THE RISK OF SEA LEVEL RISE:*

A Delphic Monte Carlo Analysis in which Twenty Researchers Specify Subjective Probability Distributions for Model Coefficients within their Respective Areas of Expertise

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Abstract. The United Nations Framework Convention on Climate Change requires nations to implement measures for adapting to rising sea level and other effects of changing climate. To decide upon an appropriate response, coastal planners and engineers must weigh the cost of these measures against the likely cost of failing to prepare, which depends on the probability of the sea rising a particular amount.

This study estimates such a probability distribution, using models employed by previous assessments, as well as the subjective assessments of twenty climate and glaciology reviewers about the values of particular model coefficients. The reviewer assumptions imply a 50 percent chance that the average global temperature will rise 2°C degrees, as well as a 5 percent chance that temperatures will rise 4.7°C by 2100. The resulting impact of climate change on sea level has a 50 percent chance of exceeding 34 cm and a 1% chance of exceeding one meter by the year 2100, as well as a 3 percent chance of a 2 meter rise and a 1 percent chance of a 4 meter rise by the year 2200.

The models and assumptions employed by this study suggest that greenhouse gases have contributed 0.5 mm/yr to sea level over the last century. Tidal gauges suggest that sea level is rising about 1.8 mm/yr worldwide, and 2.5-3.0 mm/yr along most of the U.S. Coast. It is reasonable to expect that sea level in most locations will continue to rise more rapidly than the contribution from climate change alone.

We provide a set of 'normalized' projections, which express the extent to which climate change is likely to accelerate the rate of sea level rise. Those projections suggest that there is a 65 percent chance that sea level will rise 1 mm/yr more rapidly in the next 30 years than it has been rising in the last century. Assuming that nonclimatic factors do not change, there is a 50 percent chance that global sea level will rise 45 cm, and a 1 percent chance of a 112 cm rise by the year 2100; the corresponding estimates for New York City are 55 and 122 cm.

Climate change impact assessments concerning agriculture, forests, water resources, and other noncoastal resources should also employ probability-based projections of regional climate change. Results from general circulation models usually provide neither the most likely scenario nor the full range of possible outcomes; probabilistic projections do convey this information. Moreover, probabilistic projections can make use of all the available knowledge, including the views of skeptics; the opinions of those who study ice cores, fossils, and other empirical evidence; and the insights of climate modelers, which may be as useful as the model results themselves.

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1. INTRODUCTION

In the last decade, projections of accelerated sea level rise resulting from a greenhouse warming have prompted some coastal zone managers to modify activities that are sensitive to sea level. In response to the potential consequences of a 30 cm rise, the (U.S.) State of South Carolina enacted a Beachfront Management Act[1] sharply curtailing shorefront development; and the State of Maine limits development in any area that would be eroded by a 90 cm rise.[2] Land reclamation projects in San Francisco and Hong Kong now include a safety margin for accelerated sea level rise, as do new seawalls in eastern Britain and the Netherlands (Nichols and Leatherman 1995). A new treaty requires many nations to develop and implement measures adapting to sea level rise and other consequences of global climate change;[3] and the Intergovernmental Panel on Climate Change (IPCC) has called on all coastal nations to implement plans preparing for sea level rise within the next decade (IPCC 1990b).

Many of these actions were taken in response to studies published during the mid-1980s which estimated that sea level would rise 50-200 cm by the year 2100,[4] based on the assumption that global temperatures will warm 4°C in the next 75-100 years. During the 1990s, more thorough assessments by IPCC (1990a; 1992) and Wigley & Raper (1992) *[hereinafter* 'recent assessments'] have helped to foster a consensus that the rate of sea level rise will increase in the next century, and that coastal nations should prepare. But those studies have also reduced the 'best estimate' from one meter[5] to approximately half a meter.

Some glaciologists, however, believe that a much larger rise is possible, albeit unlikely, due to the poorly understood impact of warmer temperatures on the West Antarctic Ice Sheet (*see e.g*.[6] Bindschadler et al. 1990). While early sea level assessments (e.g. NAS 1985; Hoffman et al. 1983) probably overestimated this risk, recent reports may have made the opposite mistake by failing to communicate this risk at all. As long as one is limited to low, medium, and high scenarios, one must either include this risk in the high scenario while knowing that some people will overreact, or exclude it and thereby fail to warn coastal planners, engineers, and policy makers of an important risk.

The difficulty of interpreting what is meant by 'high scenario' led the U.S. National Academy of Engineering (Dean et al. 1987) to recommend that assessments of sea level rise provide probability estimates. Explicitly or implicitly, one must convert a scenario into a probability estimate before one can decide whether the risk warrants a particular action. Coastal engineers regularly employ probability information when designing structures for floods; and courts use probabilities to determine the value of land expropriated by regulations.

This paper estimates the probability distribution of future sea level rise implied by the subjective assessments of 20 climate and glacial process modelers regarding particular processes on which they have developed some expertise. The next section (2) discusses our methods. We then discuss (3) the motivation, limitations, and implications of our methods in more detail. After that, we present (4) the

[1] S.C Code §48-39-250 et seq.
[2] Coastal Sand Dune Rules. Code Me. §355.
[3] United Nations Framework Convention on Climate Change. Art. IV, §1(b).
[4] E.g. U.S. Environmental Protection Agency. 1983. 'Protecting Future Sea Level Rise'. The commonly cited 50-200cm range was based on a composite of NAS 1985 (glacial contribution of 10-160 cm) and NAS 1983 (nonglacial contribution of 40 cm).
[5] See e.g. IPCC (1990c) at 1. (Based on the existing literature, the studies have used several scenarios .. [including] a sea level rise of … about 1 m by 2100.").
[6] When a proposition in the text is clearly stated by a study, we simply cite the study without a signal. When the proposition is a logically necessary implication of what the study says, we introduce a proposition in the study cited, we introduce the report using the signal *cf*. When the proposition in the text is contradicted by a study, we use the signal *but see*. Finally, when the study is one of several studies that would support the proposition in the text, we use the signals *e.g.*, *see e.g.*, or *cf. e.g.*, as appropriate.

models and the assumptions of particular reviewers. Finally, we summarize (5) the results from combining all the models and reviewer assumptions; and (6) present a procedure for projecting sea level at particular locations. We conclude with a brief sketch of the implications of this study.

2. METHODS

Our goal was to estimate a probability distribution of future sea level rise to be used by coastal planners, engineers, lawyers, and policy analysts. Doing so required us to obtain existing models; develop new models to handle processes ignored by previous IPCC projections; write software to carry out the computations and process the output data; convince experts who had never done so to specify probability distributions for various climate parameters; and put all the simulations and opinions together to provide a single probability distribution. Given our budget of $100,000,[7]no part of this study will satisfy every expert.

Although our resources were insufficient to undertake a flawless assessment, they were sufficient to estimate a probability distribution that improves the current practice, in which economists and coastal engineers essentially pull numbers ‘out a hat’ by looking at the *results* of previous sea level assessments. At the very least, the calculated distribution can be based on the uncertainties surrounding the various processes that *contribute* to our overall uncertainty. Even if one of us–an economist– does the guesswork in defining the constituent uncertainties, such an analysis–which we call Phase I–is a step forward: Results can be based on the same models that people already use to project sea level; reviewers can examine particular parameters and comment on whether the uncertainty is reasonably described; and the analysis can be modified over time as new information on particular processes accumulates.

But why should economists, coastal planners, or engineers do the guesswork at all? There are scientists who have spent most of their careers analyzing the particular processes involved; surely it would be better to base decisions on their informed guesswork than on an economist's reading of the literature. That analysis--which we call Phase II–is a further step forward, since it is based on the judgments of experts in various fields.[8]

Thus, our study differs from recent assessments in two fundamental respects. First, we specified *probability distributions* for each model coefficient, rather than following the usual procedure of picking low, medium, and high values. (*See* Titus and Narayanan (1995) [*hereinafter* ‘T&N’]). Second, we circulated the draft report of that analysis [hereinafter "draft"] to various expert reviewers qualified to render judgments on particular processes, and obtained *subjective probability distributions* for the values of the various model coefficients.

This section discusses general methodological issues for each of the two phases of the study, including (2.1.1) our specifications of models and parameters, (2.1.2) our computational algorithms, (2.2.1) how we obtained the reviewer assessments, and (2.2.2) how we combined the opinions to develop our final results.

2.1 PHASE I: THE DRAFT MONTE CARLO ANALYSIS

2.1.1 Specifying Models and Parameter Distributions

Like recent assessments, our analysis assumes that anthropogenic emissions increase the atmospheric concentrations of greenhouse gases (and offsetting aerosols); the net effect is to increase the radiation

[7] This figure includes contracting and EPA staff time for the substantive work; it excludes the costs of revising and editing the final report.

[8] As a practical matter, out own specification would have less credibility because one of us had spent over a decade advocating strategies for adapting to sea level rise (*see e.g.* Titus, 1984, 1991, 1994). Moreover, this approach could help future efforts by motivating glaciologists to think probabilistically about the processes they study.

received at the earth's surface. The additional radiative forcing[9] warms the land and sea surfaces, which in turn raises sea level due to the expansion of ocean water and the melting of glacial ice.

To the extent possible, we used existing models; where no model was available to describe a particular process, we developed our own specification. Figure 1 illustrates the relationships between the various models we used or developed. Existing models were available to capture the relationship between emissions, concentrations, radiative forcing, global temperatures, and thermal expansion, provided that one was willing to assume no change in the rate of oceanic upwelling; we developed simple models of how upwelling might change so that we could relax that assumption part of the time.[10]

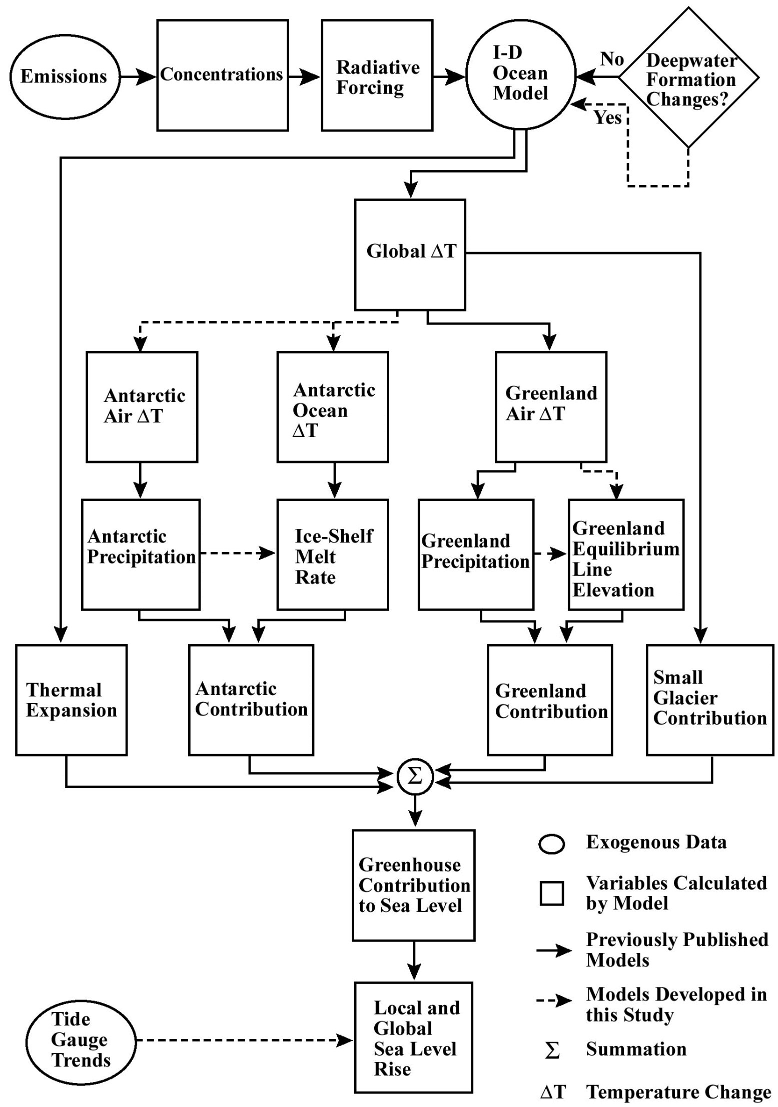

Figure 1. **Relationship between the models we used to project sea level.**

[9] This paper follows the IPCC convention of using the term 'radiative forcing' to refer to the *increase* in radiation striking the earth's surface. See IPCC (1944) at 169 ("in a global and annual mean sense the surface and troposphere are so closely coupled that they behave as a single thermodynamic system"). The standard definition of forcing, by contrast, is the imbalance between incoming an outgoing radiation at the tropopause or top of the atmosphere.

[10] We added additional models in the second phase, based on the expert reviews. After this manuscript was submitted, IPCC (1995a) adopted a variation of one of those models in its projections.

As Figure 1 shows, the linkages between global temperatures and the potential contribution of the polar ice sheets had not been completely modeled when we began our effort. Models were available, for example, that showed the potential impact of ice-shelf melting on the Antarctic contribution to sea level; but we had to develop equations to express the impact of global warming on the ice shelf melt rate; we also developed additional models of the Antarctic contribution, based on criticisms of the existing models. For Greenland, we specified equations to describe the impact of higher temperatures on the elevation at which snowmelt can run off to the sea (rather than refreeze in place). Finally, we developed a procedure to estimate relative sea level at specific locations, in light of local subsidence and the inability of climate change models to explain more than about one-third of the historic rate of global sea level rise.

In deciding which processes to include, we were guided by a goal of estimating the rise in sea level with at least a 1 percent chance of occurring (*hereinafter* '1%-high'). We doubted that we could address more remote risks without a considerably greater degree of process modeling. Moreover, this probability level also seemed appropriate for practitioners. The Dutch flood-control system, for example, is designed for the one-in-10,000-year storm, which has a 1 percent chance of occurring in a given century; in the United States, engineers generally focus on the 100-year storm. Thus, we deliberately excluded contingencies that could conceivably occur but that are generally viewed as much less than 1 percent likely, such as a runaway greenhouse effect or the possibility that the West Antarctic ice sheet might collapse soon for reasons unrelated to global warming. *See* Bindschadler (1990); *cf*. MacAyeal (1992).

We specified probability distributions for 35 model parameters based on the literature.[11] We generally assumed the shapes of the distributions to be lognormal, unless the parameter could plausibly take on negative values, in which case we usually assumed a normal distribution. For processes where we used two or more alternative models (e.g. impact of warming on upwelling), we also specified the probability of each model, based on our own subjective assessment of how the scientific community would allocate probabilities among the various particular models.

Although most parameter values were assumed to be independent, we did allow for functional correlations between some of the parameters. For example, our equilibrium polar temperature amplification parameters for antarctic air (P_{ant}) and water (P_{cdw}) were assumed to have a 0.5 correlation.

Our overall approach for specifying probability distributions was to treat published estimates as if they represented independent observations[12] from an underlying distribution. If there were two published estimates of a parameter, for example, we usually treated them as σ-low and σ-high limits; if there were six published estimates, we calculated the mean and standard deviations of the observations, and based the distribution on those parameters. Wherever the literature seemed to suggest that the value of a parameter is surely within a particular range, we treated the range as 2 σ limits.

In two cases, we simply adopted a consensus range that had been developed by previous studies. Since NAS (1979), there has been a broad consensus that the impact of a CO_2 doubling would be to raise the earth's average temperature in equilibrium by 1.5–4.5°C. For the last four years, governments have agreed to focus on the six IPCC (1992) emissions scenarios. We saw no reason to expect that we could improve on those ranges, which have been so carefully scrutinized over the years.

Unlike previous assessments, we report all results through the year 2200, rather than stopping at the year 2100. Both Antarctic Ocean warming and the resulting impact on ice sheets are likely to have response times of at least a century. As a result, stopping the analysis at the year 2100 could erroneously convey the impression that there is no significant risk that greenhouse gases could cause a major Antarctic

[11] *See* T&N for a discussion of the actual parameter values we picked and the sea level rise projections that resulted from those values. This paper examines only the parameter values picked by the reviewers.

[12] Our primary motivation for this assumption was that it is operational and transparent. In some cases, two different estimates truly are independent, as when two estimates are based on two different ice cores, or one estimate is based on fossil evidence while the other is based on a general circulation mode. In many cases, the observations rely on at least some common data and as such are not truly independent; in those cases, our approach understates uncertainty.

contribution to sea level. Inclusion of 200-year results is consistent with the IPCC policy assessment[13], as well as recent coupled ocean-atmosphere (Manabe and Stouffer 1993) and economic (Cline 1992) studies. Although the most substantial impacts of warmer temperatures on sea level would probably take at least 500 years,[14] extending the analysis out that far would have taken it beyond the time horizon of virtually all decision-makers.

2.1.2 Computational Algorithms

Given the models and the assumed probability distributions of the 'input' parameters, we required a procedure by which to estimate the probability distribution of the "output" variable, sea level rise. Because the models are complex nonlinear functions, it is impossible to analytically solve the equations to calculate the probability distribution of sea level rise; so we had to pick a procedure for numerically approximating this distribution. Considering the tradeoff between accuracy and computational time, we decided that a numerical standard error of about 1 cm for the year 2100 was sufficiently accurate.

We considered three numerical algorithms. The simplest approach, which we decided was sufficient, is the standard Monte Carlo technique in which parameters are randomly drawn from the underlying multivariate distribution. By running 10,000 simulations, the numerical error of the 1%-high projection was slightly less than 1cm[15]; the numerical error for more likely scenarios was substantially less.

We also considered, but rejected, the 'Latin Hypercube' and "Importance Sampling" methods. Latin Hypercube would have required us to increase the number of simulations by one or two orders of magnitude, and modify the standard algorithm.[16] Compared with the high cost of this approach, we saw little benefit: The method is designed to capture the overall probability distribution; our concern was on the upper tails of the distribution.

Importance Sampling was a closer call. For estimating the 1%-high scenario, Monte Carlo "wastes" 80-90 percent of the simulations on parameter values within the middle and lower end of the range. Importance Sampling allows one to deliberately avoid some of this waste by (1) dividing a distribution into alternative fractiles (e.g. top 10 percent and bottom 90 percent), and (2) sampling more parameter values from the fractile that would result in the highest risk (Clark 1961).

Unfortunately, with our 35 parameters, Importance Sampling would have required 2^{35} (over 35 billion) different subsamples; even if we only subdivided the ten most important variables, we would have required more than 4000 difference subsamples, which would probably imply 100,000 simulations. Monte Carlo, by definition, gave us 100 simulations in the top 1 percentile with only 10,000 runs. Had we been interested in the one-in-ten-thousand risk, our desire to avoid running the model a million times would have made Importance Sampling more appealing.

2.2 PHASE II: INCORPORATING EXPERT JUDGMENT

2.2.1 *Obtaining the Subjective Assessments*

Using the aforementioned algorithm, models, and parameter distributions, we calculated the probability distribution of future sea level rise. Because the input distributions reasonably represented

[13] *See* IPCC (1995c), Chapter 6.
[14] *See e.g.* Harvey (1994); Lingle (1985). For further discussion of the adjustment times of our models, *see* T&N at 23-29 (thermal expansion continues for over 500 years after CO_2 doubling); *Id.* At 48 (several reviewers project circumpolar ocean warming to lag warming elsewhere by about a century); and *Id.* At 96-99 (Thomas model implies that rate of ice cream contribution increases for several centuries in response to increased melt rates).
[15] This estimate was based on the standard error of the 1%-high estimate from eight successive subsamples of 1250 simulations.
[16] Latin Hypercube divides each distribution into several equiprobable fractiles, and samples on value from each (McKay et al., 1979). The ocean- and antarctic-model-selection parameters, however, can not be divided into equiprobalbe intervals, because the models are not equally probable.

existing knowledge, the resulting probabilities from Phase I would have been an improvement over the sea level assumptions that coastal decisionmakers had been using. Nevertheless, we decided at the outset that the final results should not be based on our own specifications.

