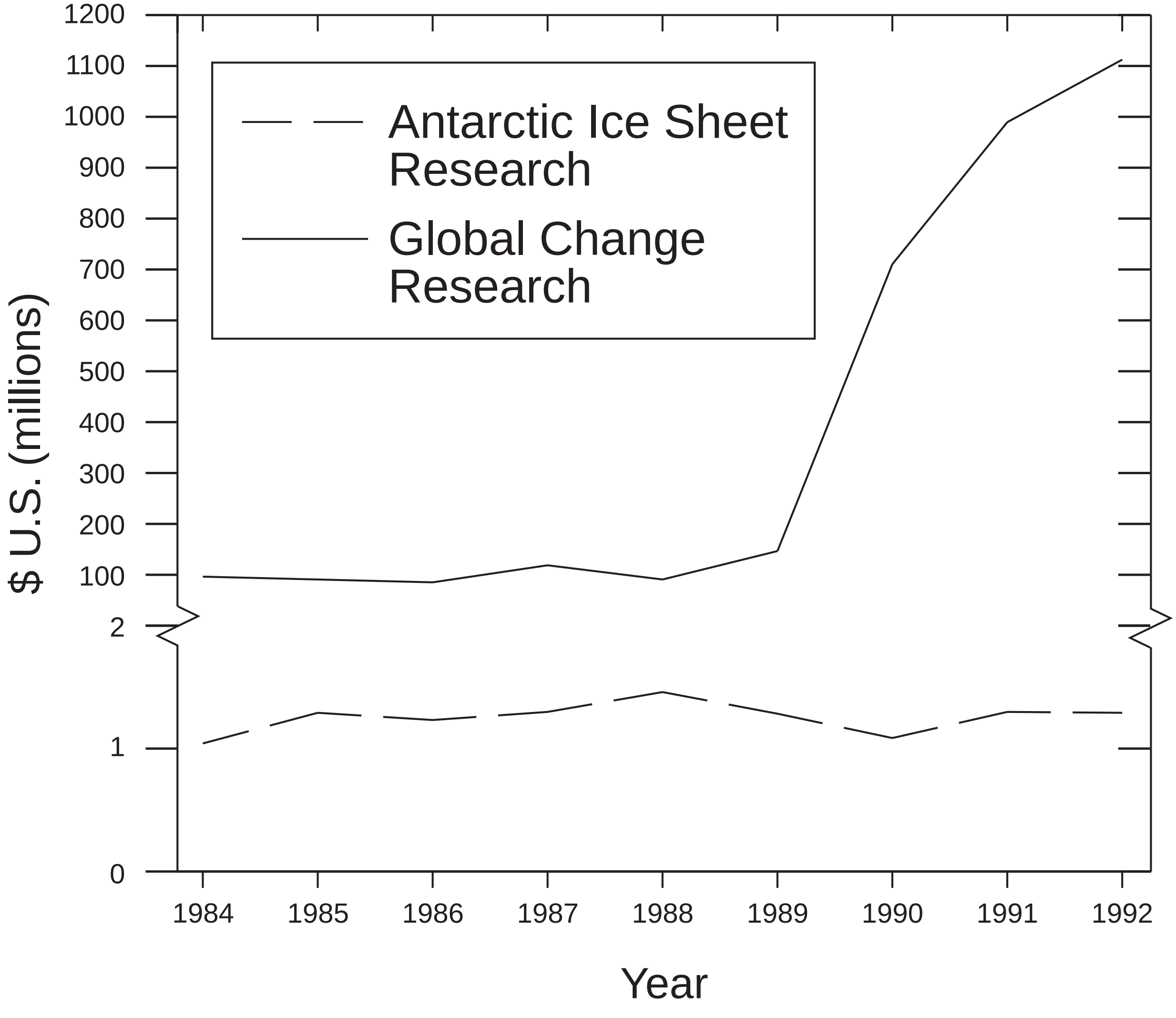

Figure A3-1. Failure of Ice Sheet Research Budgets to Benefit from Increased Global Change Research.

SOURCE: National Science Foundation; Annual Reports of the United States Global Climate Research Program Office and the predecessor National Climate Program Office.

