CHAPTER 5

ANTARCTIC ICE SHEET

Background

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3. The Thomas ice stream model.[2]

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

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

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

Approach

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

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

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

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

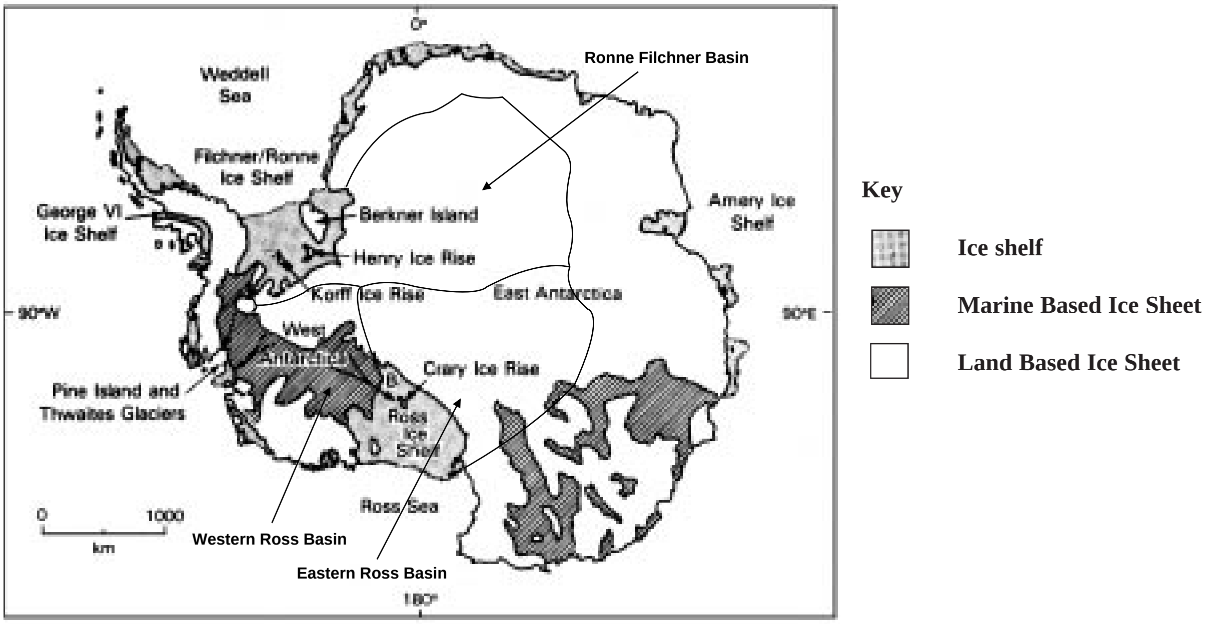

Figure 5-1. The Antarctic Basins Used in This Report.

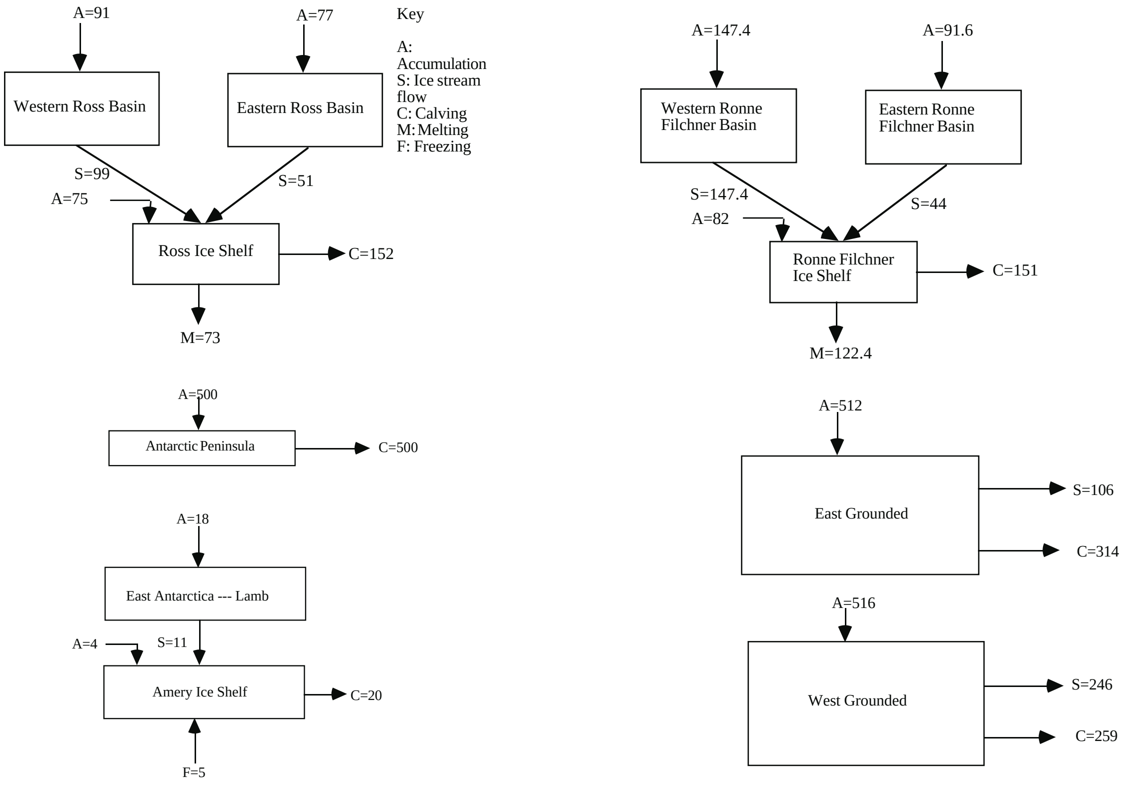

Figure 5-2. Schematic of the Antarctic Mass Flows Used in This Report.

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

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

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

TABLE 5-1 (continued)

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

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

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

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

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

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

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

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

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

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

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

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

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

[c] Includes Amery Ice Shelf.

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

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

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

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

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

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

<u>Ross Ice Shelf</u>

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

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

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

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

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

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

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

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

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

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

However, this equation has to be modified, because it implies that the warm intrusion today has a temperature of 3/(1+A_1SEAICE) above the *in situ* melting temperature when, in fact, the temperature is 0.5˚C above the *in situ* melting temperature, regardless of the value for A_1. Therefore, we subtract 3/(1+A_1SEAICE)–0.5. This adjustment is in turn multiplied by SEAICE; as