Hence, we sought subjective assessments of the probabilities of various models and model coefficients from the people most qualified to render judgments on particular processes, including authors of a 1985 assessment by the National Academy of Sciences' Polar Research Board (NAS 1985) and the chapters on transient temperatures and sea level rise in the IPCC (1990) assessment. In addition, we sought representatives from two groups whose thinking has been excluded from recent assessments: (1) climatologists who expect that the warming from greenhouse gases will be trivial (*e.g.* Michaels et al. 1992; Balling et al. 1990) and (2) glaciologists who believe that warmer temperatures may lead to a collapse of the West Antarctic Ice Sheet.

Table 1 lists the reviewers who provided subjective probability distributions. The eight climate reviewers include both the father of one-dimensional upwelling-diffusion models (Hoffert) and the most prolific practitioners of that art (Wigley & Raper), to whom the IPCC has turned year after year. They also included the principal architect of the GFDL three-dimensional general circulation model (Manabe), one of the senior contributors to the GISS model (Rind), a former Deputy Director of the National Center for Atmospheric Research (Schneider), and the Director of the U.S. Global Change Research Program (MacCracken). The glaciology reviewers included the chairman of the Polar Research Board at the time of the NAS (1985) report (Bentley), the authors of two of the three ice sheet models that the NAS panel reviewed (Thomas and Lingle), the author of the first model of the Greenland contribution and primary organizer of ice sheet research strategies (Bindschadler), the only nongovernmental U.S. researcher to estimate sea level rise (van der Veen), the first researcher to publish results on satellite altimetry of Greenland (Zwally), and a member of the team that has recently used ice core data to show that polar precipitation may rise much less than is commonly assumed (Alley).

We provided each of the reviewers with the 200-page draft, which included a table of all the parameters and the distributions that we had selected. We asked the reviewers to edit the table to reflect the values that they would have preferred (for their particular areas of expertise) and to provide any other suggestions that they thought were appropriate. Five of the reviewers wrote back with their suggested distributions; thirteen read the report but did not provide distributions until we called and asked them; one did not read the report but still answered our questions over the phone; and one reviewer (Bretherton) read the report and concluded that our initial specifications were close enough. Six reviewers also suggested model specifications that had not been included in our original draft. After obtaining the reviewer specifications, we shared with each reviewer our proposed text[17] detailing the assumptions of each reviewer and the resulting calculations. We also made changes in those cases where the reviewers changed their minds regarding the likely distributions.

2.2.2 *Combining Reviewer Opinions*

If every reviewer had provided an assessment on every parameter, we could develop twenty different estimates of sea level rise, report all of them, and let the reader decide which to use. With the exception of Wigley & Raper, however, the reviewers only provided opinions on the subset of parameters that they had studied. The parameter specifications suggested by the various reviewers could potentially leave us with two hundred different probability distributions of future sea level rise: The Manabe climate assumptions, for example, could be coupled with eight different sets of Antarctic parameters, each of which could be coupled with four different precipitation assumptions. For this reason, we had to devise a procedure for combining the different reviewer opinions, before we could calculate the probability distribution of sea level rise.

[17] Eventually published as sections entitled ‘Expert Judgement’ in T&N.

Table I. Reviewers Who Contributed to This Analysis

Global climate and polar temperature assumptions	
Robert Balling	Arizona State University
Frances Bretherton	University of Wisconsin
Martin I. Hoffert	New York University
Michael MacCracken	U.S. Global Change Research Program
Syukuro Manabe	NOAA/Princeton Geophysical Fluid Dynamics Laboratory
David Rind	NASA/Goddard Institute for Space Studies
Stephen Schneider	Stanford University
Sarah Raper[b]	University of East Anglia
Tom Wigley[b]	University Corporation for Atmospheric Research
Polar precipitation assumptions	
Richard Alley	Pennsylvania State University
Michael Kuhn	Innsbruck University
Mike MacCracken	Lawrence Livermore National Laboratory
David Rind	NASA/Goddard Institute for Space Studies
Stephen Schneider	Stanford University
Jay Zwally	NASA/Goddard Space Flight Center
Antarctic assumption	
Richard Alley	Penn State University
Anonymous	University Professor
Charles Bentley	University of Wisconsin
Robert Bindschadler	NASA/Goddard Space Flight Center
Stan Jacobs	Lamont Doherty/Columbia University
Craig Lingle	University of Alaska
Robert Thomas	NASA/Greenland Ice Core Project
C.J. van der Veen	Ohio State University
Jay Zwally	NASA/Goddard Space Flight Center
Greenland Reviewersa	
Walter Ambach	University of Innsbruck (Austria)
Robert Bindschadler	NASA/Goddard Space Flight Center
Roger Braithwaite	Geological Survey of Greenland (Denmark)
Mark Meier	University of Colorado
Robert Thomas	NASA/Greenland Ice Core Project
T.Wigley and S. Raper	University of East Anglia
Jay Zwally	NASA/Goddard Space Flight Center

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

[b] Wigley and Raper provided a joint review based on their revisions to an unpublished analysis initiated by Richard Warrick, lead author of the IPCC (1990; 1995) sea level chapters. Wigley relocated to UCAR while this study was under review.

For reasons discussed in section 3, we chose the simplest approach: weighting all reviewer assumptions equally. The next question was whether to develop a composite distribution for each parameter. We decided against that approach. Instead, a given simulation used all the climate parameters from a particular climate reviewer, all of the antarctic assumptions from a particular antarctic reviewer, and all the precipitation assumptions from a particular precipitation reviewer.

Our approach preserves the "consistent visions" of individual reviewers; in effect, we assume that there is information in the unstated functional correlations between parameters, across reviewers. For example, only one reviewer specified a correlation between Greenland warming and upwelling; but the reviewers who expect upwelling (and deepwater formation) to decline generally expect less Greenland warming than those who do not expect such a decline (or believe an increase to be possible as well). Given the relationship between deepwater formation and North Atlantic temperatures, this functional correlation across reviewers was worth preserving.

3. MOTIVATIONS, LIMITATIONS, AND IMPLICATIONS OF OUR METHODS

Probability and frequency are not the same thing. This generation will only warm the planet once; the experiment can not be repeated. So the meaning of (and the method of calculating) the probability of sea level rise is different from a weather forecast, where an estimate of the probability of precipitation is based on empirical observations of how frequently rainfall occurs after particular meteorological conditions.

A projection does not have to be literally true to be useful; it merely has to be better than what one would otherwise use. For example, the macroeconomic projections that national legislatures use to set taxing and spending policies are often filled with erroneous assumptions. Nevertheless, they generally consider the next recession, the subsequent economic rebound, and long-term economic growth. As such, these projections enable professionals in one field (macroeconomics) to provide professionals in another field (budget analysis) with assumptions that are imperfect but superior to the constant-revenue assumption that the budget analysts would otherwise provide the Legislature.

Given the interdisciplinary nature of this journal, this section begins by (3.1) outlining some decisions that require estimates of the probability of sea level rise. Next, we present (3.2) our reasons for weighting all the reviewer estimates equally, as well as (3.3) some criticisms of that approach. Finally, we discuss (3.4) why our approach should be applied to projections of regional climate change.

3.1 DECISIONS AFFECTED BY SEA LEVEL RISE

Many people who follow the climate change issue view the decision regarding when and how to reduce greenhouse gas emissions as the only important decision that depends on projections of future climate and sea level. Readers with that perspective may be disappointed that we do not focus on the impact of alternative energy consumption scenarios on the probability of sea level rise.[18] But decisions regarding emission reductions are not likely to depend anytime soon on whether a 1 meter rise in sea level has a 1% or a 15% chance of occurring. While such an analysis may be interesting--and better assessment methods are always welcome--low and high projections are probably sufficient for these purposes.[19]

Coastal decision makers, by contrast, need probability information. Eventually, the greatest need may occur as the private and public sectors take measures to ensure that rising sea level does not eliminate wetlands and beaches (See EPA 1989, Maine 1994). Courts and government agencies will have to calculate the financial costs from altering the bundle of rights that accompany land ownership.

Consider, for example, the economic loss that one suffers from transferring to someone else a rolling easement, that is, the right to take over a parcel of land whenever the sea rises by a particular amount. [20] A

[18] Nevertheless, section 5 briefly presents results for a few alternative emission scenarios.
[19] Even with these projections, decision makers have a more precise understanding of the consequences of sea level rise than the impacts of climate change on agriculture, forests, water supplies, terrestrial ecosystems, and human health.
[20] A rolling easement is a title to a narrow strip of coastal property – often the intertidal zone but potentially including land above the high water mark – which migrates inland as the shore erodes. The easement gives the owner the right to prevent the abutting land owner from erecting a bulkhead or otherwise holding back the sea. The net effect of a rolling easement is to transfer the risk of sea level rise from the public to the private land owner, by giving migrating ecosystems the right of way over coastal structures.

developer who tries to win the acquiescence of environmental groups by donating a rolling easement to a conservancy would presumably claim the donation as a charitable gift and need to prove the value of that donation to the Internal Revenue Service.[21] A state government that declares the publicly owned shoreline to include a rolling easement, might be required to compensate certain property owners who had been told by the state that they have the right to build a bulkhead to stop the erosion.[22]

Given the procedures by which the courts calculate the value of contingent interests,[23] a consultant or expert witness will have to estimate the present expected value of the easement. Someone will have to plug a set of probability estimates into a formula.[24] Administrative agencies in the United States may only have to show that their approach is neither arbitrary nor capricious; but taxpayers may have to show that their estimate is more accurate than that of the Treasury Department. Until now, no study has provided this probability information.

Since the 1982 dissemination of EPA's first set of sea level rise projections (Hoffman et al. 1983), many coastal policies have been revised to incorporate the assumption that sea level will continue to rise. [25]Taking the next step and planning for an acceleration, however, has been stymied by the inability to know whether to plan for the low, medium, or high scenarios from recent assessments. Where policies have been based on an explicit projection, agencies have generally adopted the ‘best-guess’ estimate. [26]This approach is reasonable for land-use regulations, which involve little rigorous analysis and must withstand court challenges with demonstrations that they are not arbitrary or capricious. But the practice of using only the best estimate is less defensible when employed by engineers who are already using sophisticated models with storm frequencies to calculate the probability of structural failure.

Yet the literature has not assigned probabilities to the sea level projections, and coastal engineers have been reluctant to guess about probabilities that are rightfully within the province of climatologists and glaciologists. While this reluctance is understandable, the net effect is to assign a probability of 100 percent to the medium scenario. Some economists have not been so reluctant, especially when undertaking decision analyses that require probability estimates (*e.g.* Yohe (1991a and 1991b); drafts have been sent to us which assumed that the high scenario has a probability of anywhere from 5 to 25 percent. Although some of those estimates may be excessive, one can not fault economists for making guesses about parameters that they need.

The lack of probability estimates has forced previous EPA coastal decision assessments to equivocate. In the case of a coastal drainage system in Charleston, S.C., we calculated the ’break even’ probability of a one-foot rise in sea level in 40 years. If the probability is greater than 30 percent, then it is cost-effective to use larger pipes in anticipation of sea level rise; but until now no one could say whether or not the probability exceeds 30 percent (Titus et al. 1987). In the case of an eroding barrier island, if one expects the high scenario, cottages destroyed by storms should not be rebuilt; but if the low scenario is expected, they should be rebuilt (Titus 1984). When building a new house or rebuilding an old house, a homeowner's decision whether to haul in fill material depends on how much the sea is expected to rise.

[21] In the United States, land owners can deduct the value of deed restrictions or donations of contingent interests in land for conservation purposes, under Internal Revenue code (28 U.S.C.) §170 (f)(3)(B) and (h).
[22] Or perhaps the property owners will have to pay the state for allowing a bulkhead, given the common law’s determination that the shores are owned by the public. For a discussion of whether a rolling easement would require compensation, *see* Titus (1994).
[23] *See e.g.* Berger (1983) at 193-97 (discounting remainder interest in life estate according to interest rate and probability distribution of owner’s death).
[24] The formula for expected present value is:

$$PV = \sum_{t=t0}^{2200} V(t)\ \text{prob(Inundation in Year } t) / (1 + r)^{t-to},$$

Where PV is present value, $V(t)$ is land value in year t, t_0 is the current year, and r is the interest rate.
[25] But *see e.g.* Titus, 1991; 1994 (wetland protection policies are based on the assumption that sea level and shorelines are stable).
[26] E.g. Code Me. §355, design of Dutch Dikes, and San Francisco land reclamation standards.

As does the community's long-term decision whether to retreat or hold back the sea by pumping sand on the beaches and gradually raising land surfaces (Titus 1990a). We have tended to use the ‘illustrative probability’ of 1 percent to demonstrate that states could protect natural shorelines by purchasing rolling easements for $10/acre, with a caveat that the actual probability could be very different (Titus 1991; 1994).

These and other examples suggest that coastal decisionmakers need probability distributions that they can use with existing decision frameworks. Discussions of the diversity of opinion are interesting and helpful; but when it is time to declare the amount of the check or the height of the dike, a single number is required. This imperative has often led decisionmakers to ignore uncertainties and simply use the best estimate of future sea level rise. The use of a probability distribution in a cost-benefit framework allows decisions to reflect the uncertainty and diversity of opinion, and yet still provide a single bottom-line estimate.

For this reason, we made two departures from the approach that experts in the field of decision analysis might ordinarily expect. First, we developed a probability distribution of sea level rise that is not contingent on a particular emissions trajectory. To a coastal engineers seeking an answer to the question: "What is the probability that the sea will rise by a particular amount?" future emissions represent only one of many processes over which one has no control.[27]

Second, we provide a ‘bottom-line’ answer to the question, even though our aggregation procedure might be characterized as ‘quick and dirty’. As we discuss below, a few reviewers with expertise in decision methods have indicated that our priorities should have been reversed; that is, we should have followed a more methodologically pure approach even if doing so prevented us from answering the ultimate question.

3.2. AGGREGATION: CALCULATING THE BOTTOM LINE

How might we derive a single probability distribution, given the various expert reviewer opinions? We considered three approaches: (1) developing our own revised probability distribution for each parameter, informed by both the reviewer opinions and the literature (see Morris 1977); (2) attempting to forge a consensus regarding the probability distribution for each parameter; and (3) devising a procedure for weighting the information provided by each reviewer. We rejected the first option for reasons described in footnote 8, *supra*, and the accompanying text.

We initially intended to hold workshops to forge a consensus on each parameter. Even without these meetings, there was a consensus on many parameters. All but one of the Greenland reviewers agreed that using the Bindschadler model would be reasonable. The energy experts we contacted agreed that our emissions assumptions should be based on the IPCC (1992) scenarios because those projections represent a consensus among governments - developed after an expenditure of several million dollars and dozens of domestic and international meetings. For the climate- and antarctic-contribution parameters, there was a consensus on some - but not all - of the probability distributions.

Plans for convening a series of workshops were abandoned when EPA management decided that the resulting delays and costs would be unacceptable. We made some effort to develop a consensus by informing each reviewer about the opinions of the other reviewers, which led some of the researchers to modify their suggestions. But still there was a substantial variation of opinion on several parameters. Because most of the experts had based their proposed distributions on studies that they had published, and were generally familiar with the opinions of the other experts, additional iterations seemed unlikely to change opinions significantly, let alone forge a consensus.

[27] This is not to say that coastal decision makers in the aggregate will have no impact on emissions policies. But even there, incorporating sea level rise into one’s design may be the most important thing a planner or engineer can do to foster understanding of global warming.

Even if a consensus had emerged, it is unclear whether it would have been helpful. The process of developing a consensus often tends to emphasize points of agreement. Because points of *dis*agreement are often the issues about which uncertainty is greatest, the process can tend to understate our total level of uncertainty, by ignoring possible outcomes that a minority (or even a majority) may view as unlikely but possible. (*Cf*. Myers and Lamm 1975.) Recent assessments, for example, have excluded the minority perspectives of the greenhouse skeptics and those who expect a large Antarctic contribution to sea level. Although exclusion of minority perspectives from a *consensus document* may be appropriate, their exclusion from a *risk assessment* may convey to policymakers more certainty than actually exists.

Accordingly, we chose the third approach, mathematically combining the expert opinions. Given that decision, the next question was how to weight those opinions. A considerable literature has developed regarding methods for weighting reviewer opinions (*e.g*. Winkler 1968, 1971; Morris 1977). The most common approaches are equal weighting, self-rating by the experts, rating by an independent group, and rating by the analyst conducting the study. To a degree, our study involved self-rating: Experts often declined to provide parameter estimates where their own expertise was lacking.

Our general approach, however, was to weight all reviewer assessments equally.[28] Most importantly, the other approaches were infeasible. The reviewers were barely comfortable with ascribing probabilities to the various parameters; but at least those assessments were within their fields of expertise.

A rating of the experts by an independent body was out of the question due to the time and effort involved in assembling a second panel. We did not want to do the rating ourselves; doing so would have been essentially a "backdoor" means of involving ourselves in the parameter selection process, which we were attempting to avoid. Moreover, we wanted our results to flow as transparently as possible from the reviewer assumptions, rather than be obscured by a weighting scheme.[29]

3.3. CRITICISM OF OUR AGGREGATION PROCEDURES

The three reviewers to whom *Climatic Change* sent this paper agreed that the modeling and solicitation of expert opinions (section 4, *infra*) were useful and worthy of publication. However, two of three felt that presenting the combined opinions (section 5, *infra*) is not appropriate; one of the two objected to the aggregation so much that she recommended that this report not be published at all unless we agreed to remove our bottom-line results. We could not agree to that condition. After obtaining the concurrence of the other two reviewers, the Editor decided to allow us to report our bottom line results, provided that we discussed this methodological disagreement and put all combinations of reviewer opinions in a separate section.[30]

We commend Professor Elisabeth Paté-Cornell of Stanford University for identifying herself as the reviewer who objected so strongly, which allowed us to discuss the matter in some detail.

Professor Paté-Cornell believes that after obtaining the expert opinions, we should have undertaken additional iterations with the experts. She recognized that some differences of opinions are unresolvable; but weighting and combining the distributions is not an appropriate way to deal with these differences, she said, especially when all reviewers are weighted equally. Moreover, one should weight models and

[28] Morgan and Henrion (1990) review about a dozen different studies in which the author of a risk assessment weighted and mathematically combined the opinions of several reviewers. Some of those studies "have found little or no difference in the performance of various differential weighing schemes over simple equal weighting" *Id.* at 167.

[29] Furthermore, all but one of the reviewers provided opinions without requesting anonymity, "[T]he formal combination of expert judgements … becomes very awkward in open public sector applications …. The administrator of the EPA, or his surrogate, is likely to have difficulty publicly saying that he finds Dr. Jone's views six times more credible than Dr. Smith's views…". Morgan and Henrion (1990) at 167.

[30] Section 4 presents reviewer-specific opinions on particular parameters, as well as results not based on alternative reviewer opinions, such as projected radiative forcing; section 5 presents' results based on the models and the combined wisdom of all the reviewers.

parameter values not reviewer opinions. Our procedure makes the results too sensitive to the composition of the panel, because adding a reviewer can change the results. Once we had conducted such a review and the required number of iterations, the professor argued, we should have either specified the probability distributions ourselves, or only reported reviewer-specific results.

