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

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

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

Final Results

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

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

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

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

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

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

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

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

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

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

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

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

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

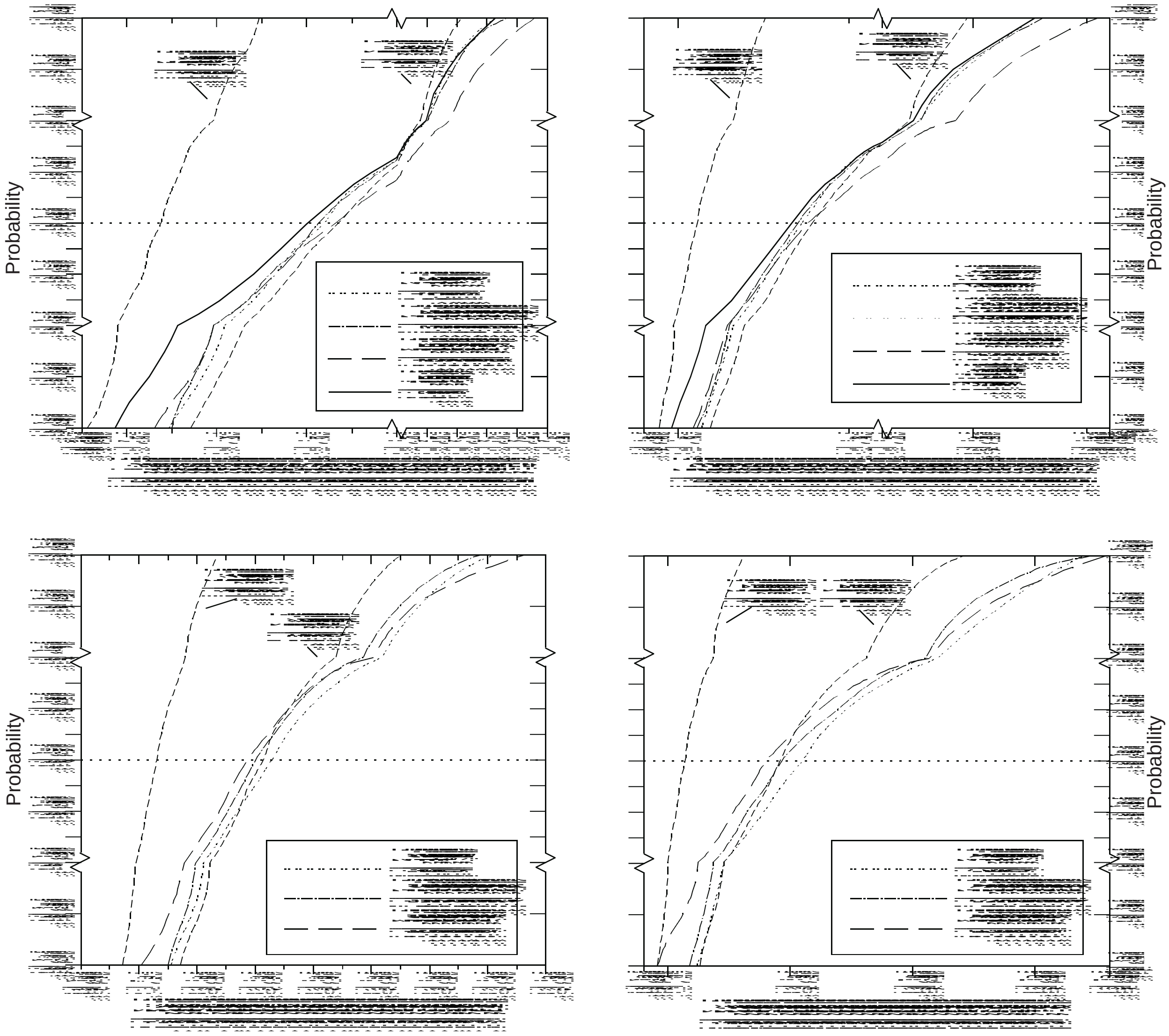


Figure 3-13. Cumulative Probability Distributions of Surface Warming and Thermal Expansion by Reviewer. Several curves were removed for clarity. The Rind estimates generally track Schneider because both include the possibility of both increased and decreased upwelling, along with high values of π. The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