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

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

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

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

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

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

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

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

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

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

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

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

Other Ice Shelves

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

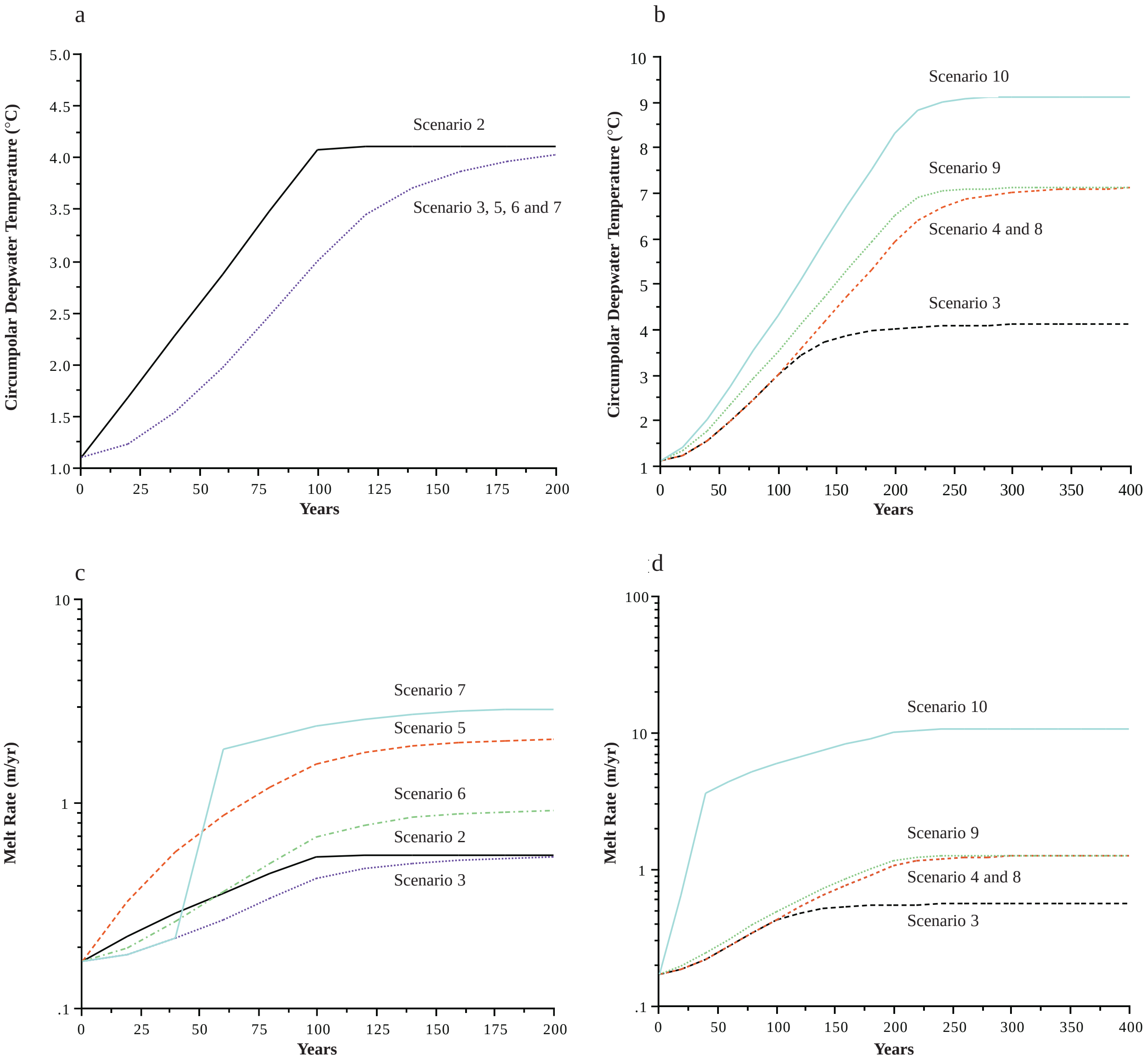

Figure 5-3. Circumpolar Deepwater Temperatures and Shelf Melt Rates for Various Scenarios. Scenarios defined in Table 5-3 are shown (a) for the first two hundred years and (b) for the first four hundred years. The corresponding shelf-melt rates are shown in (c) and (d). Scenario 3 is shown for comparison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

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

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

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

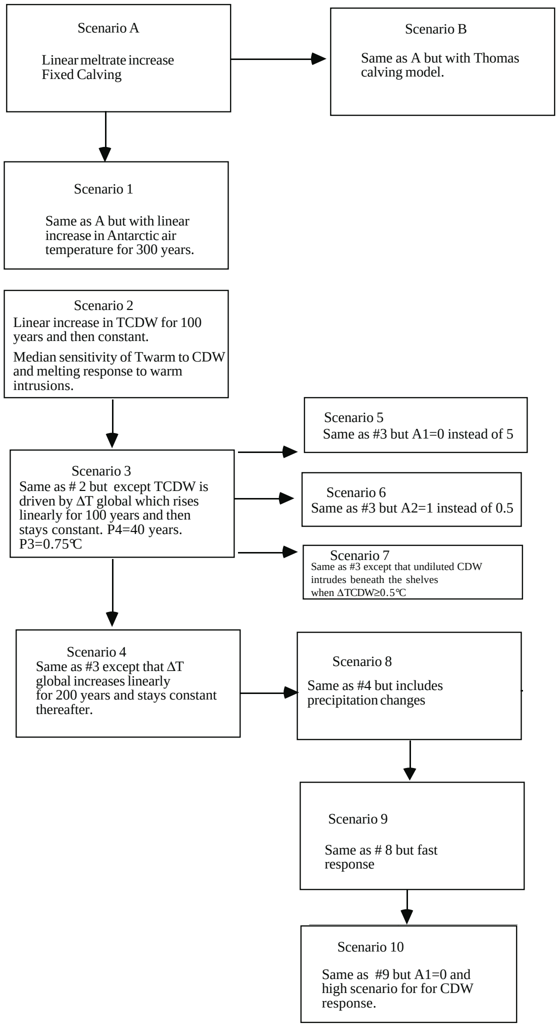

Figure 5-4. The Relationships Between the Sensitivity Runs.

Impact of Basal Melting on Grounded Ice

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

Simple Model Based on Melting (AM2)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