Paté-Cornell has correctly identified some limitations of this study. She is correct, for example, that our results are sensitive to the panel we pick.[31] But not all of her criticisms are accurate: Equally weighting reviewer opinions can be theoretically optimal[32]–besides being straightforward, transparent, and fair. Weighting models or parameter values is impossible without at least implicitly deciding how much weight to place on each reviewer opinion, and may yield mathematically equivalent results anyway. And additional iterations would probably not have been productive.[33]

But even if all of her criticisms were well founded,[34] our procedure is at least as reasonable as Professor Paté-Cornell's suggested course of action. Had we not combined reviewer opinions at all, we would have had to report two hundred different probability distributions, since there were two hundred different combinations of climate, precipitation, and antarctic reviewer opinions. (Only Wigley & Raper provided values for all the parameters necessary to project sea level). Even if it were possible to pare that set down to ten or twenty representative distributions, omitting the aggregation would not eliminate the need to resort to *ad hoc* calculations. Instead, it would pass the problem downstream to the users of this information, who would probably want to weight our results equally anyway. But except for the mean, the values of a probability distribution are not additive. To properly convert our results into a useful estimate, users would each have to perform their own Monte Carlo analysis. Because this would be too much work, they would probably simply take the average of the distributions, which is not even arithmetically correct.

Because the equal weighting of opinions is a common practice in practical situations, it was reasonable for us to apply this approach. By combining models with the subjective probability distributions of experts who each had a strong basis for their opinions, we made a more efficient use of the varying degrees of expertise among climate modelers, polar climate experts, and ice-sheet experts, than we would have made if we had simply estimated the parameters ourselves, given our preservation of consistent visions (*see* section 2.2).

The reviewer criticisms should help the reader to remain skeptical of this and any other projection of the impacts of changing climate; but they did not demonstrate that another procedure would have developed a better probability distribution given a $100,000 budget. Our inclusion of reviewer-based probabilities moves the body of literature in the direction that Professor Paté-Cornell would like to see; the reader interested in improving upon this study is welcome to use our models.

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[31] Nevertheless, we are in no position to declare whether a model is more likely or less likely than implied by support within the scientific community, given our premise that they are experts and we are not. Thus, proportionally is a reasonable, if imperfect, compromise.

[32] The approach would be optimal if each reviewer's opinion was based on an equal amount of independent information. (For example, if each reviewer had rolled an odd-shaped die ten times, the best estimate of the distribution would be based on an equal weighting of each observation and hence each reviewer opinion.) In some cases, drastically different opinions were based on independent information. For example, the polar amplification parameters (*i.e.* the ratio of polar warming to global warming, *see* Section 4.3.1, *infra*) have the greatest discrepancy across reviewers. Hoffert and Rind base their opinions on paleoclimatic data and the resulting large amplification; Manabe tends to believe his own model which shows small amplification.

[33] *See* Section 3.2, *supra*.

[34] For a more detailed account of our response, *see* various letters from Jim Titus to the Editor of *Climatic Change* concerning this paper.

3.4. PROBABILISTIC ASSESSMENT AS AN ALTERNATIVE TO GENERAL CIRCULATION MODEL OUTPUT

For a variety of reasons, people along the coast are beginning to prepare for the consequences of sea level rise, while those vulnerable to other consequences of global warming are not. While coastal engineers and planners are ready to rigorously analyze the costs and benefits of alternative designs and land use practices, researchers in other fields have identified few instances where taking adaptive measures now could be justified even under a pessimistic projection of future climate.[35]

Nevertheless, probability-based projections of other climate variables are urgently needed by those attempting to estimate the impacts of climate change on noncoastal systems. While high and low scenarios have been available for sea level rise since 1982, they still are not available for changes in regional climate. Instead, assessments of the impacts on agriculture, forests, and water resources generally use the outputs from three or four representative general circulation models (GCMs). The GCM scenarios do not necessarily span the entire range of uncertainty for particular regions,[36] and even when they do, the impact studies are unable to indicate which is the more likely outcome.

Like those studies, our estimates of sea level rise required regional projections of temperature and precipitation. For the same reason that we avoided reliance on GCM output, we believe that the time has come for impact assessments to shift toward the use of probability assessments that employ all available information. Doing so enabled us to include the insights of those whose opinions were based on fossil and ice-core data (e.g. Hoffert and Alley). We still included the information produced by the GCMs; but we found that modelers themselves (e.g. Manabe, Rind) generally had many insights not conveyed by their models, allowing them to both specify an uncertainty range and adjust model outputs for specific regions to account for factors left out of the model. Even conceding the limitations of our approach, probabilistic impact assessments would almost certainly be more reliable and more useful than studies based on point estimates of regional climate change from models that were not designed for that purpose.[37]

4. MODELING ASSUMPTIONS AND EXPERT OPINIONS

We now describe the models we used, the parameter distributions suggested by the reviewers, and some of the resulting probability distributions implied by the assumptions of individual reviewers. Opinions attributed to specific reviewers represent informal subjective assessments unless that reviewer provides a citation to a study. We discuss only the parameters where reviewer opinions differed and the difference had a significant impact on the results; for a complete discussion of all 35 parameters, see T&N.

[35] *Compare* Section 3.1, *supra* (enumerating current decisions that are sensitive to the probability of sea level rise) *and* IPCC (1990b) (same) *with* IPCC (1995b) (failing to identify policies that should be changed now even if the high scenario of climate change is expected, other than those relating to emission reduction and coastal infrastructure). *But cf.* Titus (1990b) (the risk of climate change may justify near-term legislation to (a) end water subsidies several decades hence (b) make all water rights marketable).

[36] *See e.g.* Smith and Tirpak 1989 at 297 (all scenarios of Great Lakes Basin have increase in annual rainfall, but also an even greater increase in evapotranspiration; hence all scenarios imply drop in Great Lake Levels).

[37] No criticism of the GCM models themselves is intended; the models are a necessary component of our understanding of the climate system; and in the spirit of interdisciplinary cooperation, the modelers have made their region-specific diagnostics available to impact researchers with appropriate cautions that regional results are not reliable. Nor would we fault those who have used GCM results for regional climate assessments in the past; no other projections were available, and those studies provided policy makers with a first-order understanding of what is at stake. But after a decade of impact assessments based on hypothetical GCM scenarios, policymakers need to be told what is likely to actually happen.

4.1. EMISSIONS, CONCENTRATIONS, AND RADIATIVE FORCING

Our probability distributions for future emissions are based on the six IPCC (1992) scenarios,[38] updated by Wigley and Raper (1992). For gases other than CFC-11 and CFC-12, we calculate the geometric means (μ*) and standard deviations (σ*) of the six scenarios through the year 2100, and assume that these moments characterize a lognormal distribution.[39] By contrast, recent sea level assessments have generally used a single scenario (A), whose emissions are well above (μ*). Because the IPCC projections stop at the year 2100, and the available analyses after that year are rather sparse,[40] we hold subsequent emissions constant.

To estimate greenhouse gas concentrations and radiative forcing, we use the gas cycle models and forcing assumptions of Wigley and Raper (1992). In the case of CO_2, we use the biological feedback version, which includes the feedback of CO_2 on plant growth, but not the potential feedback of changing ocean temperatures and circulation on the carbon cycle. For each hemisphere, we adjust atmospheric forcing (ΔQ) downward to account for sulphate aerosols and ozone depletion *(see* Wigley and Raper 1992); considering the regional pattern (*see* e.g. Schneider 1994) of these 'negative forcings' was beyond our scope. For gases other than CO_2, we used published ranges of atmospheric lifetimes as F limits (see WMO 1992; Vaghjiani and Ravishankara 1991).

Using a single carbon cycle model leads us to understate the uncertainty regarding future CO_2 concentrations. Existing models vary by about 100 ppm in the concentration resulting from emissions Scenario A (IPCC 1994 at 60), which would correspond to about 1 W/m^2 . We considered using a range of atmospheric lifetimes for CO_2 to account for this variation; but several reviewers advised against that approach since it would still tend to omit the potentially greatest uncertainty, possible climatic feedbacks onto the carbon cycle.[41]

We also omit two recent findings that would roughly offset one another: (1) Wigley (1994) now estimates that CO_2 concentrations will probably be somewhat less than projected by Wigley & Raper's (1992) analysis; and (2) the cooling effect of sulphate forcing may also be somewhat less than assumed by Wigley and Raper, if the climate is less sensitive to aerosol forcing than greenhouse forcing.[42] Our resulting range for Q brackets previous estimates for the six IPCC scenarios (Figure 2).

The emissions-based projections of atmospheric forcing were adjusted to reflect climate change from other causes. Balling and Schneider suggested a serially correlated random forcing with σ equivalent to 0.4°C on a century timescale, so that the analysis allows for a small chance of global cooling. Although modeling studies suggest natural variability of about 0.3°C/century (Wigley and Raper 1990), increases or decreases on the order of 0.5°C/century appear to occur about three times per millennia (*see e.g.* IPCC (1990) at Fig. 7.1; and Schneider (1994) at 346).

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[38] Although the IPCC scenarios were not designed for probabilistic assessments, several key IPCC participants (including the originator of the emissions scenarios) told us that we should use the entire range of IPCC scenarios to represent our uncertainty of future emissions,

[39] In the case of the two CFC's we had to modify this procedure to account for the two IPCC scenarios in which these gases decline to zero, which a lognormal distribution can not accommodate. We developed a lognormal distribution from the four nonzero scenarios; drew from that distribution 2/3 of the time, and drew from the zero-approaching scenarios the other 1/3 of the time.

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

[41] We also use only a single model to calculate radiative forcing. Because the direct radiative effect of greenhouse gases has been established with precision, ignoring this source of uncertainty has little or no effect on the results.

[42] *See* Taylor and Penner (1994) (aerosol forcing of 1W/m^2 appears to have smaller total cooling effect the 1 W/m^2 reduction of greenhouse forcing).

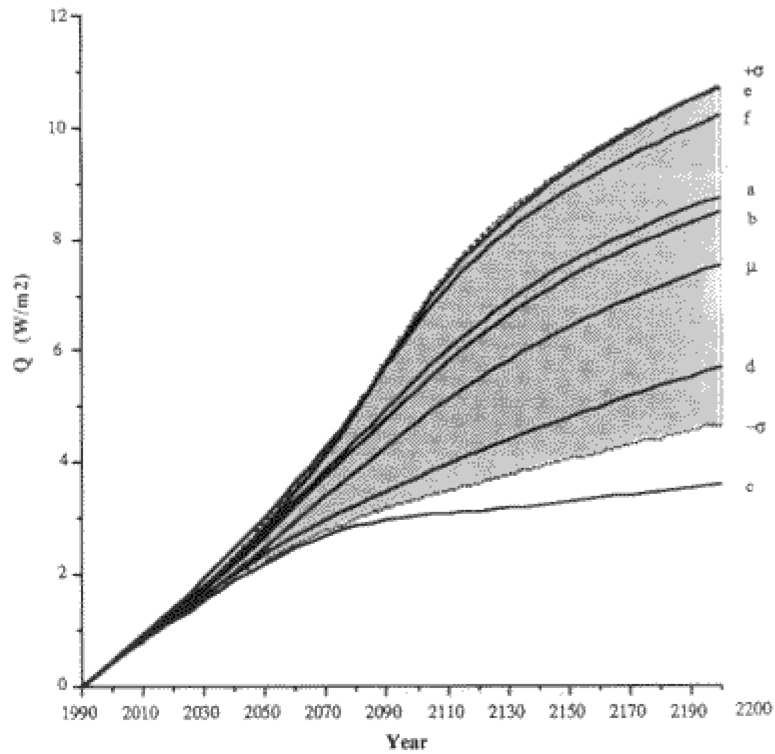


***Figure 2*. Comparison of greenhouse forcing probability distribution with forcing implied by IPCC (1992) emission scenarios. The shaded region shows the σ-limits for our analysis; μ represents our median. The curves representing IPCC scenarios IS92a….IS92f were calculated using models and assumptions reported by Wigley and Raper (1992), except that emissions are assumed to be constant after the year 2100.**

4.2 GLOBAL TEMPERATURES AND THERMAL EXPANSION

4.2.1 *Equilibrium Temperature Sensitivity* (ΔT_{2X})

Following established convention (NAS 1979), seven of the eight reviewers suggested that a CO_2 doubling[43] would warm the earth's average surface temperature 1.5–4.5°C. Although early reports (*e.g.* NAS 1979) treated this range as s limits, Wigley & Raper suggested that accumulating evidence[44] over the last decade has narrowed the uncertainty enough to view it as a 90% confidence range. Manabe indicated that the 1.5-4.5°C range for ΔT_{2X} is a 90% confidence limit for the results of a randomly selected general circulation model; but the likely behavior of the actual atmosphere is less certain. Hence he recommended treating the range as s limits; the other reviewers generally agreed with Manabe.[45]

The sole exception was Balling, a representative of the so-called 'greenhouse skeptics'. Based on Idso and Balling (1991), he suggested that ΔT_{2X} should be viewed as normally distributed with σ limits of 0 and 0.7°C and the distribution truncated at zero.

We followed the convention of recent assessments by assuming that for a given value of Δ2X, global warming is proportional to greenhouse forcing, *i.e.*, our uncertainty about the impact of a large increase in greenhouse gases is no greater than the uncertainty regarding a small increase. If there were no climatic

[43] *I.e.*, a 4.4W/m^2 increase in radiative forcing.
[44] *E.g.* the historic record fit to a 1-D model by Wigley and Raper (1992)\, and the narrower range of estimates from coupled deep-ocean general circulation models. *See* IPCC 1992.
[45] The contemporaneous study by Morgan and Keith (1995) found that only two of sixteen climate experts agreed with Wigley's conclusion that the 5%-high estimate of Δ*T* is no more than 4.5°C. Seven of the researchers place the 5%-high at greater than 6°C while another 5jplace it between 4.5 and 6°C.

feedbacks (i.e. ΔT_{2X} =1.2°C), then this assumption would be theoretically correct. Some feedbacks, such as the water-vapor feedback, probably are proportional to temperature; and general circulation model results for CO_2 doubling and quadrupling also have found warming to be roughly proportional to forcing. (*See e.g*. Manabe and Stouffer 1993). Nevertheless, we suspect that most of the climate reviewers are more confident that a 2.2W/m^2 increase in forcing would warm the earth by 0.75 to 2.25°C, than they are that an 8.8W/m^2 increase would warm the earth by 3 to 9°C. Future assessments, in our view, should reflect the notion that there is more uncertainty for large than for small increases in greenhouse gases. The simplest way to do so is to continue to use a median scenario in which equilibrium warming is a linear function of forcing; but add a parameter so that low and high climate sensitivity scenarios respectively show less-than-proportional and more-than-proportional increases in equilibrium warming as total forcing increases.[46]

4.2.2 *Transient Temperature and Thermal Expansion*

Like recent assessments, we use the one-dimensional upwelling-diffusion model by Wigley and Raper (1987, 1993) to estimate changes in surface temperature and thermal expansion of ocean water for given values of Q and ΔT_{2X}. Upwelling-diffusion models reproduce the observed vertical profile of water temperatures primarily through the use of two parameters: (1) a diffusivity parameter k which controls the downward penetration of heat; and (2) an "upwelling" parameter w which accounts for the annual rate of deepwater formation in polar areas, and thus the rate at which ocean water elsewhere upwells to the surface (Hoffert et al. 1980). We include the constraint k/w_0=500m to ensure that the model duplicates today's temperature profile; because of that constraint, the results are not very sensitive to k or w_0.

The results are sensitive, however, to two other parameters: (1) the ratio of the warming of newly formed deep water to global average warming (π) and (2) the change in the rate of deepwater formation (θ). Previous IPCC assessments made the straightforward assumptions that *newly formed* deepwater will warm as much as average temperatures (i.e. π =1.0); and that the rate of deepwater formation will be constant (i.e. $w=w_0$; $\theta=0$). A common justification for the value π =1.0 is that in the *long run*, the deep ocean is likely to warm as much as the earth's surface. However, one can also reach this result with a low value of π and a significant decline in deepwater formation; recent modeling efforts suggest that the latter specification is more realistic. (See e.g. Manabe and Stouffer 1993).

Other modeling efforts have suggested that p may be in the range of 0.2 (Wigley and Raper 1991) to 0.4 (Schlesinger and Jiang 1991). The value of π= 0.2 can be justified by a hemispheric disaggregation. In the Southern Hemisphere, where 80 percent of deep water is formed, π should be zero: Antarctic bottom water is created as surface water freezes, forming sea ice and transferring the salt to adjacent waters, which become more dense and hence sink; because freezing will occur at the same temperature even as the world warms, the polar sinking water should have the same temperature as today. In the Northern Hemisphere, by contrast, deepwater formation is caused by high salinities generated by increased evaporation from higher temperatures; as a result, a reasonable first approximation is that the deepwater will warm by as much as the North Atlantic and global temperatures in general, which implies that π is about one for the northern hemisphere. Weighting the two hemispheric values of π by their respective contributions to total deep water, we get a global π of 0.2. (See T&N at 22-29 for elaboration.)

Compared with the assumption π = 1, the assumption π = 0.2 *increases* ΔT by 13% over the next few centuries, and *decreases* thermal expansion by 25 to 33%, using our median assumptions for Q and ΔT_{2X} (Figure 3). However, even a gradual decline in upwelling (θ = 0.15) more than offsets the impact of the

[46] For example, $T^{eq}\ \Delta T_{2x}(\Delta Q/4.4)^{POWER}$,
where POWER = $(\Delta T_{2x}/2.6)^G$,T_{eq} is equilibrium temperature, 2.6 is the median temperature sensitivity (that s, the square root of 1.5 x 4.5), and G is a parameter that describes how uncertainty changes with increased forcing. A value of G = 0 retains the assumption of threefold uncertainty for large and small changes in greenhouse gases; e.g. a CO_2 quadrupling implies a warming of 3-9°C. A value of G = 0.53 increases the uncertainty by 50 percent for a quadrupling; that is, a warming of 2.5-11.4°C, a 4½-fold uncertainty change.

lower π; some modelers (*e.g*. Hoffert 1990; Manabe and Stouffer 1993) have suggested that thermohaline circulation could decline by more than 80% for 4°C<Δ*T* <6°C.