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

“bumpy” changes in global temperatures, except for

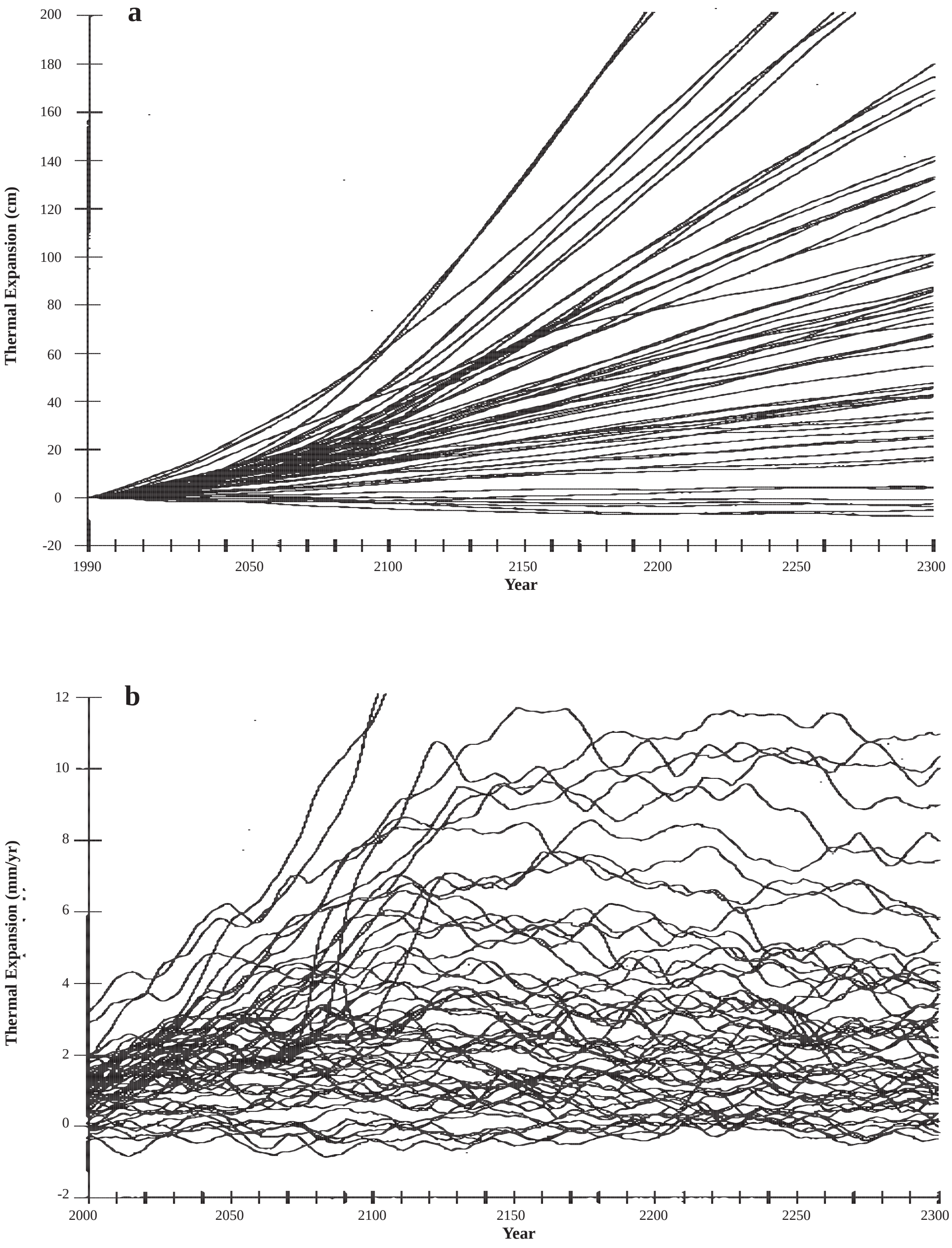


Figure 3-14. Spaghetti Diagrams of Thermal Expansion. Selected simulations for (a) thermal expansion and (b) rate of thermal expansion for the years 1990-2300. See Figure 2-5 and accompanying text for additional explanation of the scenarios selected.