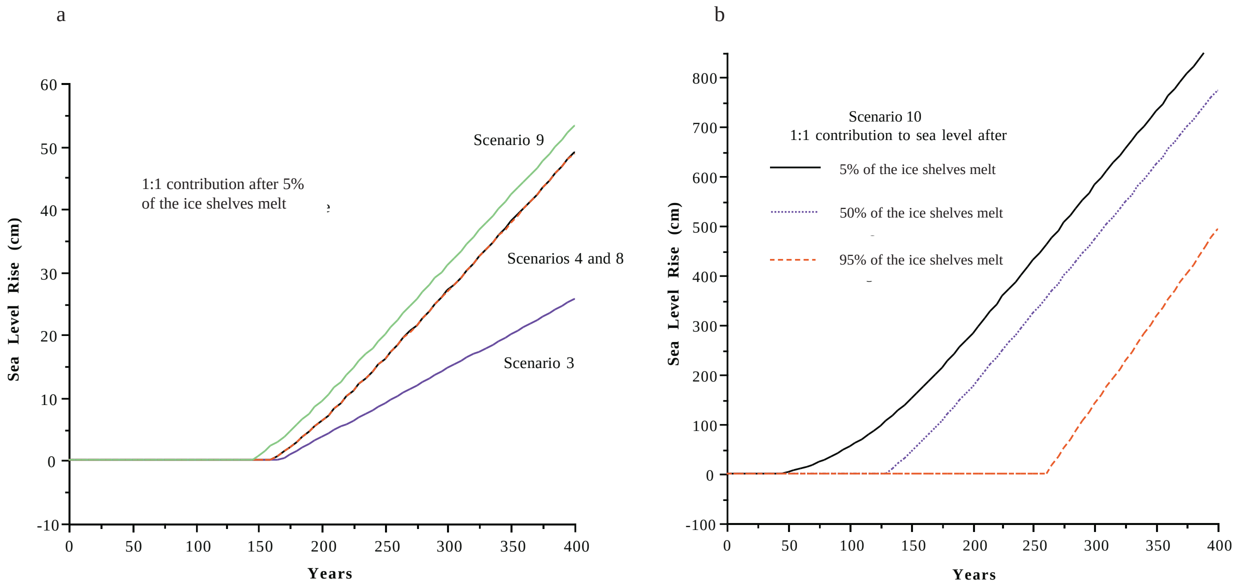

Figure 5-5. Antarctic Contribution for the Draft Melt-Only Model. Sea level contribution for (a) scenarios 3, 4, 8, and 9 (see Table 5-3), given the assumption that $(A_7)^{1/2}$ (the fraction of the ice sheet that must melt before melting contributes to sea level rise) is equal to 0.05, and (b) scenario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

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

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

and thus,

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

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

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

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

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

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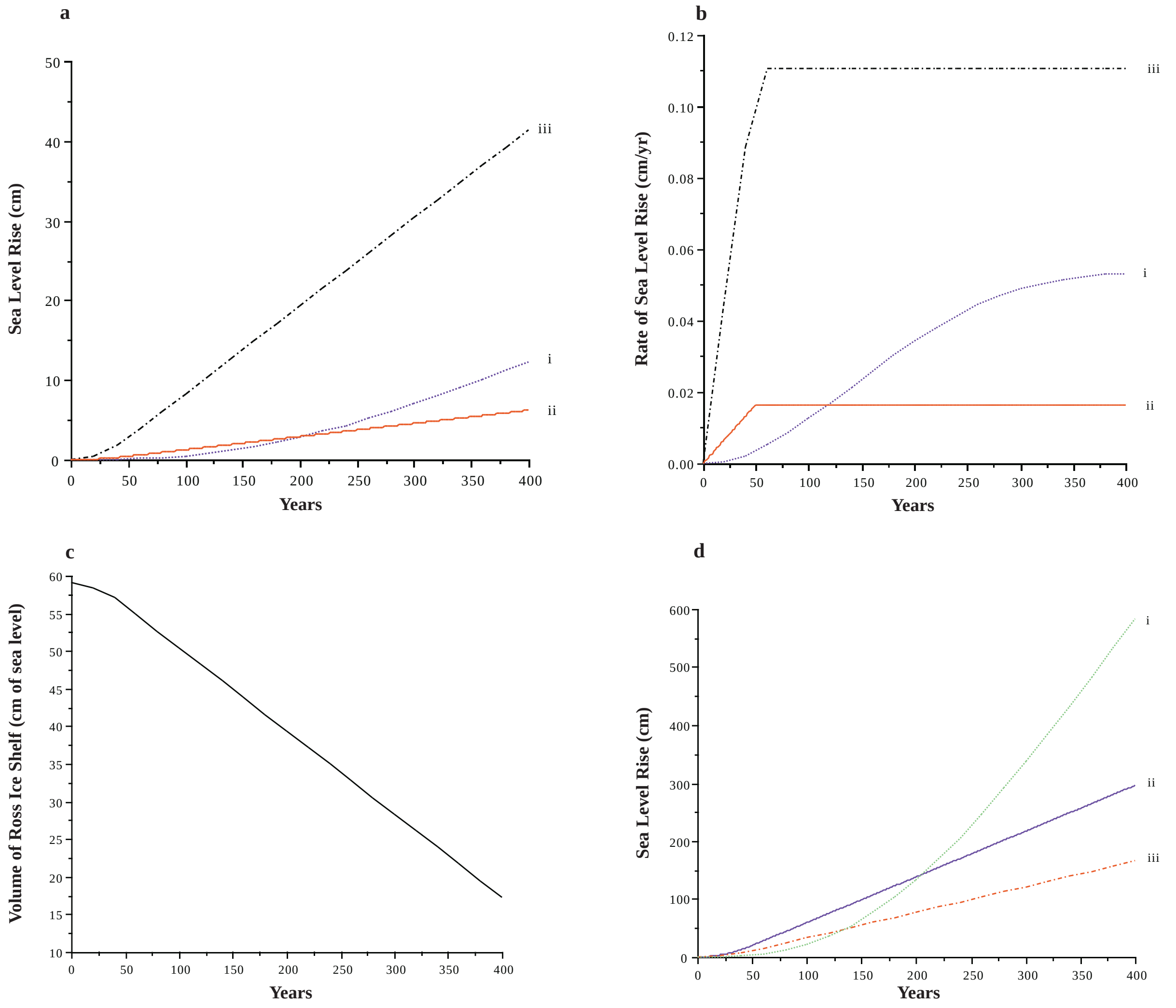
[5] Area is represented by length in this 2-D model.



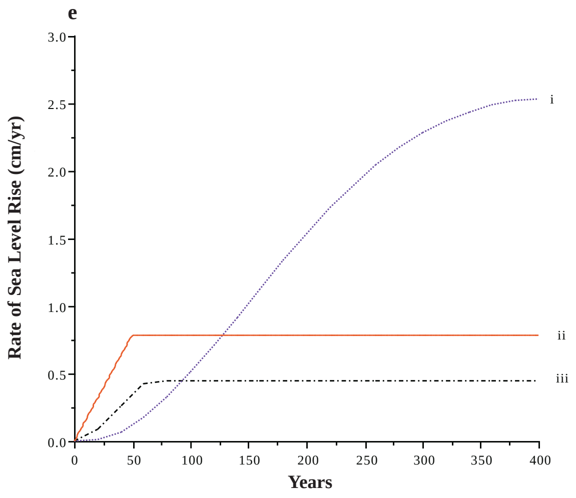


Figure 5-6. Contribution to Sea Level from Ice Stream B and Antarctica Predicted by Thomas (1985). These scenarios assume that the Ross Ice Shelf melt rate accelerates from 0 to 1 m/yr linearly in the first 50 years and is constant thereafter. (a) Sea level equivalents of (i) Ice Stream B contribution,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

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

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

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

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

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

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

Alternative Scaling of the Thomas Model

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

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

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

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

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

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

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

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

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

Disaggregating the Thomas Model into Different Ice Streams (AM6)