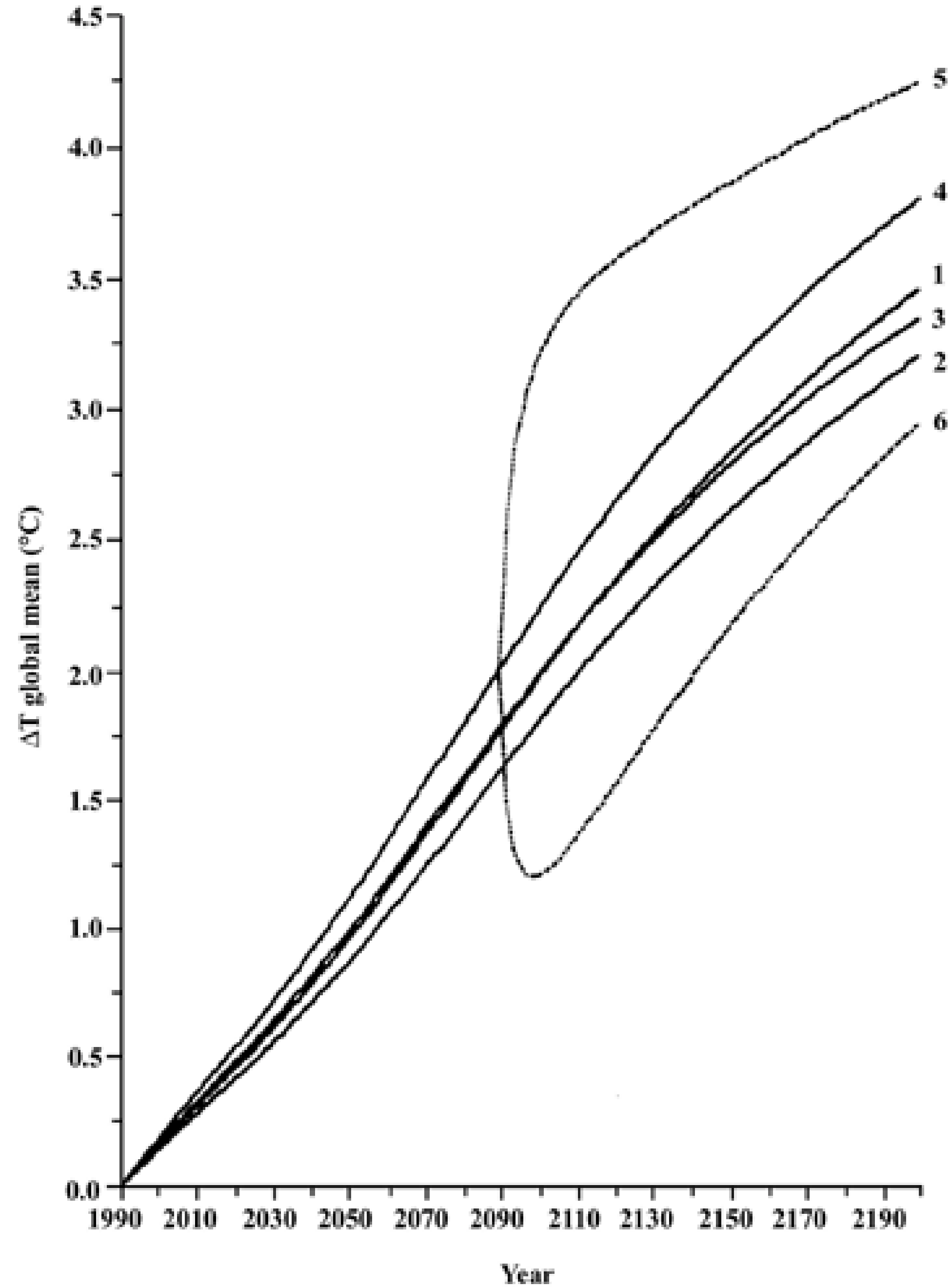
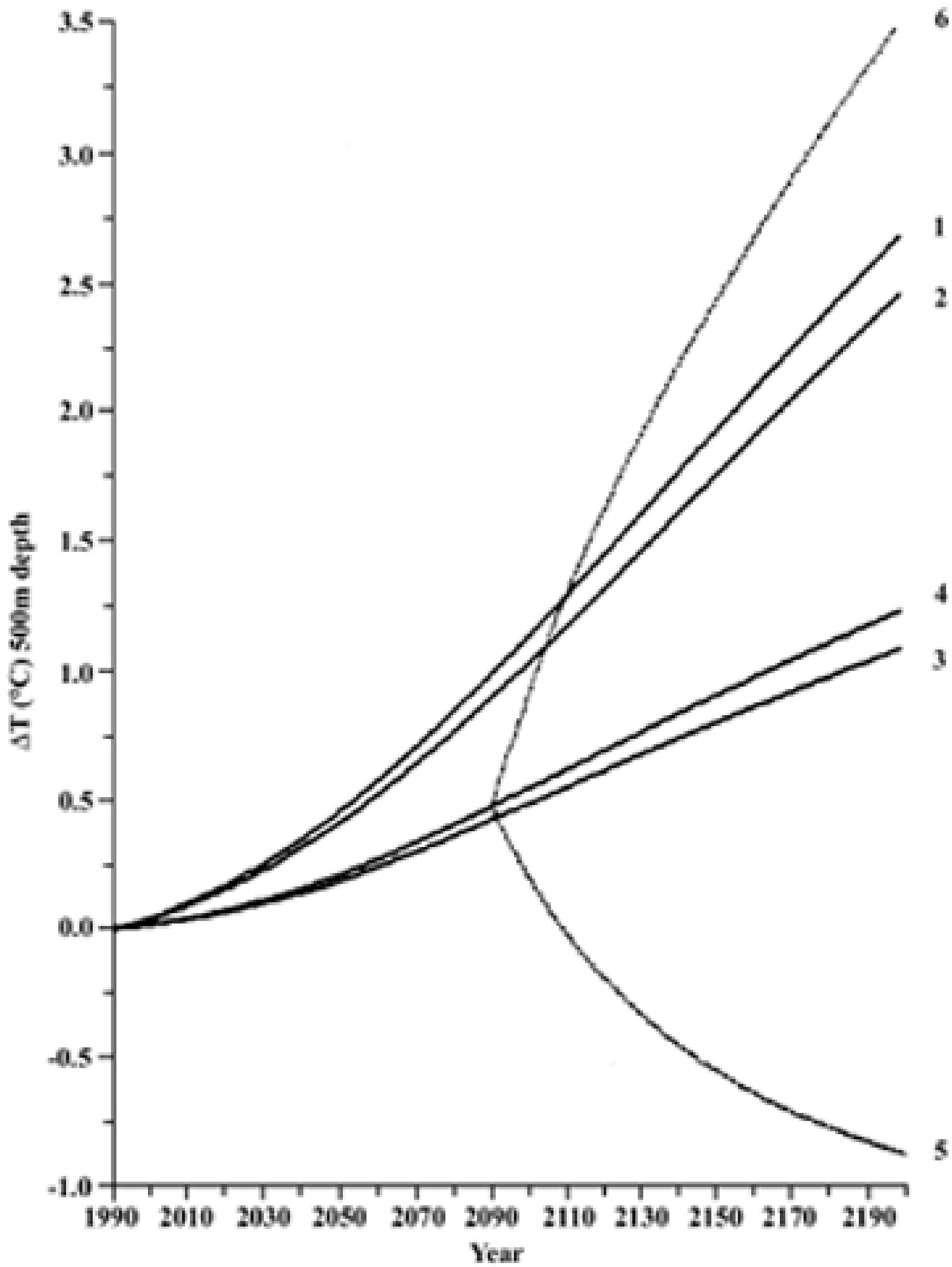


Figure 3a.

Figure 3: Sensitivity of temperature and thermal expansion projections to alternate values of π and w. Using our median scenario for radiative forcing (Q) and temperature sensitivity (ΔT_{2x}), this figure illustrates (a) average surface warming; (b) the average warming at a depth of 500 meters; and (c) sea level rise resulting rom thermal expansion, for six combinations of π and w: (1) π = 0.2; θ = 0.15 (i.e., upwelling declines 15%/^{o}C); (2) π = 1.0, θ = 0.15; (3) π = 1.0, θ = 0; (4) π = 0.2, θ = 0; (5) π = 0.2 and w suddenly increases 80% when ΔT > 2^{o}C; and (6) π = 0.2 and w suddenly decreases 80% when Δ > 2^{o}C. Although a decline in upwelling (1 and 6) causes cooler surface temperatures, the reduction in surface expansion is more than offset by the increased expansion from the greater warming of the thermocline (500 m depth).



ΔT (°C) 500m depth
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1990 2010 2030 2050 2070 2090 2110 2130 2150 2170 2190
Year
6
1
2
4
3
5

Figure 3b.

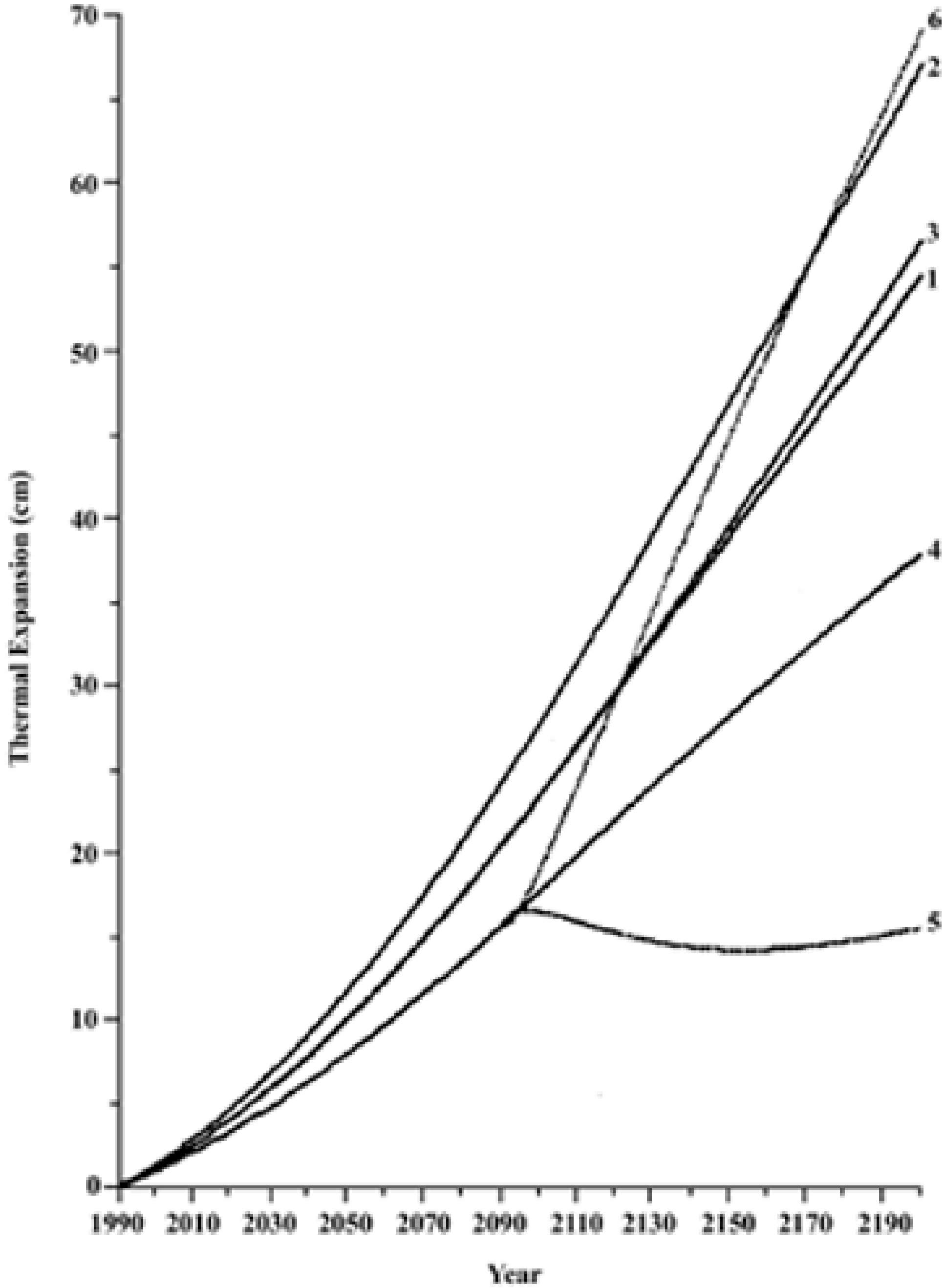


Figure 3c.

The reviewers provided a variety of specifications for π and *w*. Most assigned at least some probability to the assumption of constant upwelling (OM1; $\theta = 0$); Wigley & Raper recommended using only that specification. Hoffert[47] and Manabe[48] suggested that *w* may decline >80% for $\Delta T \approx$ 4-6°C; and three other reviewers suggested a 5–35% chance of a sudden 80% decline occurring for 1°C<ΔT < 4°C. Rind and Schneider[49] suggested that if salinity changes, w might increase.

[47] Based on Hoffert (1990).
[48] Based on Manabe and Stouffer (1993).
[49] Based on Harvey and Schneider (1985).

The reviewers mostly agree that π <1.0. Nevertheless, in the Northern Hemisphere, Rind favors the assumption that the deepwater formation temperature will rise as much as polar temperatures generally (i.e. $\pi_{NH}=P_{Green}$). Hoffert assumes such a relationship to be 50% probable for both hemispheres.[50]

The importance of the different assumptions for π and w increases over time. Figure 4 shows the cumulative probability distributions of temperature and thermal expansion, by reviewer, for the years 2100 and 2200. By 2100, the Manabe assumptions imply a median thermal expansion 27% greater than the Schneider median, which is depressed by Schneider's assumed 20% 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, both of which increase thermal expansion. Wigley and 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 temperature projections show less variation across reviewers.

4.3 POLAR CLIMATE

Estimating the possible contributions to sea level from Greenland and Antarctica require estimates of how polar temperatures and precipitation may change.

4.3.1 Polar Temperatures

The models we use required us to consider polar air temperatures in both hemispheres, as well as Antarctic circumpolar ocean temperatures. In Greenland, most precipitation and virtually all melting occur during the warmest months of the year; hence we focused on summer warming (ΔT_{Green}). In Antarctica, increased precipitation would depend mostly on the change in summer air temperatures (ΔT_{Ant}), while melting would depend on the change in water temperatures (ΔT_{cdw}). (We follow the convention of NAS (1985) in using the term ‘circumpolar deep water’ when referring to polar ocean water a few hundred meters below the surface.)

Early assessments (e.g. NAS 1979, 1982) concluded that in equilibrium, polar air temperatures are likely to warm two to three times the global average warming, based largely on results of general circulation models with mixed-layer oceans; paleoclimate evidence supports a similar (or larger) amplification in polar temperatures (Hoffert and Covey 1992). Recent simulations with coupled deep oceans, however, suggest that on a century timescale, there is little or no amplification (i.e. $P \approx 1$) during the summer. Winter amplification results primarily from a retreat in sea ice, which warms winter surface temperatures by tens of degrees in formerly ice-covered regions (Manabe and Stouffer 1980).

We use a simple two-parameter linear adjustment:

$$\Delta TAnt(t) = \Delta TAnt\ (t-1) + [PAnt\Delta T\ (t) - \Delta TAnt(t-1)]/\Upsilon Ant$$

where PAnt is the equilibrium temperature amplification factor for summer antarctic temperatures and TAnt is the time constant in years. We focus on summer temperatures because all melting and most precipitation occur then. The reviewers mostly accepted our suggested assumption that Pant should have a median of 1.0, with adjustment times ranging from 1 to 20 years.

For antarctic circumpolar ocean temperatures (ΔT_{cdw}), by contrast, the reviewers offered more disparate assessments. Manabe and Schneider expect that in equilibrium, $\Delta T_{cdw}. \approx \Delta T$. Manabe suggested a lag of 100–300 years, implying that for the year 2100, Prob(ΔT_{cdw} <1.0) = 75% and Prob(ΔT_{cdw} <2) = 98%. Schneider, by contrast, suggested a more rapid response, implying that Prob(ΔT_{cdw} >1) = 80% and Prob(ΔT_{cdw} > 4) = 5%. Three reviewers accepted a median response of P_{cdw} = 0.5 with a lag of 40 years, a formulation which yields approximately the same median result as Manabe's assumptions, albeit greater uncertainty. Hoffert and Rind believe that in equilibrium, ΔT_{cdw} could be two to four times ΔT; but long

[50] Based on Hoffert (1990).

adjustment times[51] keep their estimates of ΔT_{cdw} from exceeding those of Schneider until after 2100. Figure 5 shows the cumulative probability distribution of circumpolar ocean warming by reviewer.

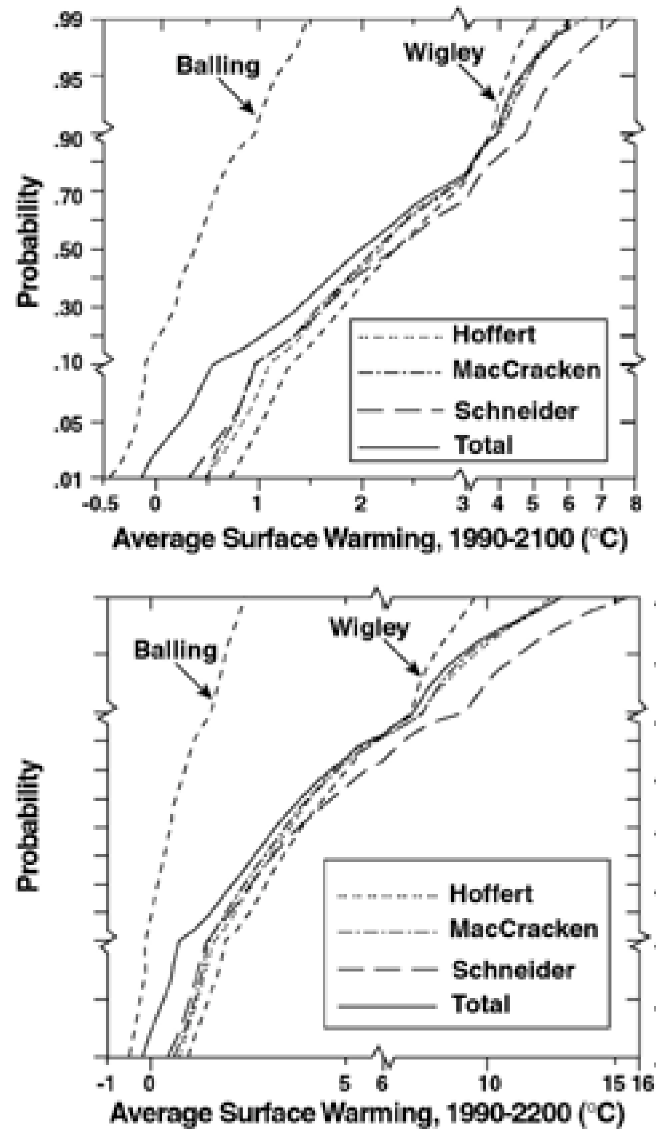


Figure 4. Cumulative probability distributions of surface warming and thermal expansion by reviewer. Several curves were removed for clarity. The Rind estimates generally track Schneider because both include the possibility of both increased and decreased upwelling, along with high values of π. The Bretherton 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. See Section 2.3 for a definition the combined 'Total' probability distributions.

[51] Based on Broeker and Takashi (1981), which estimated that North Atlantic deepwater takes 80-90 years to reach the circumpolar ocean, Rind suggested an absolute lag (e.g. $\Delta T_{cdw} = P_{cdw}\Delta T(t\text{-}85)$. Based on Hoffert (1990), Hoffert suggested that P_{cdw} would be 1.0 for $\Delta T < 1.0$, and would asymptotically approach a terminal value with 2σ limits of 2.0 and 4.0.