October 1991

Dr. John Houghton, Chairman
IPCC Working Group I
Meteorological Office
London Road
Bracknell
United Kingdom

Dear Dr. Houghton:

We congratulate you on the contributions you have been making to the assessment of environmental implications of increasing greenhouse gases. Because we understand that you are considering possible revisions of the analysis, we would like to offer a number of comments on the chapter on sea level rise.

In 1985 the seven of us authored a National Academy of Sciences Report entitled "Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change" which provided perhaps the first comprehensive report on the possible contributions of land-based ice to future changes of sea level. From that experience, we are very sympathetic with the difficulties you face in attempting to develop low, medium and high scenarios of sea level rise. Given the lack of sufficient observations and validated models that describe how glaciers respond to changing climate, one must inevitably make assumptions based on far less evidence than one would like.

We are pleased that in a number of ways, the IPCC report went beyond our 1985 report. However, we are concerned by the conclusion that even in the worst-case scenario there will be no positive Antarctic contribution to sea level change.

Our 1985 report included three glacial modeling efforts, two of which projected the contribution from Antarctica to be less than 10 cm in the next century. The third study, by Robert Thomas of NASA, however, suggested that the contribution from Antarctica was likely to be 24 cm with a high scenario of about 80 cm and a worst case scenario of 220 cm. Considering all three modeling studies and the likelihood of increased snowfall over Antarctica, we concluded that the contribution of Antarctica to global sea level change by 2100 was likely to be between -10 and +100 cm, with values in the range 0 to 30 cm considered most likely. By contrast, the IPCC report appears to project an Antarctic contribution of -10 to 0 cm by the year 2100 (calculated using the equations on p. 276 and the temperature graph on page 190).

Our concern is that we do not believe there is any new evidence which justifies the implicit IPCC conclusion that we can project the Antarctic contribution to sea level change much more accurately now than we could in 1985. Specifically:

(1) There seems to be no new evidence indicating that the Thomas study is necessarily wrong. Certainly it relies on unproven assumptions, such as extrapolating data from a single ice stream to the rest of the continental margin. But so the IPCC report could be criticized; for example, although it takes great care in parameterizing large scale meteorology and simulating frozen-bed ice dynamics, it does not realistically simulate the wet-bed, sliding ice dynamics that dominate West Antarctica and parts of East Antarctica. Moreover, IPCC equations imply that global cooling of a few degrees would cause glaciers to retreat, in contradiction to empirical evidence. Also, note that Jenkins (1991) recently estimated that a warming of even 0.6˚C beneath the Ronne ice shelf could accelerate the basal melt rate from a current value of 0.5 meters per year to 2.5 meters per year; by contrast, Thomas' scenarios with 24-80 cm sea level rise were based on the assumption that the increase in basal melt rates would be only one meter per year.

(2) Several new results support the hypothesis that the West Antarctic ice sheet has a history of repeated rapid discharges. First, sea level records with increased temporal resolution (e.g., at Barbados) suggest repeated periods of rapid sea level rise, for which the only plausible mechanism would seem to be discharge of grounded ice. Second, the sedimentary record in the seas around West Antarctica reveals repeated advances and retreats of the ice sheet during the last 20,000 years. Third, diatoms collected under the ice sheet 700 km from the present margin indicate that site was an open marine environment at some time in the past 600,000 years, possibly during the previous interglacial period; most of the West Antarctic ice sheet must have disappeared for marine conditions to exist so far into the ice sheet interior. These results need to be considered along with recent observations of large rapid changes in the flow of parts of the West Antarctic ice sheet.

(3) No credible global climate model/ice sheet simulations have been carried out for transient changes next century. Indeed, in view of possible nonlinearities of some ice sheet processes with increasing global temperature, we do not believe we can reliably state the sign of Antarctic contributions to sea level change for the full range of climate change scenarios considered by IPCC.

In summary, although we do not have difficulty with a position that the Antarctic contribution to sea level change in the next century is likely to be small, possibly negative, we believe that there is still a large degree of uncertainty. We hope that this viewpoint can be represented in the revised IPCC analysis.

Sincerely,

Mark F. Meier

David G. Aubrey
Charles R. Bentley
Wallace S. Broecker

James E. Hansen
W. Richard Peltier
Richard C. J. Somerville