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

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

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

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

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

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

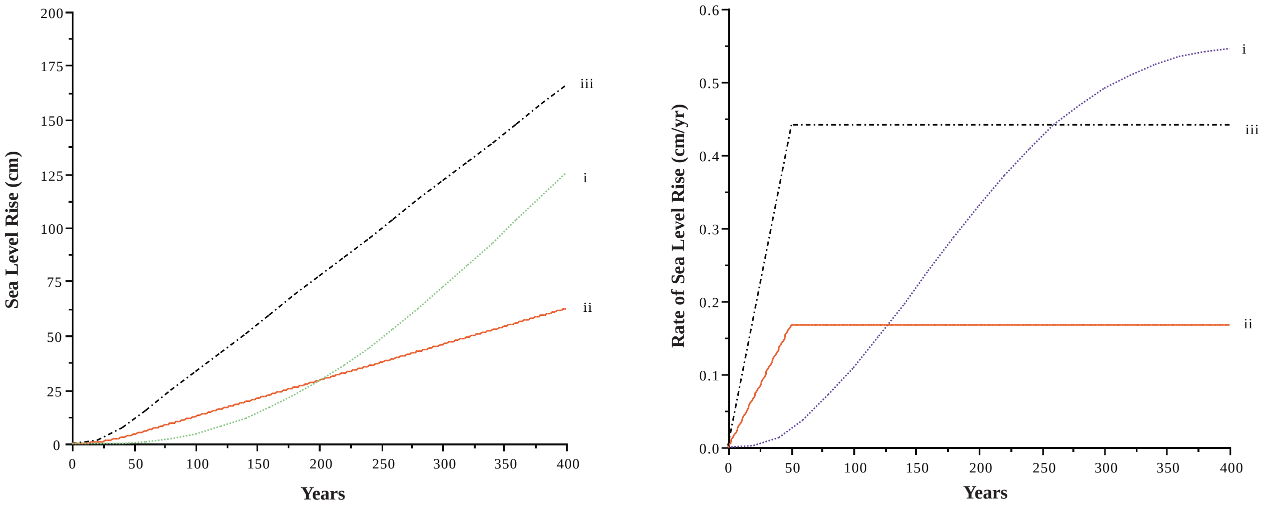

Figure 5-7. Antarctic Contribution to Sea Level According to Model AM4. Same as Figure 5-6 (d) and (e), except based on AM4; *i.e.*, Ice Stream B results scaled by the contribution of ice streams feeding Ross and Ronne-Filchner Ice Shelves.

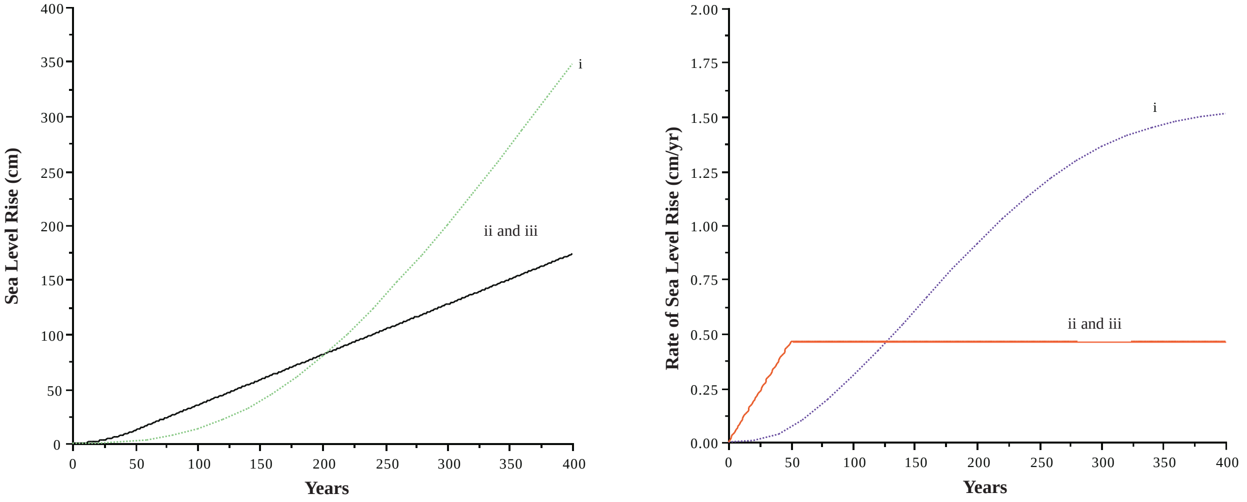

Figure 5-8. Antarctic Contribution to Sea Level According to Model AM5. Same as Figure 5-6 (d) and (e), but for AM5.

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

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

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

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

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

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

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

Sensitivity Runs and Selected Simulations

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

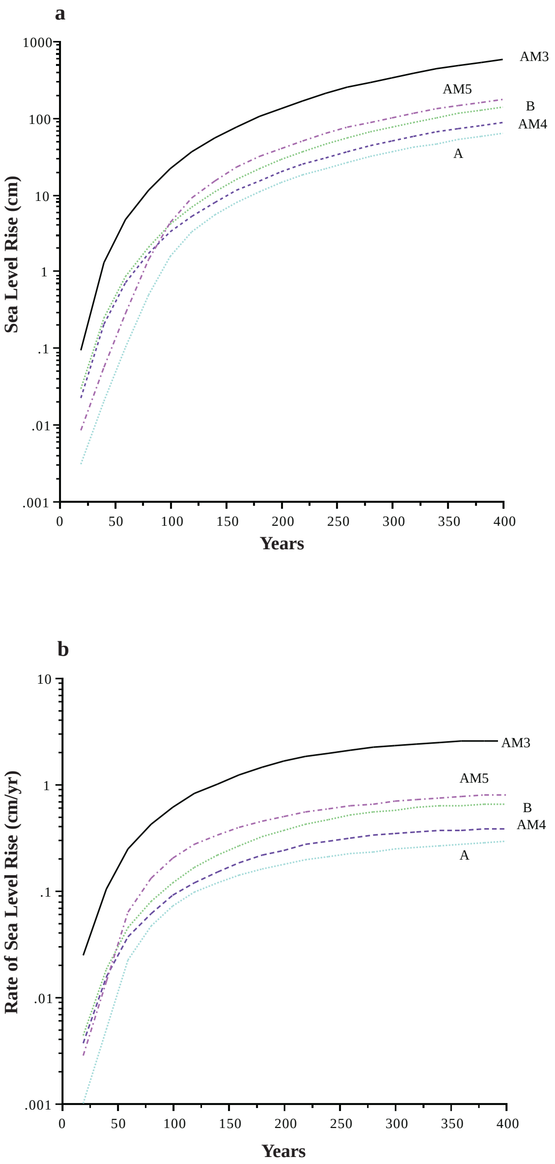

Figure 5-9. Comparison of Alternate Scalings of the Thomas Model. Estimates of (a) total sea level and (b) rate of sea level rise contribution from Antarctica, for the various extrapolations of the Thomas model (AM3, AM4, AM5), as well as our more disaggregated version (A=AM6 with fixed calving, and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