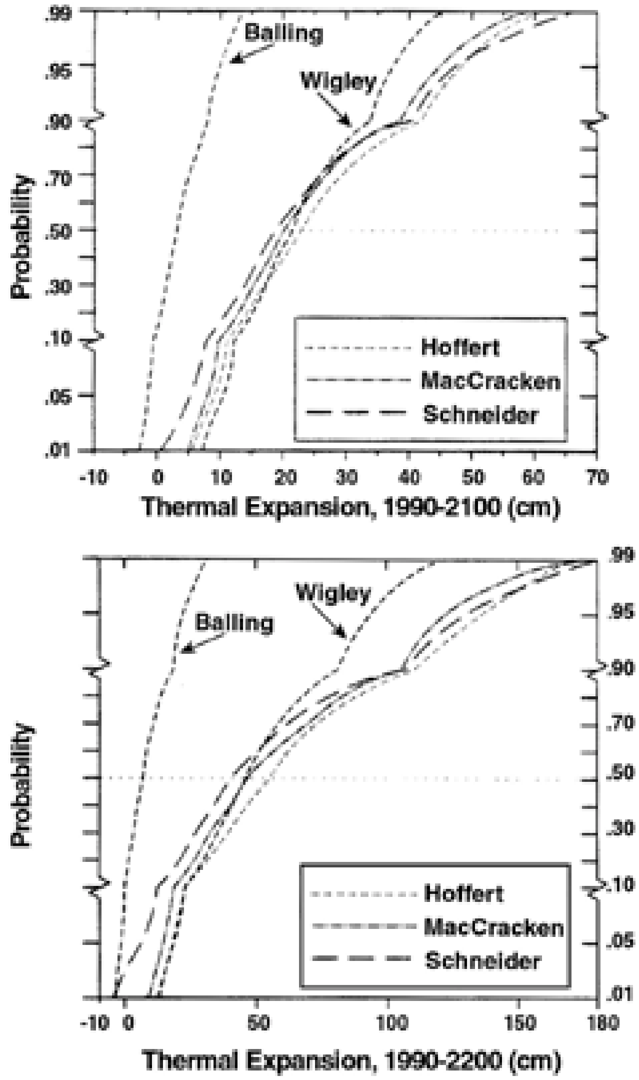


Figure 4. Continued

The reviewers generally agree that Greenland summer temperatures (ΔT_{Green}) should not significantly lag behind ΔT. (*See e.g*. Manabe et al. 1991.) Most agreed with recent assessments that the amplification P_{Green} is likely to be around 1.5. Manabe and MacCracken, however, thought that P_{Green} would probably be less because decreased formation of North Atlantic deepwater would diminish the warming effect of the Gulf Stream; MacCracken added that Greenland's sea level contribution depends on the warming 1000m above sea level, which would be less than the warming at sea level. Rind agrees that $P_{Green}= 0.5$ is a reasonable assumption if deepwater declines drastically, and assumed a - 0.5 correlation between θ and P_{Green}. As with Antarctic temperatures, Hoffert assumes that P_{Green} would gradually rise from 1.0 for ΔT <1 to a terminal value between 2.0 and 4.0. Figure 6a shows that about half the reviewer assumptions imply a median warming of 3°C by 2100, but the Manabe and MacCracken assumptions suggest respective probabilities of 10 and 30 percent.

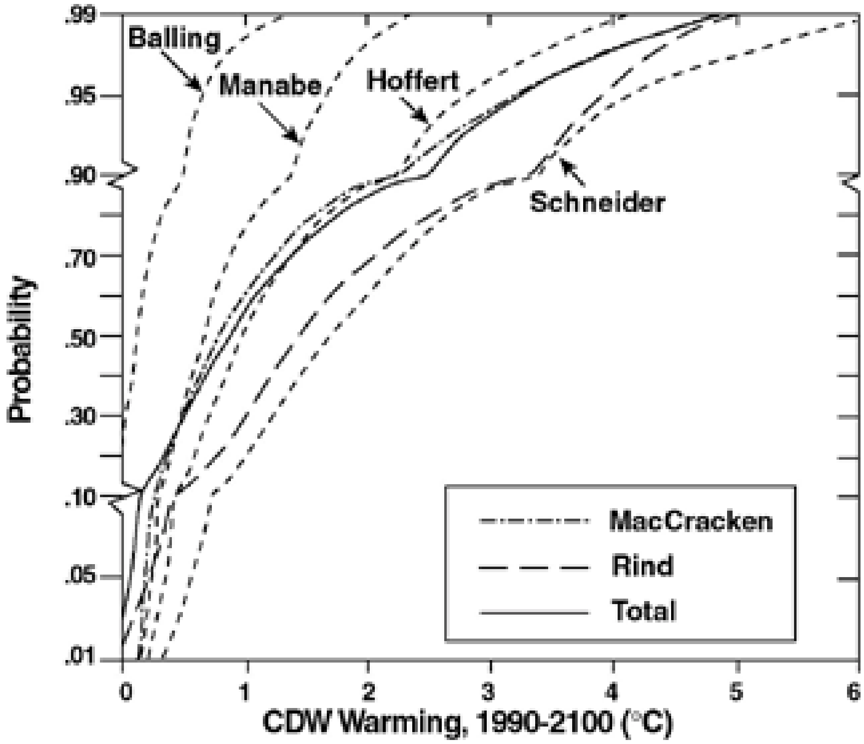


Figure 5. Cumulative probability distributions of circumpolar ocean warming. The long lag times between average global warming and antarctic deepwater results in a median estimate of only 1°C by the year 2100. See Section 2.3 for a definition the combined 'Total' probability distributions.

4.3.2 Polar Precipitation

A doubling of precipitation over Greenland and Antarctica would lower sea level 1.3 mm/yr (*see* Ohmura and Reeh 1991) and 4.2 mm/yr (*see* Bentley and Giovinetto 1990), respectively. Of the six reviewers offering an opinion, four favored assuming that precipitation would increase in proportion to changes in the saturation vapor pressure (Huybrechts and Oerlemans 1990). Zwally suggested a much wider uncertainty range of 3 to 20%/°C[52]. Alley, by contrast, suggested that precipitation should only increase between 1%[53] and 5%/°C[54] in Greenland, and 4 to 12%/°C in Antarctica. For Greenland, the precipitation sensitivities are applied to the $\Delta T_{\mathrm{Green}}$ or ΔT, whichever is greatest. The primary justification for simulations in which $\Delta T_{\mathrm{Green}} < \Delta T$ was a reduction in North Atlantic deepwater formation resulting from *increased* precipitation at higher latitudes; thus it would have been unreasonable to assume *less* precipitation over Greenland than for cases where $\Delta T_{\mathrm{Green}} = \Delta T$.

4.4 ANTARCTIC CONTRIBUTION TO SEA LEVEL

Because 'most glaciologists agree'[55] that the marine-based West Antarctic Ice Sheet is potentially vulnerable to a climate warming (Mercer 1978), early assessments (*e.g.* Schneider and Chen 1980) of a greenhouse warming-induced sea level rise focused on this contributor, which could potentially raise sea level by six meters over a period of several centuries (Bentley 1983). More recent assessments, by contrast, have assumed that on a timescale of a century, warmer temperatures will not accelerate the

[52] Based on Zwally (1989).
[53] Based on Kapsner, 1993; Kapsner et al., 1994.
[54] Based on Claussen et al. (1988).
[55] Van der Veen (1987) at 33.

discharge of antarctic ice, and that the additional precipitation at higher temperatures (Huybrechts and Oerlemans 1990) will increase the mass of the Antarctic Ice Sheet and thereby lower sea level.

The tendency for recent assessments to attribute less importance to the West Antarctic Ice Sheet can not be explained by new information demonstrating the ice sheet to be stable. Rather it appears to have resulted from a shift in focus: The 1980s assessments tended to focus on what *could* happen; whereas the 1990s assessments focus on what *is likely*. For our purposes, choosing between these two objectives is not necessary.

Like other assessments, we assume that cold antarctic temperatures will prevent the surface melting of a significant amount of the ice sheet. Instead we focus on the possibility that warmer circumpolar ocean water will intrude beneath the ice shelves, increase their rates of basal melting, decrease the backpressure that they exert on the ice streams, and thereby accelerate the rates at which ice streams convey ice from the antarctic interior toward the oceans.

Table II. Variables and other symbols

Q	≡	Primary radiative forcing from greenhouse gases, with negative effects of SO_4 and 0_3 depletion netted out.
ΔT	≡	Average Surface Warming by a particular year over 1900 levels.
T_{2x}	≡	Average Equilibrium Surface Warming from a doubling of atmospheric CO_2
π	≡	The ratio $\Delta T_{down}/\Delta T$, *where* T_{down} is the average temperature at which surface waters in polar areas sink to form deepwater or bottomwater.
π_{NH}	≡	The value of $\pi$for a particular hemisphere
π_{SH}	≡	
W	≡	The rate of oceanic upwelling, averaged over all the oceans.
θ	≡	The sensitivity of w to ΔT; *e.g.* $w = w_o (1 - \theta)^{\Delta T}$
P	≡	The polar amplification parameter, i.e., the ratio of warming in polar areas to global average warming.
ΔT_{Ant}	≡	Surface warming for Antarctic air and water temperatures.
ΔT_{cdw}	≡	Surface warming for Antactic circumpolar water at a depth equal to the depth of the ice shelves (i.e. a few hundred meters below the surface).
ΔT_{Green}	≡	Warming of Greenland temperatures.
ΔT_{shelf}	≡	Warming of the water beneath the Ross Ice Shelf.
P_{cdw}	≡	Polar amplification for Antarctic circumpolar ocean waters at depths similar to the ice shelves ($\Delta T_{cdw}/\Delta T$)
P_{Green}	≡	Polar amplification for Greenland during the summer melting season.
P_{Ant}	≡	Polar amplification for Antarctic air.
Υ_{cdw}	≡	Time constant, e-folding time, for $T_{cdw.}$
Υ_{ice}	≡	Time constant for ice stream response to ice shelf melting.
μ	≡	Mean of a normal distribution
$\mu*$	≡	Geometric mean of a lognormal distribution (i.e. the exponentiation of the mean of the logarithm of the variable).
σ	≡	Standard deviation
$\sigma*$	≡	Geometric standard deviation (i.e. the exponentiation of the standard deviation of the logarithm of the variable).
σ limits	≡	$\mu - \sigma$ and $\mu + \sigma$ for normal distributions μ/σ and $\mu\sigma$ for lognormal distributions.
Prob ($x < y$)	≡	The probability that x is less than y.

Table III. Global climate and polar temperature assumptions

	Balling	Breth./Draft	Hoffert	MacCra.	Manabe	Rind	Schneid	Wigley[c] & Raper
Global climate parameters								
T_{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 (or π_{NH}, π_{SH})								
2σ - low	0.2[d]	0.2[d]	P_{Green},0.2	0.04	0.2	P_{Green},0.0	0.2	-0.04[c]
2σ - high	1.0[d]	1.0[d]	P_{Green},1.0	1.0[tl]	0.2	P_{Green},1.0	1.0	0.58[c]
w/w0 given ΔT = 4°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	15	0
OM4	0	0	0	0	0	5	10	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.
Υ_{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 and Raper specification with fixed $w = w_0$ and specified distribution of π.

OM2: w declines geometrically: $w = w_0 (1-\theta)^{\Delta T;}$ $\theta > 0$.

OM2.1: w increases geometrically: $w = w_0 (1-\theta)^{\Delta T;}$ $\theta < 0$.

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 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 fixed at 0.2, and *w* declines linearly with temperature: $w = (1 - 0.15\,\Delta T)\,w_0$ for $0 < \Delta T < 6$, and $w = 0.1$ for $\Delta T > 6$.

[c] Reviewer's estimates 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.

[h] Hoffert assumes the $P = 1$ for $\Delta T < 1.0$ For $1.0 < \Delta < T_w$, *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.

\- Reviewer did not consider OM5 and/or OM6; those options were proposed *sua sponte* by Hoffert and Manabe, respectively.

[t9] Distribution truncated at a value of 9.

? Rind and Schneider subsequently revised their estimates of Υ to 20-100 and 20-200, respectively. Although these revisions have offsetting impacts on median T_{cdw} projections, they would broaden the range somewhat.

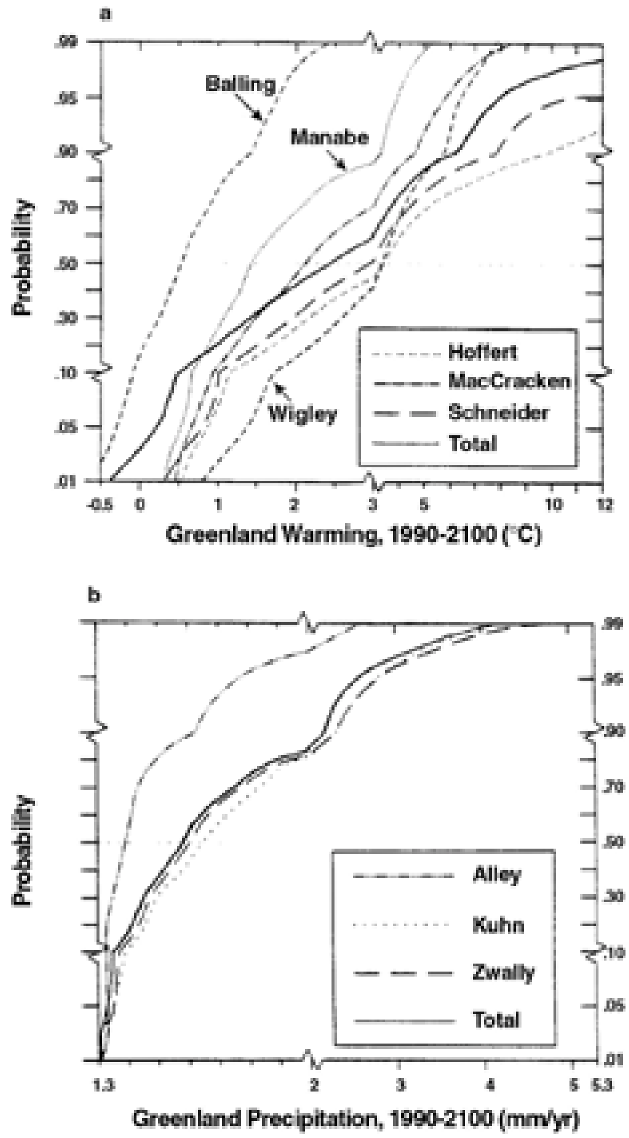


Figure 6. Climate change in Greenland. Cumulative probability of (a) warming by the year 2100; (b) sea level equivalent of annual precipitation in 2100, assuming that the current rate is 1.33 mm/yr; and Greenland contribution to sea level through the years (c) 2100 and (d) 2200. The Rind, MacCracken, 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 Bindschadler (1985) model employed with the consensus assumptions adopted by the glaciology reviewers. See Section 2.3 for a definition the combined 'Total' probability distributions.

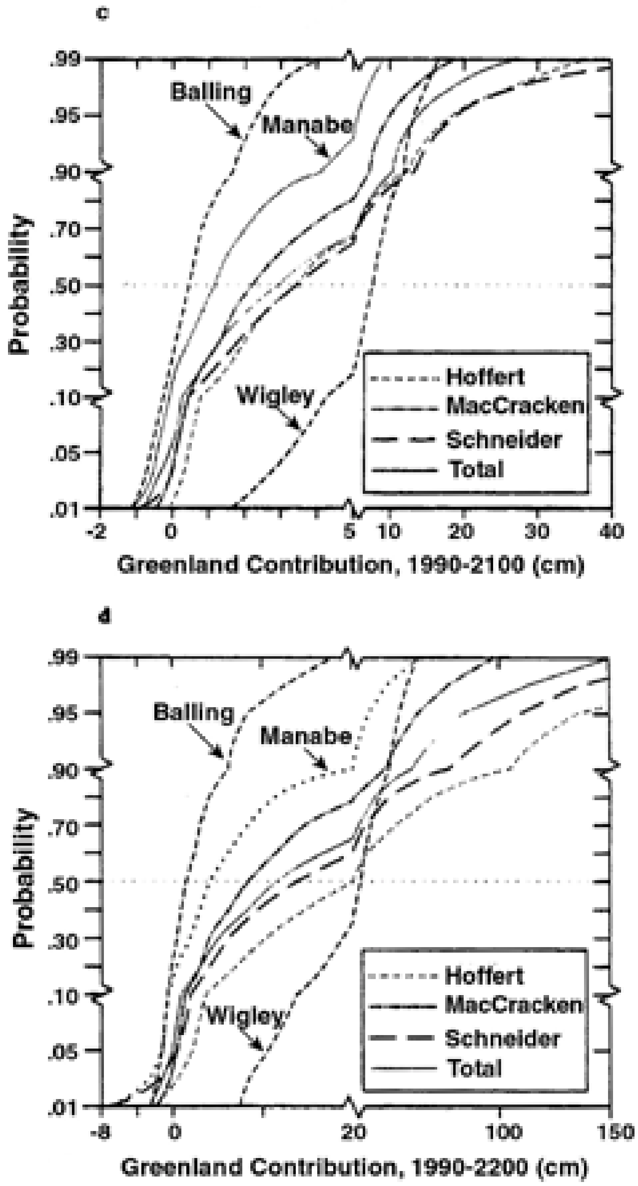


Figure 6. Continued.

4.4.1 Rate of Shelf Melt

We assume that the current 0.17m/yr average rate of Ross Ice Shelf basal melting can be explained by circulation beneath the ice shelves of high-salinity water approximately 0.5°C above the *in situ* freezing point at the base of the ice shelf (Jacobs et al., 1992). Our median assumption is that an increase in T_{cdw} results in a proportionate increase in shelf melting, which we implement by increasing the temperature of the subshelf circulation 0.2°C for every 1°C warming of the circumpolar deep water; i.e. melting would double for ΔT_{cdw}=3°C. Based on NAS (1985), we also allow for the possibility that if circumpolar ocean temperatures exceed a threshold, undiluted circumpolar deep water will intrude beneath the ice shelves; we assume that there is a 25 percent chance that such a threshold exists, and that the threshold is uniformly distributed between 0 and 5°C.

Figure 7. Cumulative probability distribution of Ross Ice Shelf melt rate for the year 2100. The combined assumptions imply a 50 percent chance that the current rate of 0.17 m/yr will increase by almost 50 percent, as a result of circumpolar ocean temperatures warming from 1.1ºC today to 2.0ºC by 2100. Ion the 5%-high scenario, circumpolar ocean temperatures warm more than 3ºC, and shelf melt rates exceed two meters per year, similar to the rate prevailing today beneath the George VI Ice Shelf. See Sections 2.3 and 5 for a discussion of the combined circumpolar ocean temperatures on which these calculations were based.

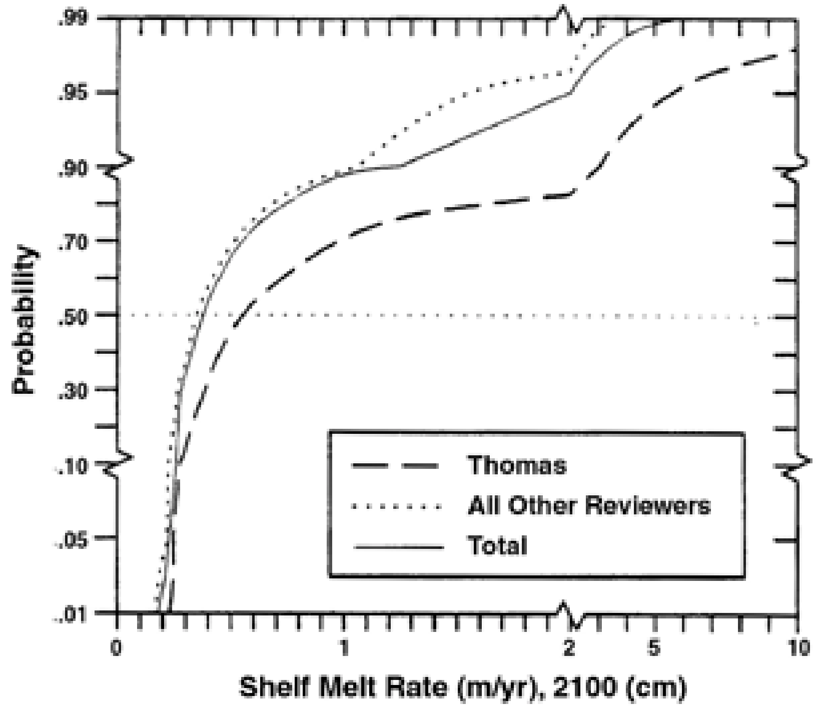


Table IV
Reviewer allocation of probabilities between the alternative models of Antarctic ice stream response to ice shelf melting

	Bindschadler	Bentley	Alley	Van der Veen	Zwally	Thomas[c]	Anonymous	Wigley and Raper	Total
Probability of particular Antarctic model									
AM1	5	25	10	30	10	0	0	-	10
AM1.1	-	-	-	-	-	-	-	100	12.5
AM2	60	25	30	30	40	45	25	-	31.9
Thomas[a]	20	25	37	10	35	30	25	-	22.75
AM3	0	0	1	0	1	5	1.1	-	1
AM4	0	0	1	0	24	0	4	-	3.6
AM5	5	0	5	0	5	25[b]	6.4	-	5.7
AM6	15	25	30	10	5	0	13.5	-	12.3
AM7	15	25	23	30	15	25	50	-	24.1
ϒice									
2σ-low	10	10	10[d]	10[d]	50	1	10[d]	NA	
2σ-high	1000	1000	1000[d]	1000[d]	200	100	1000[d]	NA	

[a] Subtotal of AM3, AM4, AM5, AM6.
[b] Favors this scaling not for reasons provided in text but because the scaling factor coincidentally is equivalent to assuming that the 60% of all Antarctic ice discharged through ice shelves would behave as Ice Stream B.
[c] Assumes that the temperature of the warm intrusion increases as follows: $T_{shelf} = T_{cdw} / (A1 - \Delta T_{cdw})$ for $\Delta T_{cdw} < 5$; $T_{shelf} = T_{cdw}$ for $\Delta T_{cdw} \geq A1 - 1$, where $A1$ has a median of 6 and a 2σ limits of 1 and 36. Also assumes that shelf melt rates increase with the square of Tshelf up to a rate of 3m/yr, and linearly thereafter.
[d] Did not disagree with the draft's suggested value, but did not explicitly endorse parameter value either.
Υ_{ice} is the time constant used in AM2 (melt only model).
N.A. Not applicable.

The ice-shelf models are probably the weakest link in our chain of assumptions: The fact that the circumpolar ocean is generally 3°C above the freezing point is weak circumstantial evidence that there is a 5:1 'dilution' with the colder ice shelf water; but because the high-salinity water results from sea-ice formation, warmer ocean temperatures would not directly raise its temperature. Nevertheless, the circumpolar ocean is the ultimate source of heat for Ross Ice Shelf melting; and proportionality is a reasonable starting point.

The lack of adequate models on Ross Ice Shelf melting forced us to assume large uncertainty limits. Our 2σ low assumption is that virtually no additional melting results from warmer temperatures. Our 2σ high assumption is that changes in T_{cdw} will be completely reflected in the temperature of water circulating beneath the ice shelves, implying that a 4°C warming could cause Ross Ice Shelf melt rates to approach the 2m/yr currently observed at the base of the George VI Ice Shelf. For the Ronne-Filchner Ice Shelf, where some modeling results are available (*e.g*. Jenkins 1991), we assume that shelf melt rates would increase by 1.9–3.3m/yr°C.

Robert Thomas suggested that these assumptions may underestimate both the temperature of subshelf intrusions of warm water and the sensitivity of shelf melt rates to those temperatures. He suggested instead that the dilution of circumpolar deep water with colder shelf water should decline as temperatures increase; he also suggested[56] that shelf melt rates would rise with the square of T_{shelf} up to a rate of 3m/yr, after which the relationship would be linear. As Figure 7 shows, the shelf melt rates were much higher in those simulations using Thomas' assumptions.

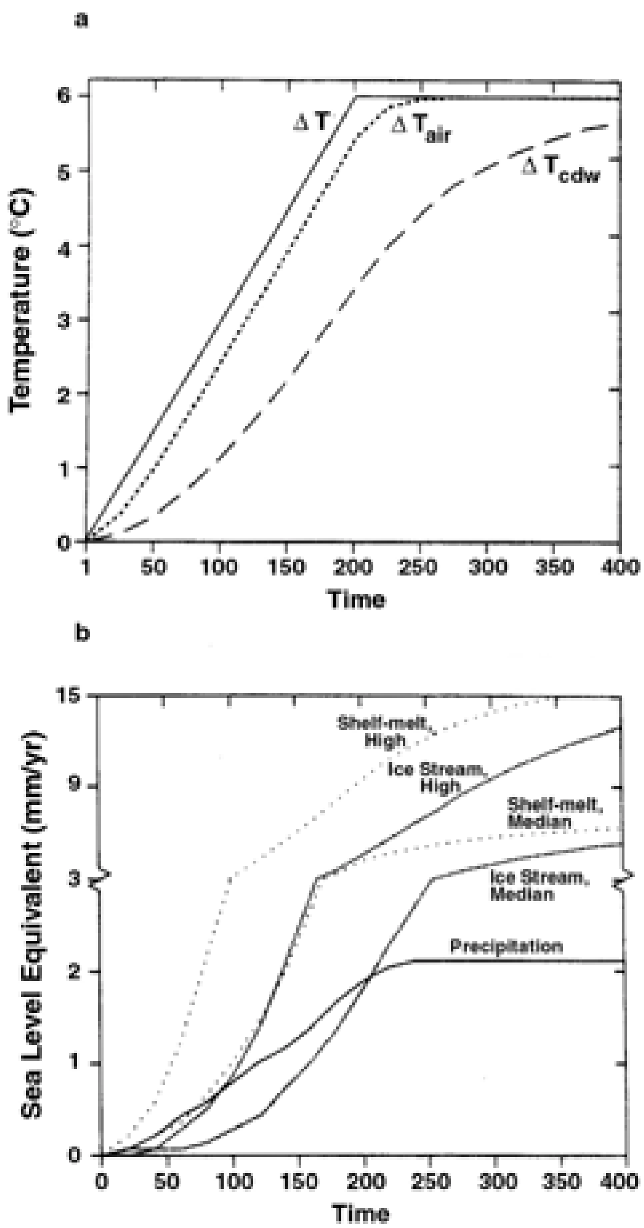


Figure 8. Models of Antarctic contribution: (a) Temperature changes using median response time assumptions. (b) The resulting annual shelf melting and precipitation (expressed as a sea level equivalent); and the Antarctic contributions to sea level implied by the stable melt-only model AM2, using median and 2σ-high assumptions for shelf-melt sensitivity, and median assumptions elsewhere. (c) Annual sea level assumptions from IPCC (1990) are shown for comparison. (d) Total Antarctic contribution to sea level for the same models.

4.4.2 Response of Ice Sheet to Shelf Melting

A one meter thinning of all Antarctic ice shelves would involve the melting of 1600 km3 of ice, equivalent to a 4 mm rise in sea level, with the Ross and Ronne/Filchner Ice shelves each accounting for 1 mm (see Menard and Smith 1966). Because the floating ice shelves already displace ocean water, however, shelf melting does not, by itself raise sea

[56] Based on MacAyeal (1984).

level. Nevertheless, melting might indirectly raise sea level, by increasing the rate at which ice flows from the ice sheets (which rest on land) to the ice shelves.

The reviewers considered eight alternative assumptions for the impact of ice shelf thinning on the mass of the Antarctic Ice Sheet (Table 4). Using representative assumptions for temperature change, Figure 8 illustrates the shelf melting, precipitation, and ice sheet responses resulting from six of the models we used. In all cases the initial effect of warming is to lower sea level due to increased precipitation; however, for all but the IPCC (1990) assumptions, the contribution eventually becomes positive as the ice sheet responds to increased shelf melting. The responses can be classified into (1) minor response, (2) large but stable response, and (3) unstable response.

Minor Response. AM1 is the IPCC (1990) assumption that there would be no increased discharge of ice from antarctica resulting from warmer temperatures. AM1.1 represents Wigley and Raper's (1992) modification of this model, in which the Antarctic contribution is $=\beta_{Ant}\ \Delta T_{Ant}$, where β_{Ant} has 2σ limits of -0.47 and +0.07 mm/yr°C. AM7 represents a linearization of results published by Huybrechts and Oerlemans (1990), who estimated that with a 1-m/yr rate of Ross and Ronne/Filchner Ice Shelf thinning, sea level would rise 2, 3, 7, 8, and 10 cm during the next five centuries, respectively.

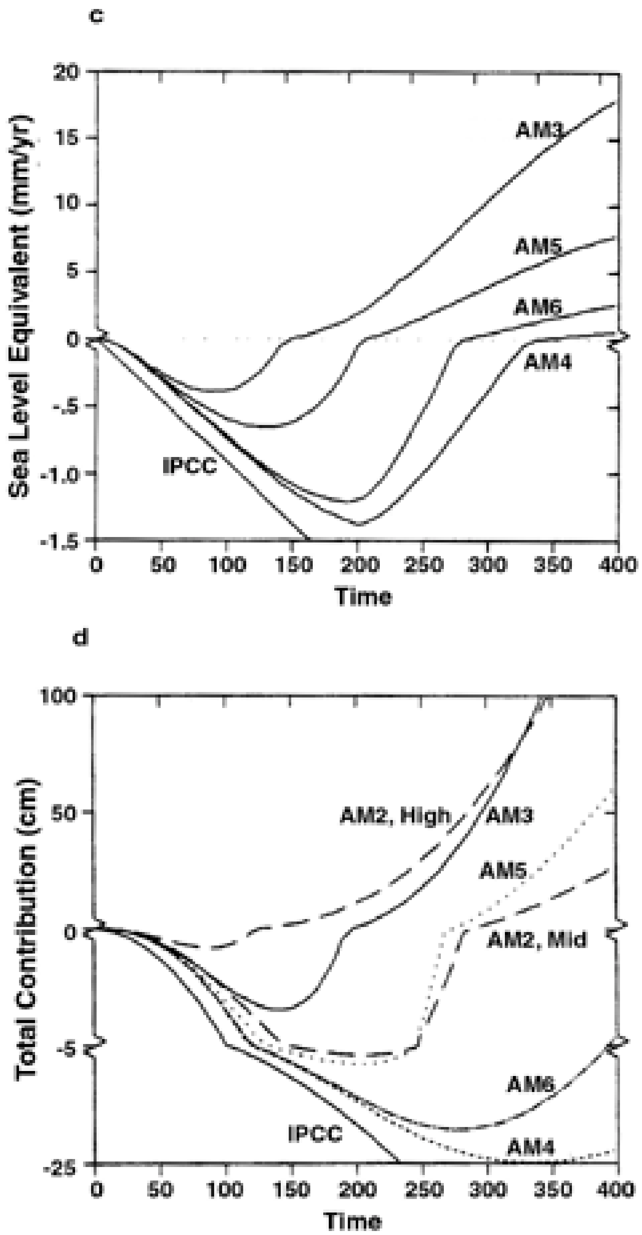


Figure 8. Continued

Stable Response. The reviewers generally thought that the simplest way to model a stable response to ice shelf melting is to assume that in equilibrium, the ice sheet and ice shelves decline in mass by the same proportions (AM2). Most of the reviewers endorsed a time constant (T_{ice}) with a median of 100 years and 2σ limits of 10 and 1000. In the median case, for example, a 1 m/yr rate of Ross and Ronne/Filchner ice shelf melting would lead to an Antarctic contribution of 1, 21, 74, and 225 cm after 10, 50, 100, and 200 years, respectively.

The reviewer assumptions imply that a stable response would eventually result in a positive antarctic contribution to sea level, but that initially the increase in precipitation will probably offset the effect of increased melting. Figure 8 considers the case where global temperatures rise 0.03°C/yr. The median assumptions imply that in equilibrium, melting would increase by a sea-level equivalent of 6mm/yr, three times the 2 mm/yr from increased precipitation. But because antarctic air temperatures warm more rapidly (Υ =20 years) than the circumpolar ocean temperatures (Υ =100 years), precipitation responds more rapidly than shelf melting. As a result, the increase in shelf melting does not exceed the precipitation increase until the 70th year; and the lag between shelf melting and ice stream contribution prevents the annual ice stream contribution from exceeding the precipitation increase until the 200th year. In the extreme case where $\Delta T_{shelf} = \Delta T_{cdw}$, increased melting immediately exceeds the increased precipitation; but even here the annual contribution is negative until the 90th year.

Unstable Response. A 1985 report by the National Academy of Sciences (NAS 1985) included a 'high scenario' in which Antarctica contributed as much as one meter to sea level by the year 2100. That projection was based on a 2-dimensional model by Thomas (1985), who analyzed possible unstable responses of Ice-Stream B to shelf melt rates of 1-3 m/yr. Thomas estimated that a 1m/yr rate of ice-shelf thinning would result in 0.12 mm/yr contribution from Ice Stream B, which accounts for about 2% of the continent's annual ice discharge. Assuming that all ice discharges would rise proportionately (AM3), Thomas (1985) scaled those results by a factor of 48, implying a contribution of 6.03mm/yr.

The reviewers generally favor a more modest scaling of those results. Even conceding the validity of the Thomas model for Ice Stream B, there is no evidence that the flows of all ice streams are impeded by the backpressure of ice shelves. Because only 20 percent of Antarctic Ice leaves through the Ross and Ronne/Filchner ice shelves, some reviewers favored a scaling factor of 10.1 (AM4). Another approach is to assume that the Thomas model appropriately characterizes the ratio of ice stream discharge to Ross and Ronne/Filchner melting, which implies a scaling factor of 28. (AM5). A final approach is to apply the Thomas model to each of the major ice streams feeding the Ross and Ronne/Filchner Ice Shelves, based on measurements of their velocities (Shabtaie and Bentley 1987) and mass fluxes (Bentley and Giovinetto 1990) (AM6).

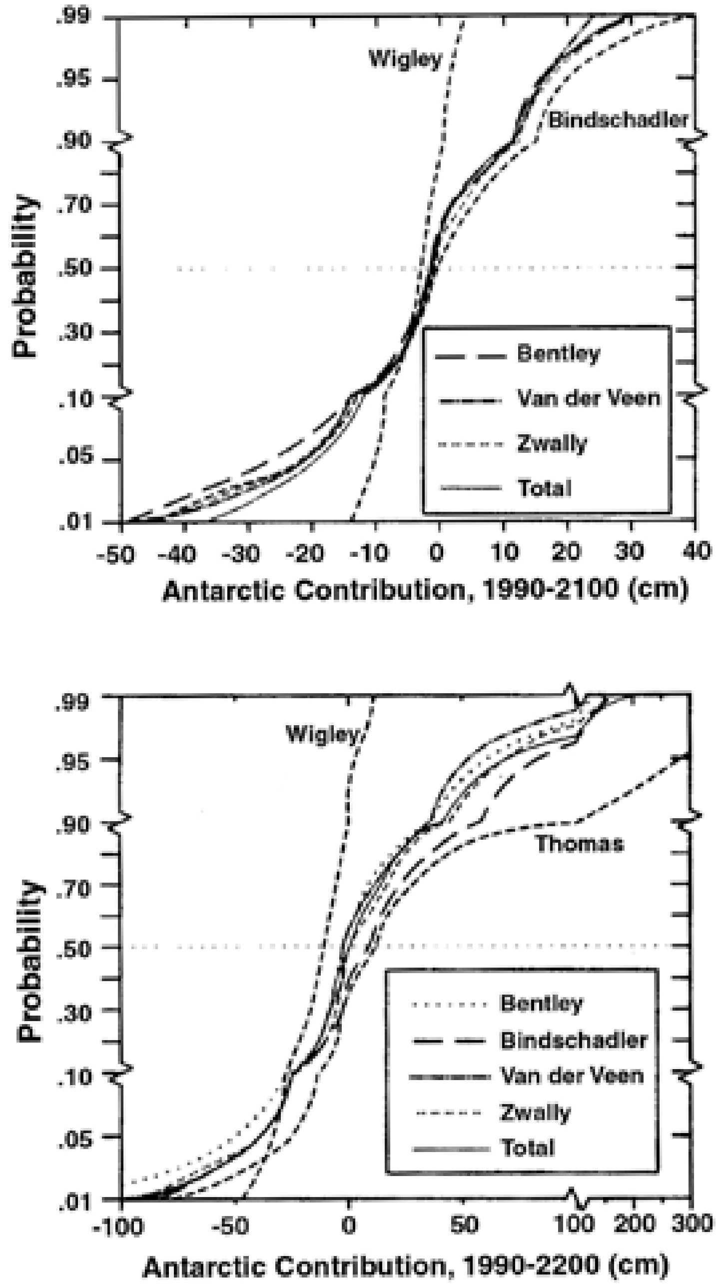


Figure 9. Cumulative probability distribution of Antarctic contribution to sea level by reviewer. A few curves have been removed for clarity: The distribution implied by the Alley and Anonymous assumptions generally tracked those of Bentley and Van Der Veen, respectively. For the year 2100, the Thomas estimates are close to those of Bindschadler; by 2200, however, they diverge markedly.

Most of the reviewers accepted a baseline assumption of a nongreenhouse antarctic contribution of –1.1 to –0.1 mm/yr, (*see* Bentley and Giovinetto 1990) based on empirical data. Jacobs and Lingle, however, believe that a positive baseline contribution is more likely. Thus, 25% of our simulations use Lingle's suggested range based on a median of +0.5mm/yr and 2ó–high of +1.6mm/yr, based on internal dynamic cycles (*see* Lingle 1989).

Figure 9 compares the Antarctic contribution implied by the assumptions of the various reviewers. The Wigley & Raper assumptions imply far more certainty, with a 90% range of –10 to +1.5 cm by 2100, and –33 to +4.5 by 2200. With the exception of Thomas, the other reviewer assumptions imply a 90% range of –20 to +15 cm for 2100 and –40 to +60 cm by 2200; the Thomas results are similar for 2100, his 90% range for 2200 is –25 to +225 cm.

4.5 GREENLAND CONTRIBUTION TO SEA LEVEL

IPCC combined the precipitation and melting effects of warmer Greenland temperatures into a single equation, which assumes the annual contribution to be proportional to ΔGreen. We disaggregate these processes because (a) different reviewers provided us with comments on changes in temperature, precipitation, and glacial melting; and (b) the NAS (1985) analysis suggests that the linearity assumption significantly understates the extent of our uncertainty under high-warming scenarios. Most of the reviewers endorsed this approach; Wigley & Raper preferred use of the IPCC model.