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

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

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

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

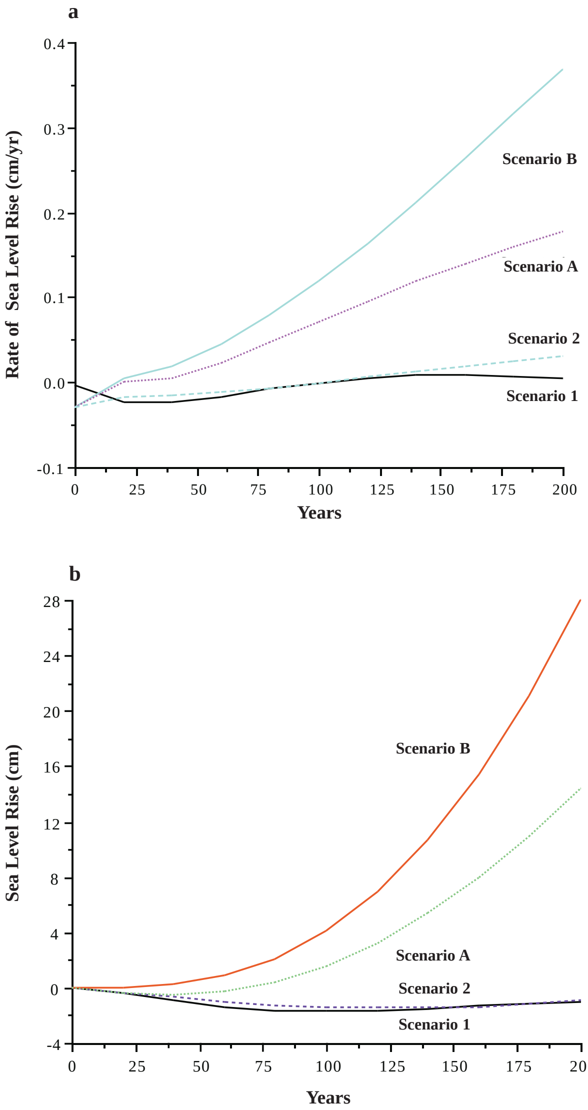

Figure 5-10. Antarctic Contribution to Sea Level According to Model AM6. Total contribution and rate of sea level rise for scenarios A, B, 1, and 2.

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

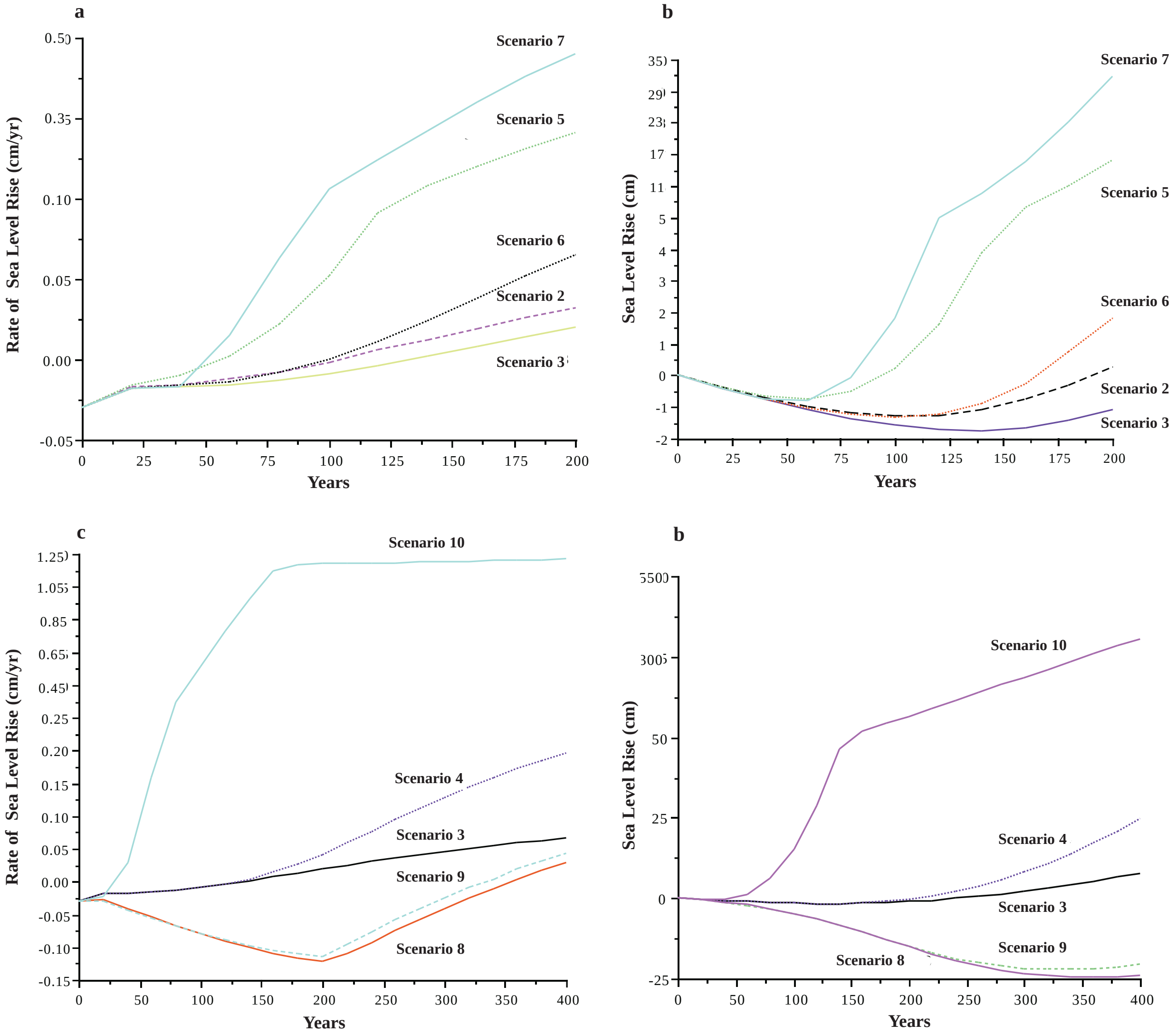

Figure 5-11. Sensitivity Analysis of Model AM6. Cumulative and annual Antarctic contribution to sea level (a and b) for scenarios 2, 3, 5, 6, and 7, and (c and d) for 3, 4, 8, 9, and 10.

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

Linearization of the Huybrechts & Oerlemans Model (AM7)