Following NAS (1985), we employ the two-dimensional model by Bindschadler (1985), which treats the ice sheet as a parabolic cylinder (Figure 10). The model assumes that (a) precipitation is 35 cm/yr; (b) melting is also 35 cm/yr at an elevation of 1500 m (the 'equilibrium line'); (c) melting decreases 1.53 m/yr per kilometer of elevation and hence is zero at an elevation of 1729 m (the 'melt line'); (d) meltwater runs off below the elevation of 1729 m (the 'runoff line'); and (e) the ice sheet currently makes no contribution to sea level. Bindschadler scaled his results by the 5000 km perimeter of Greenland. Because the implied annual accumulation (695 km3) was higher than a recent estimate (535 km3) by Ohmura and Reeh (1990), our scaling factor was 23% less.57

The reviewers accepted Bindschadler's (1985) assumption that the equilibrium line rises 89 to 167 m/°C,58 which implies an increase in current melt rates of 17 to 28 cm/yr°C. However, we modified the model to allow for the possibility that initially, in areas

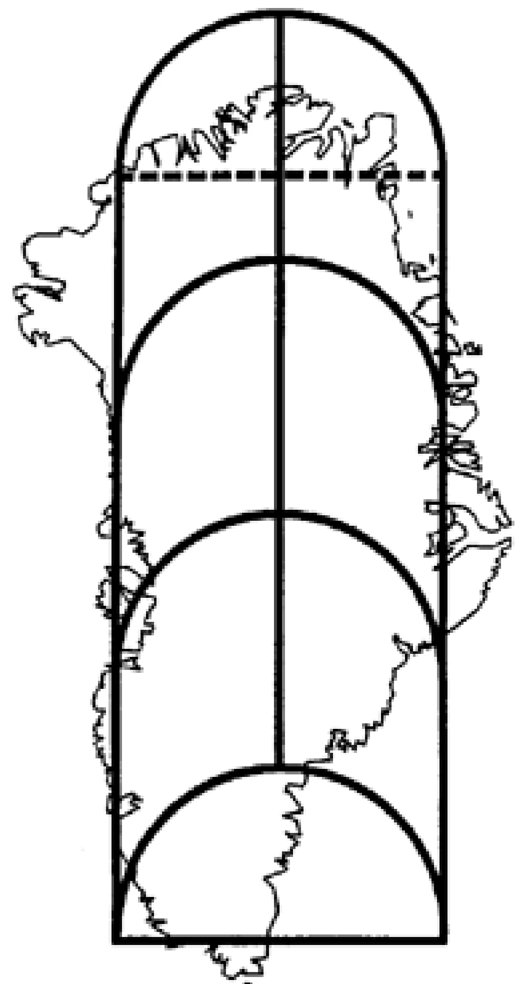


Figure 10. Schematic of bindschadler (1985) model. Extrapolating the 2-D model to three dimensions by a scaling factor of 5000 km is equivalent to assuming two parabolic cylinders back-to-back, with transverse (longitudinal) length of 2500 cm. Greenland is drawn to the same scale.

[57] *See* T&N, Chapter 4, for further details.

[58] Including the resulting increase in precipitation, Bindschadler's (1985) assumptions implied that the zero-runoff line would rise 111.1 to 186.3 m/°C.

just above today's melt line, the ice sheet is porous. Therefore, if warmer temperatures allow melting to take place, the meltwater may percolate through the various holes in the ice and refreeze, rather than flow to the oceans. Eventually, this process will fill the holes and water will be able to flow to the oceans. Based on Pfeffer et al. (1991), we assume that this process will take a median of 25 years, with σ limits of 12.5 and 50 years. Figure 11 illustrates the results of the model for a linear temperature trend of 3°C per century.

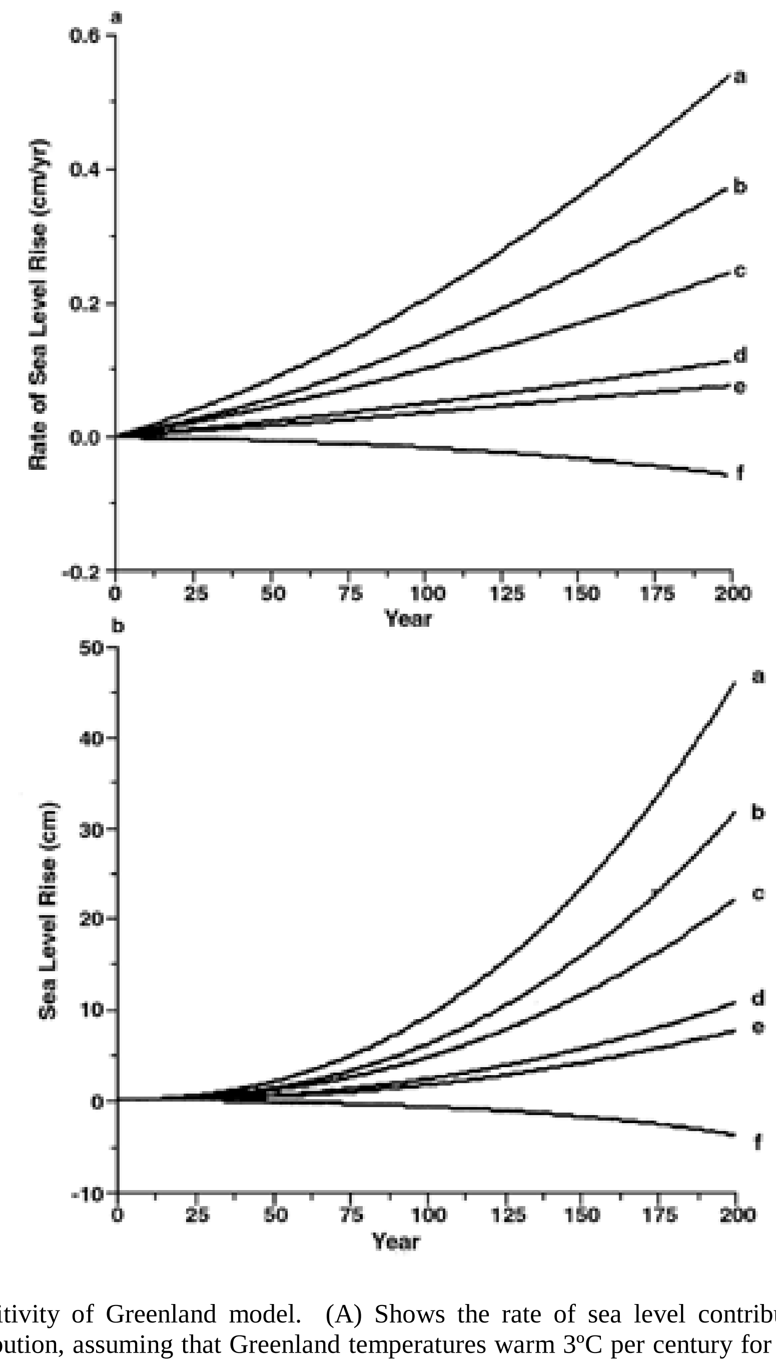


Figure 11. Sensitivity of Greenland model. (A) Shows the rate of sea level contribution and (B) shows the cumulative contribution, assuming that Greenland temperatures warm 3ºC per century for 2000 years. Curves a, c, and d use the 2σ-high, median, and 2σ-low assumptions for equilibrium line sensitivity, espectively, along with the 2σ-low precipitation sensitivity (2.5%/ºC). Curves b, e, and f use the same equilibrium line sensitivities, along with the 2σ-high assumption for precipitation sensitivity (15%/ºC*).*

Combining the nonlinear Bindschadler model with the assumptions from particular climate reviewers for the year 2100 results in a median Greenland contribution of about 1 cm for Manabe and about 2 to 4 cm for most of the other reviewers, much less than the 7½ cm implied by the linearity assumptions favored by Wigley & Raper (Figure 6). By the year 2200, the median estimates of the various reviewer assumptions range from 2 to 20 cm; and the 5%-high estimates range from less than 30 cm for Balling and Manabe to over one meter for Hoffert, Schneider, and Rind.

4.6 SMALL GLACIER CONTRIBUTION

We adopted the functional specification employed by recent assessments, which explain the historic small glacier contribution as a function of temperatures and adjustment times ranging from 10 to 30 years. Those studies used Meier's (1984) estimate of 2.8±1.6 cm in the period 1900-61; but more detailed analysis (Oerlemans and Fortuin 1992) suggests that the contribution was only 1.2 cm. We employ the more recent value, which decreases the median contribution by over half through the year 2100.

5. FINAL RESULTS

5.1 PROCESSES THAT CONTRIBUTE TO SEA LEVEL

Assuming that the 20 reviewers fairly represent current scientific understanding, the following results can be viewed as the probability distribution of the various processes that contribute to sea level.

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 (*see* Figure 4, *supra*). Although a 2°C warming is most likely by the year 2100, there is a 7 percent chance that it will occur by 2050.

Figure 12 illustrates the projected global warming for selected simulations; the top and bottom seven simulations are drawn from the upper and lower 1 percent of the simulations; otherwise, the scenarios represent equal probability. Even though we assumed emissions to be constant after the year 2100, temperatures are projected to continue rising throughout the 22nd century. In three cases, temperatures warm, then cool about a degree, and then warm

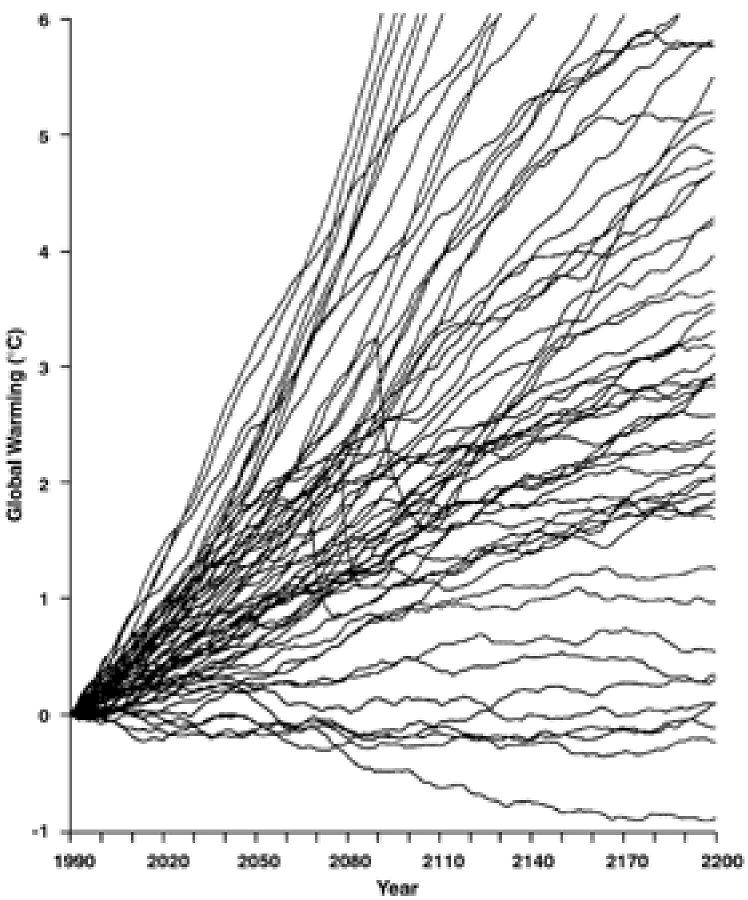


Figure 12. Global warming for selected simulations. This and other spaghetti diagrams illustrate simulations 1, 2, 5, 10, 20, 50, 100, 200, 400, 600…9400, 9600, 9800, 9901, 9951, 9981, 9991, 9996, 9999, 10000, where 1 and 10000 represent the simulations with the highest and lowest estimates of sea level rise for the year 2200.

again; the sudden cooling results from the sudden drop in deepwater formation that three of the reviewers suggested might take place if temperatures cross a threshold. In several other cases, the assumptions regarding natural climatic cycles result in minor cooling for a few decades, before temperatures return to their warming trend.

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 heat is able to penetrate into the intermediate and deep layers of the ocean. A decline in deepwater formation, for example, 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 2½ percent chance that expansion will exceed 50 cm. Although global temperatures are projected to rise 20 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 (*see* Figure 4, *supra*).

Greenland Climate. The likely contribution of Greenland to sea level will depend on the magnitude of increases in precipitation and melting resulting from 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 15 percent chance of a warming greater than 5°C, and a 2½ percent chance that the warming will exceed 10°C (*see* Figure 6, *supra*).

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 contribution to sea level through 2100. Mostly because our temperature estimates are lower, these are significantly less than the low, medium, and high projections (2.5, 7.5, and 15 cm) by Wigley and 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.

Antarctica's temperatures are well below freezing; so unlike Greenland, warmer *air* temperatures will not cause a significant degree of 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.

Figure 13a shows our projections of the change in circumpolar ocean temperatures. Most of the scenarios show gradual changes, due to the assumption that circumpolar temperatures reflect a weighted average of the global temperature over the last century or so. A few scenarios are bumpier, because Rind assumed that circumpolar ocean temperatures reflect the global temperature that prevailed eight decades previously. Considering all of the reviewer assumptions, 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.

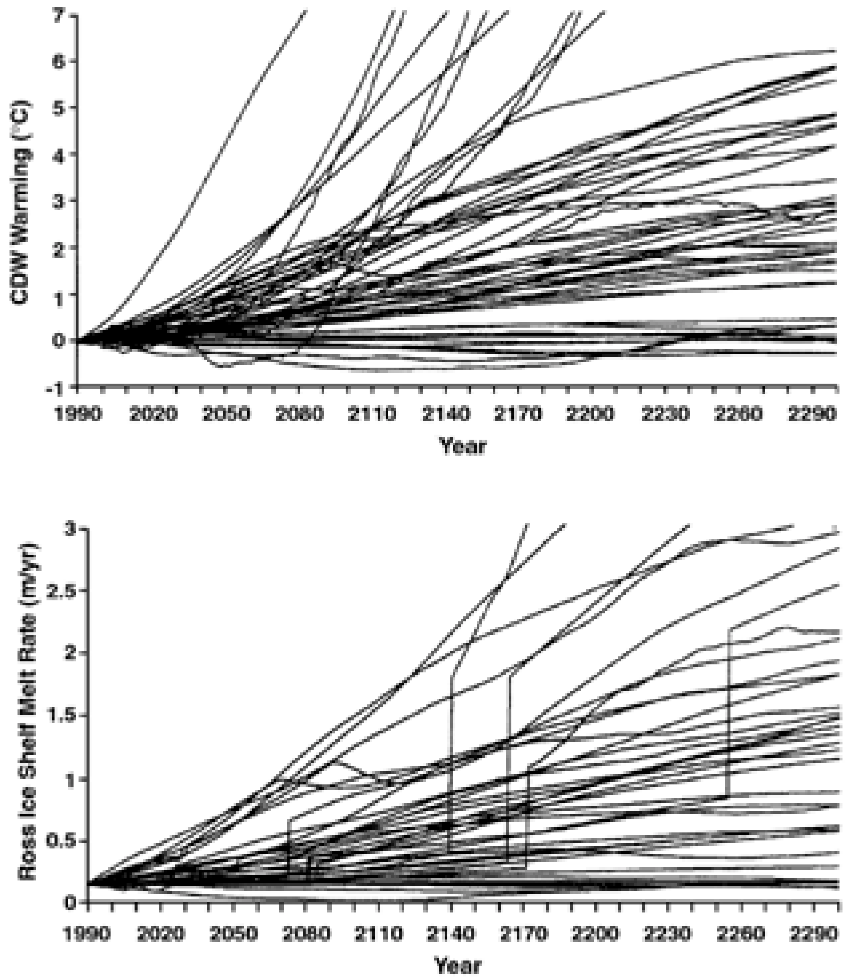


Figure 13. Spaghetti diagrams of the impact of climate change on Antarctic Ocean and ice. Changes in (a) circumpolar ocean temperatures and (b) melt rates of the Ross Ice Shelf. See Figure 12 for explanation of the scenarios shown.

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 0.2 m/yr to 0.4 m/yr, by the year 2100 (*see* Figure 5, *supra*.) Although a doubling may seem significant, most previous studies have suggested that the rate of melting would have to increase by 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.

Figure 13b shows selected simulations of Ross Ice Shelf melt rates. Several of the simulations show sudden jumps, due to the assumption of a threshold after which point undiluted circumpolar deepwater intrudes beneath the 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 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. (*See* Figure 9, *supra*.) 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.

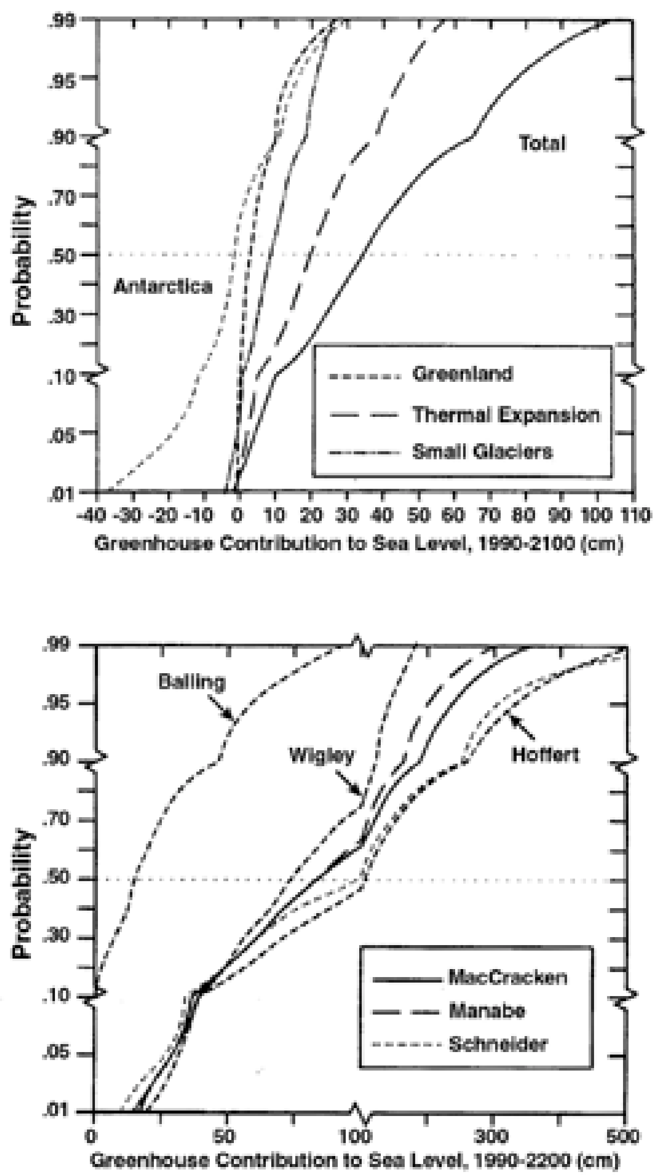


Figure 14. Greenhouse contributions to sea level. These cumulative probability distributions show (a) the greenhouse contribution by 2100 for the various component contributors, and (b) the contribution for the year 2200 by climate reviewer. Wigley and Raper provided assumptions for Greenland and Antarctica; otherwise, the displayed distributions combine the reviewer's climate assumptions with random samples of the assumptions suggested by the precipitation and Antarctic reviewers.

5.2 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, 104cm by 2100, and over 4m by 2200. The most likely (median) contribution, however, is only about one-third as great: 15cm by 2050, 34cm 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. Our median estimate is that climate change will be adding 4.2 mm/yr to sea level by the year 2100, only a modest acceleration over the 3.2 mm/yr average over the next century; but we also estimate a 10 percent chances that the contribution will exceed 10 mm/yr by 2100, and a 1 percent chance that it will exceed 20 mm/yr. Figure 14a illustrates the cumulative probability distribution of the primary contributors to sea level for the year 2100.

Our 34cm median estimate is lower than the new IPCC (1995a) estimate (48 cm by 2100) for four reasons.[59] First, our inclusion of the Balling assumption lowered our median temperature sensitivity, which in turn lowered the median scenario by about 4 cm. Second, IPCC employed a new model of small glacier sensitivity

[59] But cf. Section 5, infra (our median estimate of total global sea level rise is 45 cm). Testifying before a Congressional Subcommittee on the results of this study, an EPA Assistant Administrator noted that the primary difference between our results and the IPCC estimate is the IPCC attributes all see level rise to climate change, while this study assumes that at least two thirds of global sea level rise results from greenhouse warming. U.S. House of Representatives, Subcommittee on Energy and Environment, Hearing on Climate Models and Projections of Potential Impacts of Global Climate Change, Testimony of David Gardiner, November 16, 1995, oral testimony.

which did not give the full effect to the Fortuin and Oerlemans estimate of the historic contribution. Third, IPCC adopted an upwelling assumption similar to the (OM6) assumptions of Manabe, which tended to lower temperatures but increase sea level rise. Finally, the IPCC estimate is based on emissions scenario A, which increases radiative forcing by about 10 percent more than the geometric mean of all six IPCC scenarios, which we use as our median.