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

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

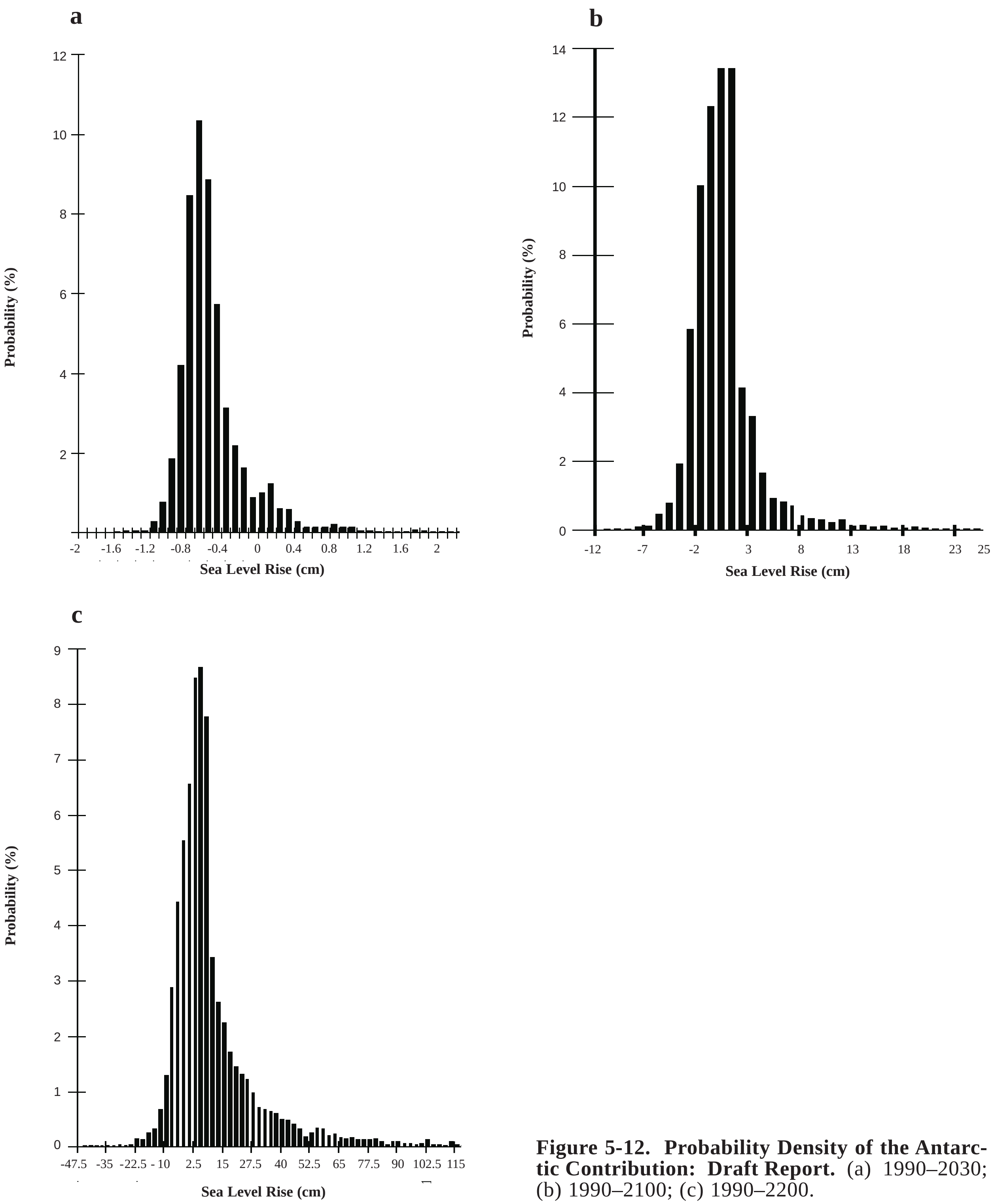

Figure 5-12. Probability Density of the Antarctic Contribution: Draft Report. (a) 1990–2030; (b) 1990–2100; (c) 1990–2200.

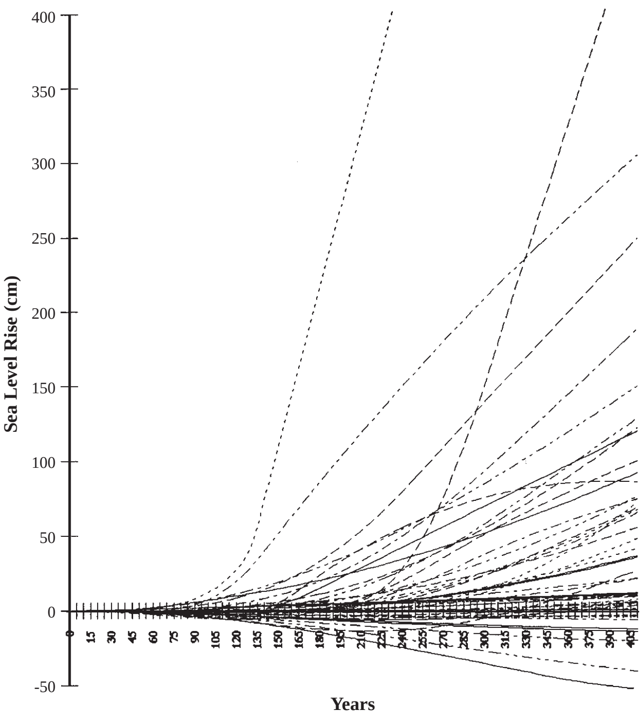

Figure 5-13. Spaghetti Diagram of Antarctic Contribution to Sea Level: Draft Report. Antarctic contribution for selected simulations. See Figure 2-5 and accompanying text for additional explanation.

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

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

Draft Results

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

Expert Judgment

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

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

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

TABLE 5-5
EXPERT REVIEWERS OF CHAPTER 5

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

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

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

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

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

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

Ice Shelf Assumptions

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

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

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

> The issue of present-day warm intrusions and how they might change with time is still an open and thorny question. The impact of warm water is best documented beneath the George VI Ice Shelf (Potter and Paren 1985), where the basal melt rate appears to be an order of magnitude higher than beneath the Ross. It is not clear how readily this Bellinghausen Sea type circulation could spread to other regions of the continental shelf. In particular, present circulation beneath the Ross Ice Shelf may be protected by the strong offshore winds that generate large amounts of sea ice and high salinity shelf water in that sector. The winds may not be as strong in the Weddell Sea, but there the Antarctic Peninsula and Weddell Gyre keep the deep water cooler. This makes some of the Jenkins estimates look a bit on the high side to us, at least on the near term.
>
> [The current report assumes] that dilution of the warm intrusion by shelf water is proportional to annual sea ice formation. Maybe so, but there are several problems with that assumption, aside from what's noted above. [The] "dilution" applies only to temperature, whereas the salinity and volume changes may be more important. At low temperatures, salinity exerts the primary control on density and the resulting thermohaline circulation. Further, the "dilution" of interest occurs only over the continental shelf, which occupies <20% of the winter sea ice extent. It might thus be argued that ice cover could change substantially without much of an impact on the shelf circulation. It has also been hypothesized that a warmer and wetter atmosphere will effectively cap vertical heat flux from the deep water, allowing sea ice to grow thicker (Manabe et al., 1991). However, so far the intuition fits the evidence, in that higher air temperatures are negatively correlated with sea ice extent.[11]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Ice Sheet Response to Shelf-Thinning

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

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

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

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

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

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

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

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

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

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

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

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

Final Results

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

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

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

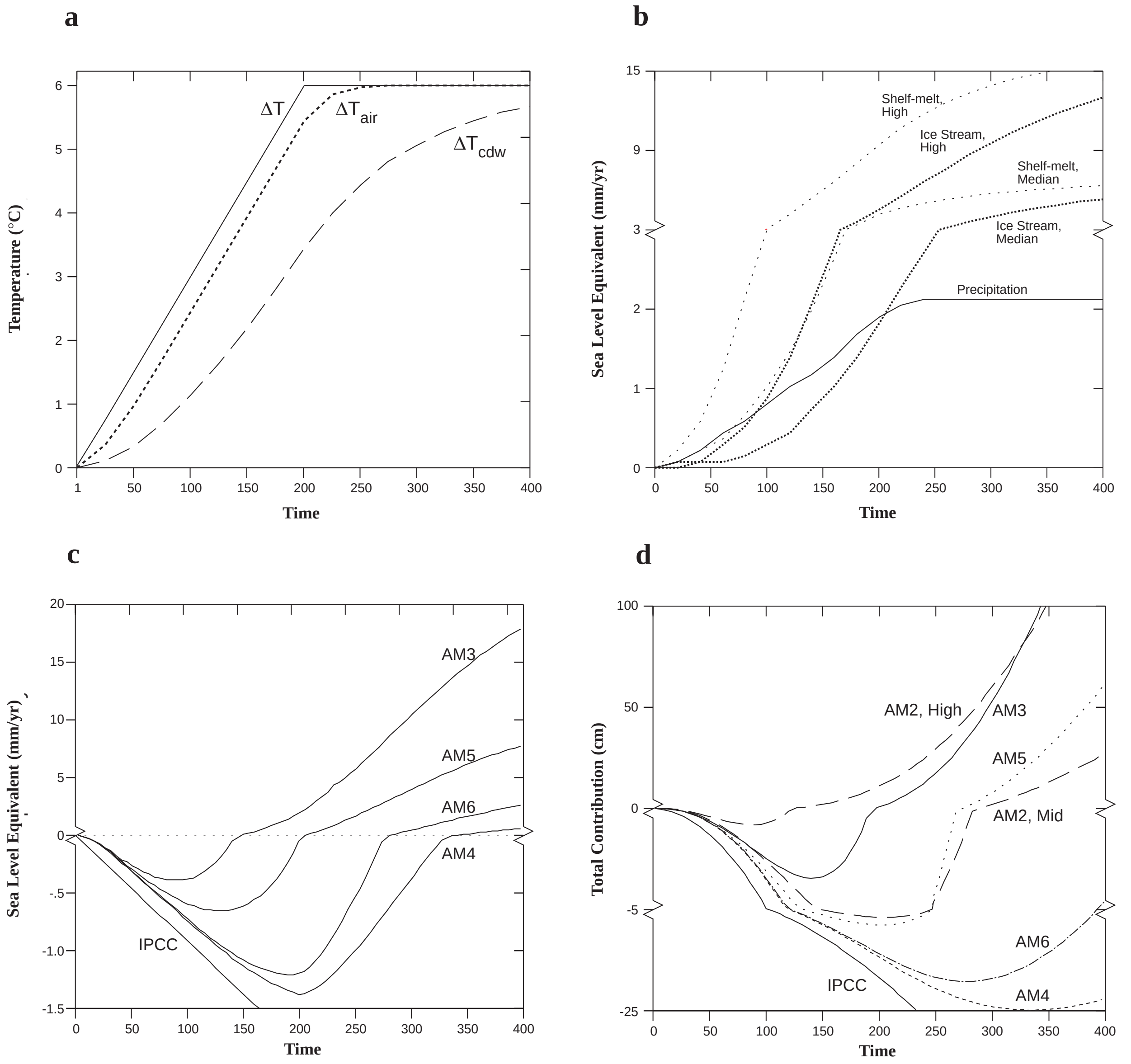

Figure 5-14. Revised Models of Antarctic Contribution. (a) Temperature changes using median response time assumptions. (b) The resulting annual shelf-melting, precipitation, and Antarctic contributions to sea level implied by the stable melt-only model AM2, using median and 2σ-high assumptions for shelf-melt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

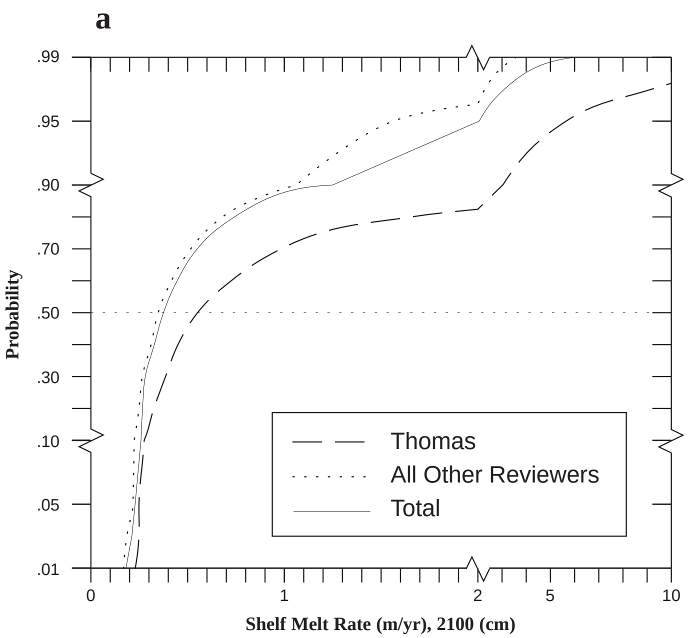

Figure 5-15. Ross Ice Shelf Melt Rates: Cumulative Probability Distribution.

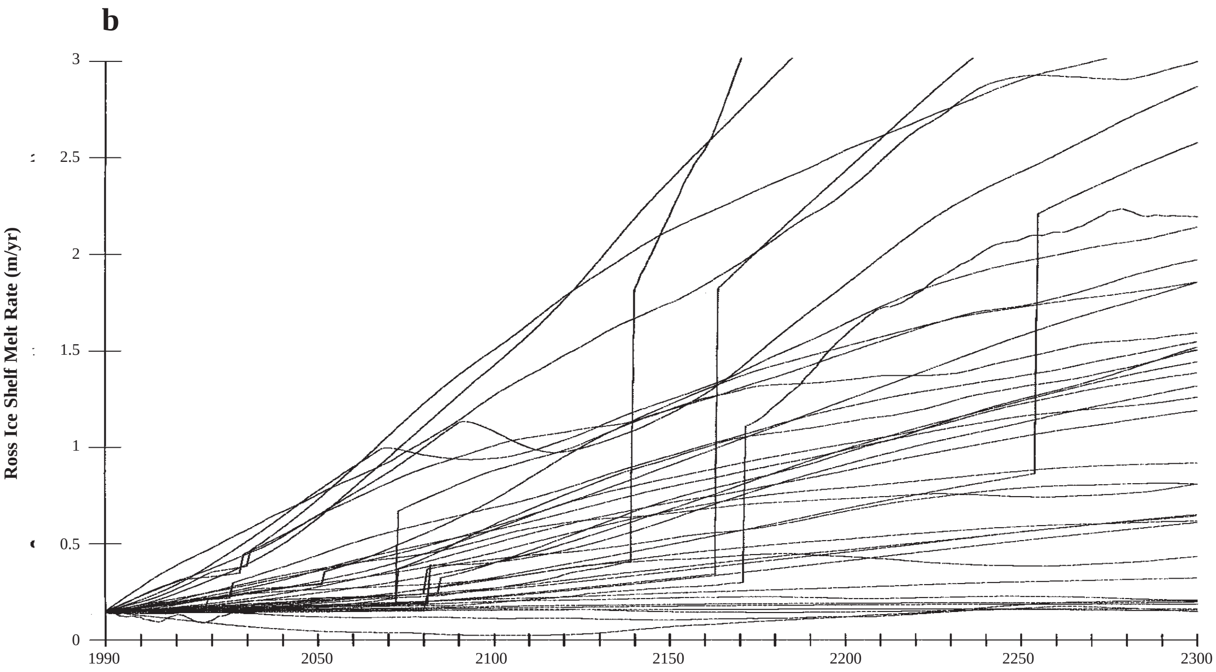

Figure 5-16. Ross Ice Shelf Melt Rates: Selected simulations for the period 1990–2300. See Figure 2-5 and accompanying text for the source of the simulations selected.