Although we have weighted the individual assessments equally, the variation of reviewer assessments may also be worth considering. Figure 14b shows the variation in sea level estimates resulting from the assumptions suggested by the various climate reviewers, weighting the precipitation and ice-sheet assumptions equally. 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 three meter rise by 2200; the Schneider, Rind, and Hoffert assumptions, by contrast, imply a 7 percent chance of a three meter rise and a 1 percent chance of a five meter rise over the next two centuries.

The assumptions by 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 did, their range of sea level projections is also narrower. 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.[60] 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.

We also examined the sensitivity of our results to the emissions scenarios and the uncertainty regarding key parameters. If IPCC emissions scenario E were expected, for example, then the most likely greenhouse contribution through 2200 is 108 cm; freezing emissions in the year 2025 would cut that contribution to 66 cm. We also found that for the year 2100, a precise estimate of the climate sensitivity parameter would reduce our uncertainty (σ) by 35 percent, while precise estimates of the polar amplification and ice-sheet parameters would only reduce uncertainty by 4 percent. For the year 2200, by contrast, climate sensitivity only explains 21 percent of our uncertainty, while the polar temperature and ice-sheet parameters are responsible for 10 and 16 percent, respectively.[61]

6. ESTIMATING SEA LEVEL RISE AT PARTICULAR LOCATIONS

6.1 THE APPROACH USED BY PREVIOUS STUDIES

With one notable exception (Revelle 1983), assessments of future sea level rise since Hoffman et al. (1983) have assumed that global sea level rise will be equal to the sum of the glacial and thermal expansion components.[62] Previous studies on the impacts of sea level rise (*e.g*. Barth and Titus 1984; Dean et al. 1987) have generally assumed that contributors to sea level other than global warming will remain constant. Based on the estimate that global sea level rose 1.2 mm/yr over the last century, these studies mostly 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, and thus projected local sea level as follows:

$$\text{Local (t)} = \text{global (t)} + (\text{trend} - 0.12) * (\text{t} - 1990),$$

[60] Since this manuscript was submitted, Wigley has come to favor the assumption that upwelling will decline in a fashion similar to OM6, suggested by Manabe. *See* IPCC (1995a) at 317.
[61] *See* T&N at 130-33 for additional details.
[62] *See* IPCC (1990) at 275 for a table of pre- 1990 studies, and IPCC (1995a) at 381 for a table of post 1990 studies.

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 more rapidly, some studies have replaced the coefficient 0.12 with 0.18 (*e.g.* Leatherman and Nichols 1995).

Implicit in this procedure was the assumption that in the next century, global warming will be the only net contributor to global sea level. As long as estimates were in the 100-200 cm range, there was probably little practical reason to distinguish between global sea level rise and the component induced by greenhouse gases. With the recent downward revisions, however, failure to make this distinction can lead to anomalous results.

For example, Wigley & Raper's (1992) low scenario projected that climate change will add 1.4 mm/yr through 2100. Because the same scenario has a negative historic climate contribution to sea level of –0.1 mm/yr,[63] the net effect of the low scenario would be a 1.5 mm/yr *acceleration*. Yet because the projection of 1.4 mm/yr is less than the 1.75 (Trupin and Wahr 1990) to 2.4 mm/yr (Peltier and Tushingham 1991) estimated rise over the last century, some coastal impact analysts have interpreted the low scenario as implying that sea level rise will be 0.3 to 1.0 mm/yr less in the next century. (See e.g. Nichols and Leatherman 1995).

As Figure 15 shows, the reviewer assumptions imply that greenhouse warming contributed a median of 0.5 mm/yr over the last century — well below recent estimates of 1.8–2.4 mm/yr. Why the discrepancy? Perhaps sea level is also rising due to nongreenhouse factors, such as groundwater depletion (Sahagian et al. 1993), a delayed response to the warming that has taken place since the last ice age, or shifts in ocean basins. Perhaps tidal gauges do not measure true global sea level rise because coasts are generally subsiding.[64] Or perhaps sea level is more sensitive to climate than we realize.

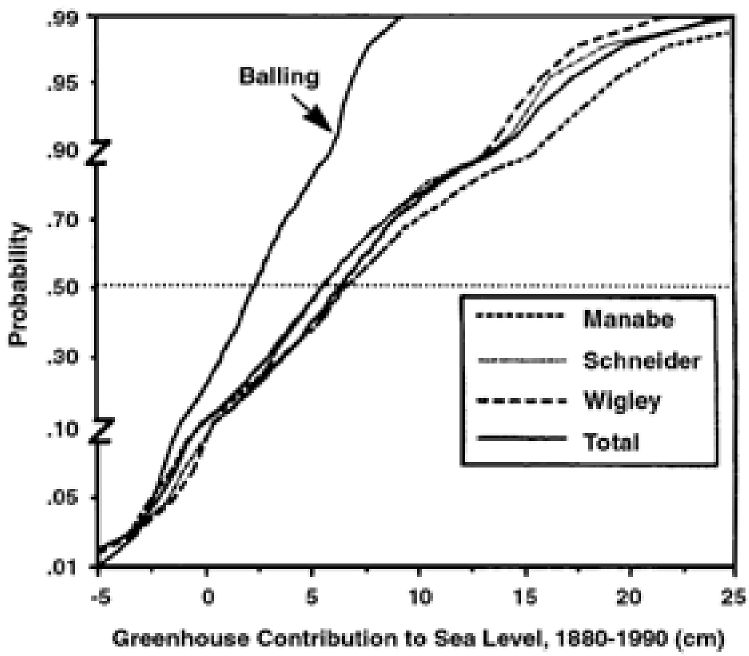


Figure 15. Historic greenhouse contribution to sea level, 1880-1990. The median estimate of the greenhouse contribution (0.5 mm/yr) is well below prevailing estimates of global sea level rise (1.0 to 2.5mm/yr). Unless the nongreenhouse contributors are likely to change, it is reasonable to assume that global sea level rise in the next century will also be 0.5 to 2.0 mm/yr greater than the greenhouse contribution. These other contributors may include aquifer depletion, changes in ocean basins, longer-term climate change, and subsidence in excess of that assumed by current estimates.

6.2 RECOMMENDED APPROACH

Until we know precisely why the models underpredict historic sea level, it seems most reasonable to extrapolate all trends other than those we are able to model. Tidal gauge measurements are already used by practitioners to extrapolate sea level trends; but if they are simply added to projections of the greenhouse-induced rise, one doublecounts the historic greenhouse contribution. We remove this double-counting by developing a set of normalized projections in which the

[63] Unpublished diagnostic from Wigley and Raper model.
[64] For example, due to the additional mass placed on the continental shelves from previous sea level rise.

historic (trend) component of the greenhouse contribution has been removed. For each simulation, the normalized projection was calculated as follows:

$$\text{Normalized}_i(t) = \text{global}_i(t) - (t-1990)\,\frac{\text{Model}_i(1990) - \text{Model}_i(1880)}{110},$$

where $\text{global}_i(t)$ is the greenhouse contribution to sea level between 1990 and the year t for the i^{th} simulation; and Model_i represents the historic greenhouse contribution to sea level estimated by the i^{th} simulation to have taken place 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 forward. Assuming that nongreenhouse factors remain constant, *the normalized projections estimate the extent to which future sea level rise will exceed what would have happened if current trends simply continued.*

Table V presents our normalized projections. Through the year 2025, there is an 85 percent chance that sea level will rise more rapidly than it has been rising in the last century, and a 10 percent chance that sea level will rise 12 cm more than would be expected based solely on extrapolating historic trends. These results also give some indication as to when the acceleration in sea level rise might be sufficient for coastal managers to be concerned. One might reasonably assume, for example, that a 1 mm/yr acceleration sustained over a period of three decades would be a cause for concern. The normalized results suggest that there is a 65 percent chance that such an acceleration will occur before the year 2025 (i.e. 3.5 cm normalized rise by 2025).

Table V
Estimating sea level rise at a specific location - normalized sea level projections, compared with 1990 levels (cm)

Cumulative probability	Sea level projection by year:					
	2025	2050	2075	2100	2150	2200
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

To estimate sea level at a particular location, add these estimates to the rise that would occur if current trends were to continue. For estimates of current rates of sea level rise in the United States, see Lyles et al. 1988.

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:

$$\text{local}(t) = \text{normalized}(t) + \text{trend} \times (t\text{-}1990).$$

Consider, for example, New York, whose trend of 2.7 mm/yr (Lyle et al. 1988) is typical of the U.S. Atlantic Coast. Thus, even current trends imply a 10 cm rise by 2025 and 30 cm by 2100. Adding the normalized projection, we calculate a 1 percent chance that sea level will rise 29 cm (almost one foot) by the year 2025, and a 50 percent chance of a 15 cm (six inch) rise.

The Table also shows that for the year 2100, the median, 7%-high and 1%-high normalized scenarios are 25, 60, and 92 cm, respectively. Thus, the reviewer assumptions imply a 50 percent chance that relative sea level at New York will rise 55 cm by 2100, and a 7 percent chance of a 90 cm rise. The '5-foot contour' on topographic maps—which is less than 4-½ feet above current sea level—has a 1% chance of being inundated in the next century and a 40 percent chance of inundation in the next two centuries (Figure 16).

One can also use the normalized scenarios to project global sea level rise. Assuming that the current global rate of sea level rise is 1.8 mm/yr, the median and 1%-high estimates for 2100 are 45 and 112 cm, respectively.

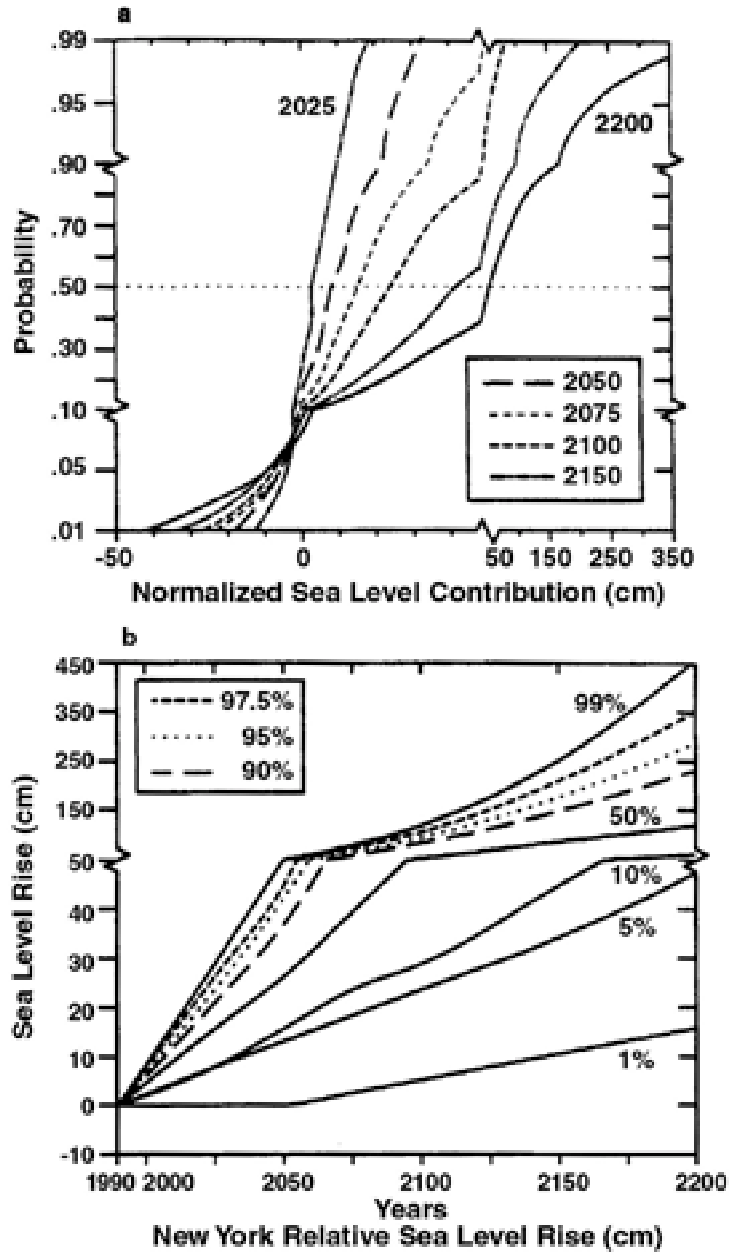


Figure 16. Future sea level rise at New York City. The normalized estimates represent the projected *acceleration* in sea level compared with historic trends. One can estimate local or global sea level by adding these estimates to trends from tide gauges. Here, the normalized estimates are added to New York's historic trend of 2.7 mm/yr, which typifies the U.S. Atlantic Coast.

7. CONCLUSION AND IMPLICATIONS

The last decade has seen an emerging scientific consensus that global temperatures will probably rise a few degrees in the next century. Nevertheless, the estimates of future warming have declined from 0.5°C per decade to about 0.2°C per decade, due to revised estimates of greenhouse gas emissions and the recent recognition of the cooling effect of anthropogenic aerosols. The estimated sensitivity of small glaciers to warmer temperatures has also been cut substantially. The combined implications of the IPCC emission scenarios and the expectations of our 20 reviewers imply a 50% chance that greenhouse gases will add 34 cm to sea level through the year 2100, and a 1% chance of a one meter contribution. Although there is still a risk of a large rise, our median is a downward revision of previous "best guess" estimates by IPCC (65 cm) and Wigley & Raper (48 cm).

Because this analysis incorporates the major uncertainties *that have been analyzed*, it provides a rational set of assumptions for use by coastal engineers and regulators. Nevertheless, because there are no experimental data from which probability estimates can be derived, our results represent *conditional* probability estimates—conditional upon the models, the reviewer-based assumptions, and our assumption that the reviewers who participated adequately reflect the range of scientific opinion. Our failure to include unknown and unquantified factors implies that our analysis probably understates the true range of uncertainty.

Does the prospect of accelerated sea level rise still warrant a response? The answer depends on the nature of the response one is considering. Even a one meter rise appears to account for only 5-10% of the likely cost of global warming (Cline 1993) so downward revisions of sea level estimates are unlikely to significantly alter a *global* cost/benefit analysis of policies to limit greenhouse gas emissions. Because coastal residents are less immediately threatened than implied by previous studies, those who are only mildly vulnerable to a one meter rise may conclude that their direct interest in reducing emissions is less than previously thought (e.g. IPCC 1990b). Nevertheless, coral atoll and deltaic nations – where a one meter rise in sea level would eliminate a major fraction of all inhabitable land (Id.) – may view even a 1 percent chance as a risk that they would prefer to avoid.

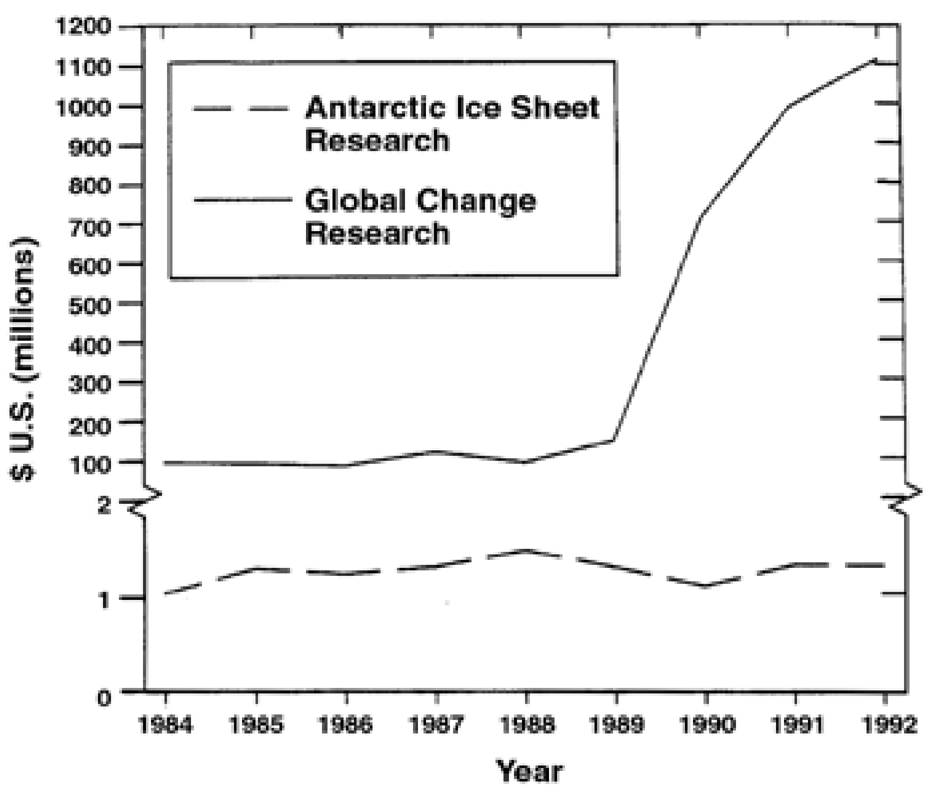


Figure 17. Failure of ice sheet research budgets to benefit from increased global change research.
Source: National Science Foundation; Annual Reports of the United States Global Climate Research Program Office and the predecessor National Climate Program Office.

The urgency of adapting to accelerated sea level rise also varies. A 30 cm rise would erode most beaches 30–60 meters (*see e.g.* Bruun 1962) which in many countries is greater than the typical setback for coastal construction. Even with the lower sea level scenarios, communities that do not want to see their public beaches and wetlands squeezed between eroding shores and development protected by seawalls must enact appropriate land use planning measures (see Titus 1991; 1994). Preparing for accelerated sea level rise is less urgent in areas that will be protected with dikes (Dean et al. 1987); but it may be cost-effective to include a safety factor for future sea level rise within the design of structures built to address current problems.

Finally, increased ice-sheet research is warranted by the small but important risk of a large Antarctic contribution to sea level. In the United States, for example, the prospect of a large rise in sea level was one of the factors that motivated policy makers to expand the national budget for climate-related assessments. The funding, however, did not filter down to the ice-sheet modeling community (Figure 17) which still lacks basic data on the relationship between global climate, polar sea temperatures, circulation below the ice shelves, and mass fluctuations of ice shelves and ice sheets (Bindschadler, 1991). If there is a global warming threshold past which a disintegration of the West Antarctic Ice Sheet would become inevitable, most policy makers would agree that such a threshold should not be exceeded. By failing to obtain the necessary baseline data, society is taking the chance that this threshold – if it exists – will be exceeded before it is discovered.

DISCLAIMER AND ACKNOWLEDGEMENTS

The opinions expressed in this paper do not necessarily reflect the views of the U.S. Environmental Protection Agency or any other agency of the United States Government. For a report that *does* reflect EPA's official opinion on the same issues, *see The Probability of Sea Level Rise,* available from the National Center for Environmental Publications and Information, P.O. Box 42419, Cincinnati, Ohio, 45242 (fax: 517-797-2730).

Words can not express our gratitude to the many people who helped us. Twenty expert reviewers provided subjective probability distributions for the key input parameters; and four other expert reviewers who suggested alternative modeling assumptions (*see* Table 1). Five of those experts provided particularly important assistance: Sarah Raper and Tom Wigley provided us with the code to their ocean model; Martin Hoffert also provided the code to his upwelling diffusion model, which we used in early versions of the analysis. Michael MacCracken provided a particularly scrupulous review of four different incarnations of this study. Stephen Schneider provided important moral support and encouragement, and first suggested that our analysis be put ‘on the record.’

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