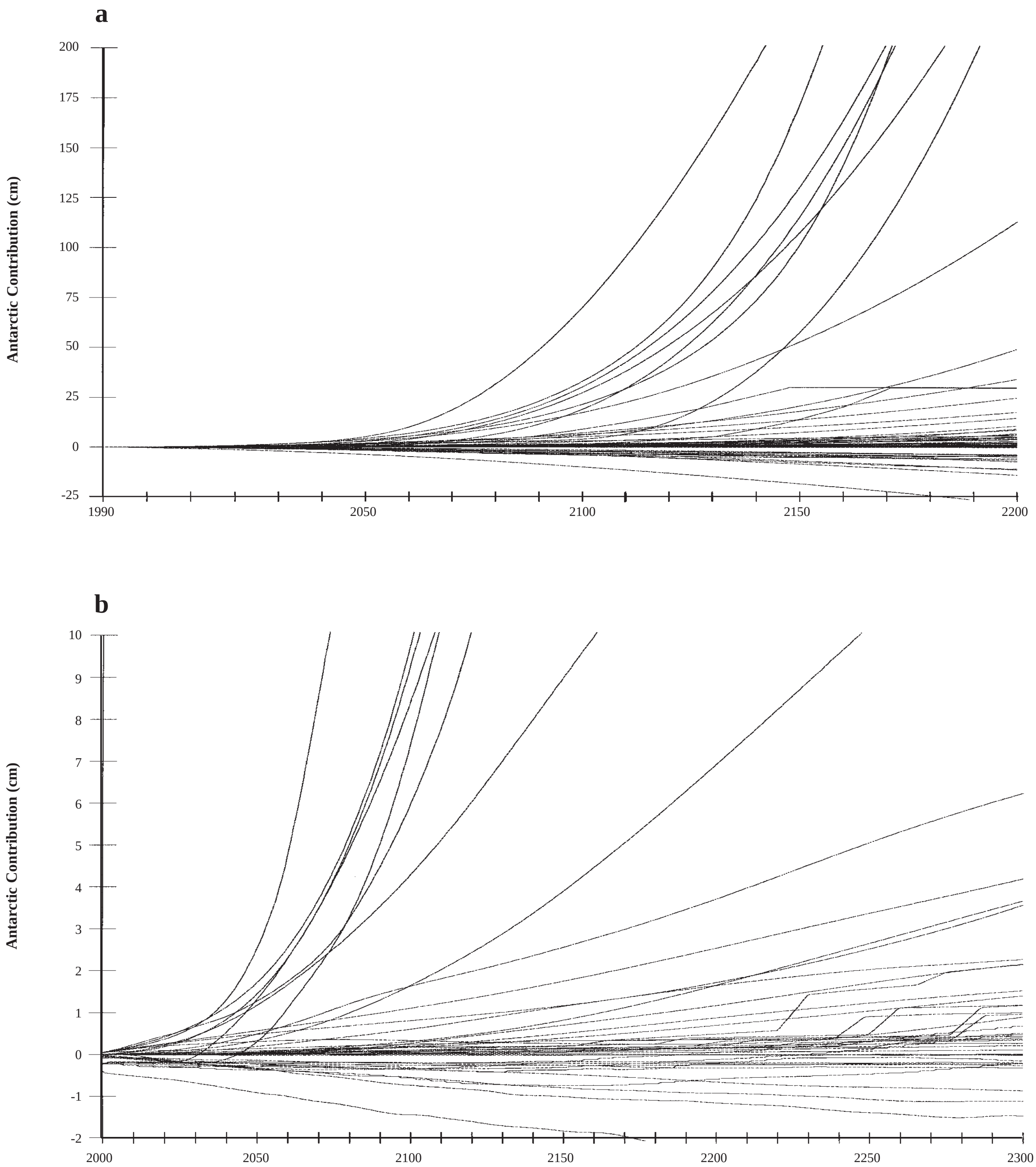

Figure 5-17. **Spaghetti Diagrams for Antarctic Contribution.** (a) Annual and (b) cumulative Antarctic contribution for selected simulations. See Figure 2-5 and accompanying text for explanation of scenarios illustrated.

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

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

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

TABLE 5-8
CUMULATIVE PROBABILITY DISTRIBUTION
ANTARCTIC CONTRIBUTION

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

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

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

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

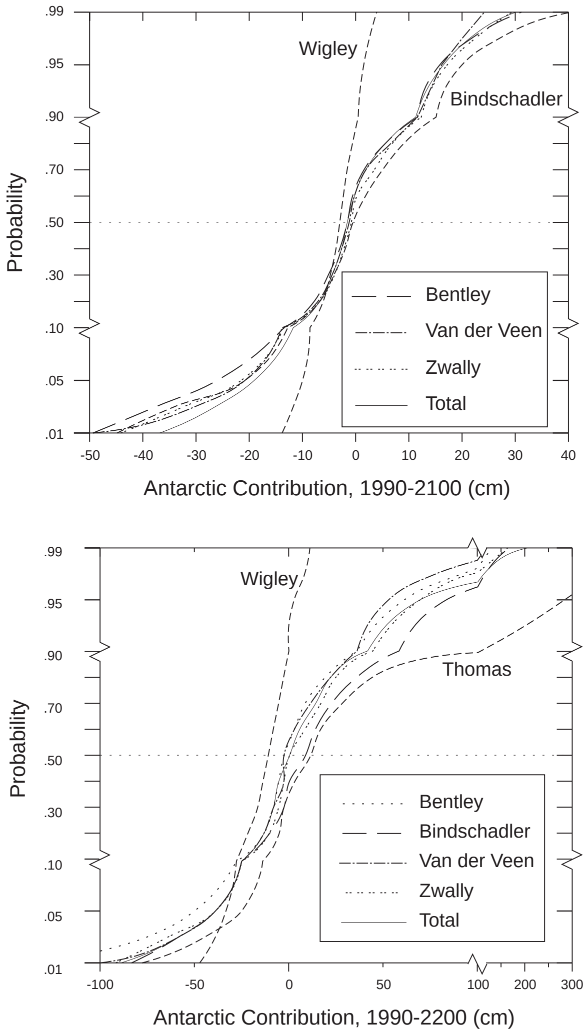

Figure 5-18. Cumulative Probability Distribution of Antarctic Contribution to Sea Level by Reviewer. A few curves have been removed for clarity: The distribution implied by the Alley and Anonymous assumptions generally tracked those of Bentley and Van Der Veen, respectively. For the year 2100, the Thomas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

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

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