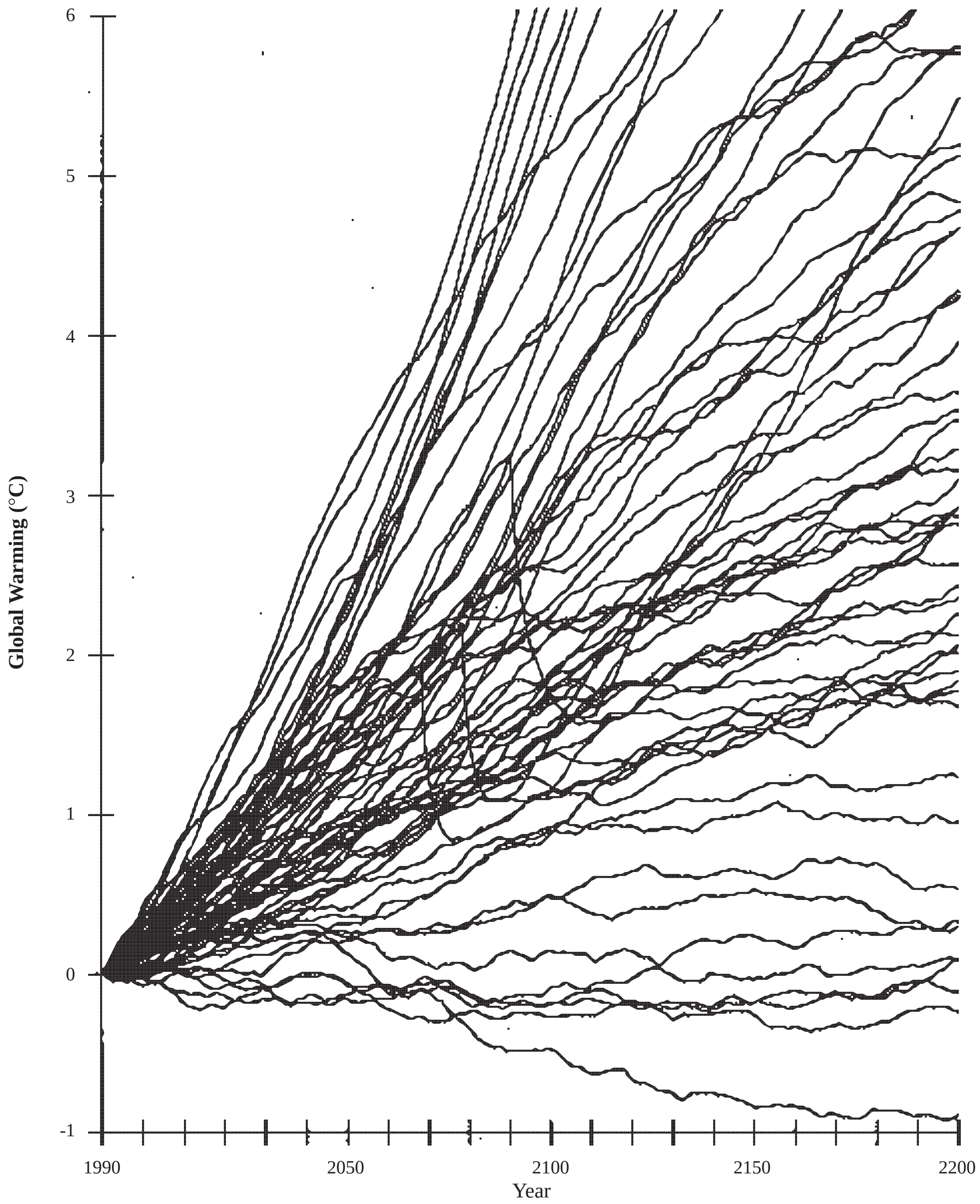
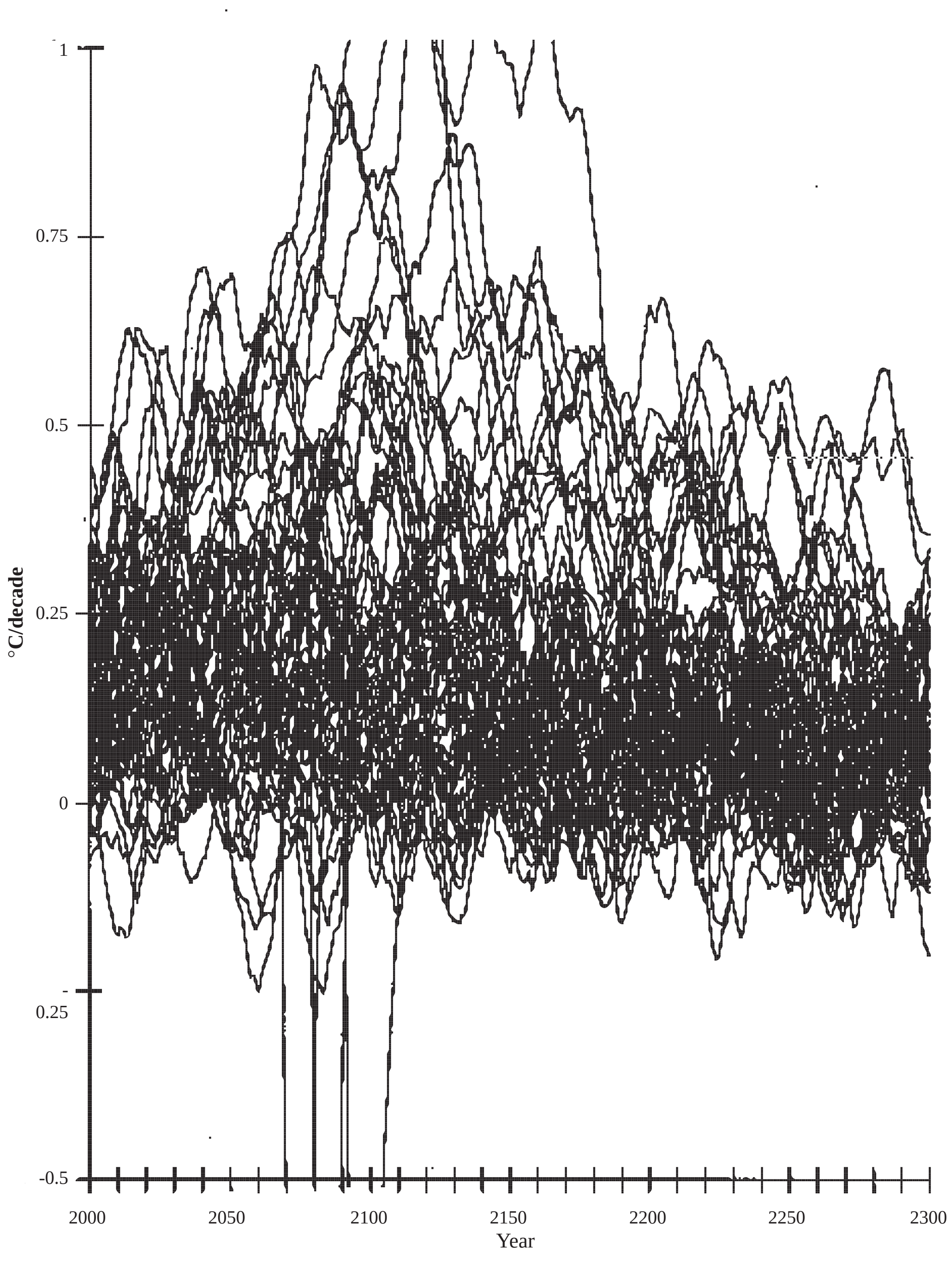


Figure 3-15. Spaghetti Diagrams of Global Warming. Selected simulations for (a) global temperatures and



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

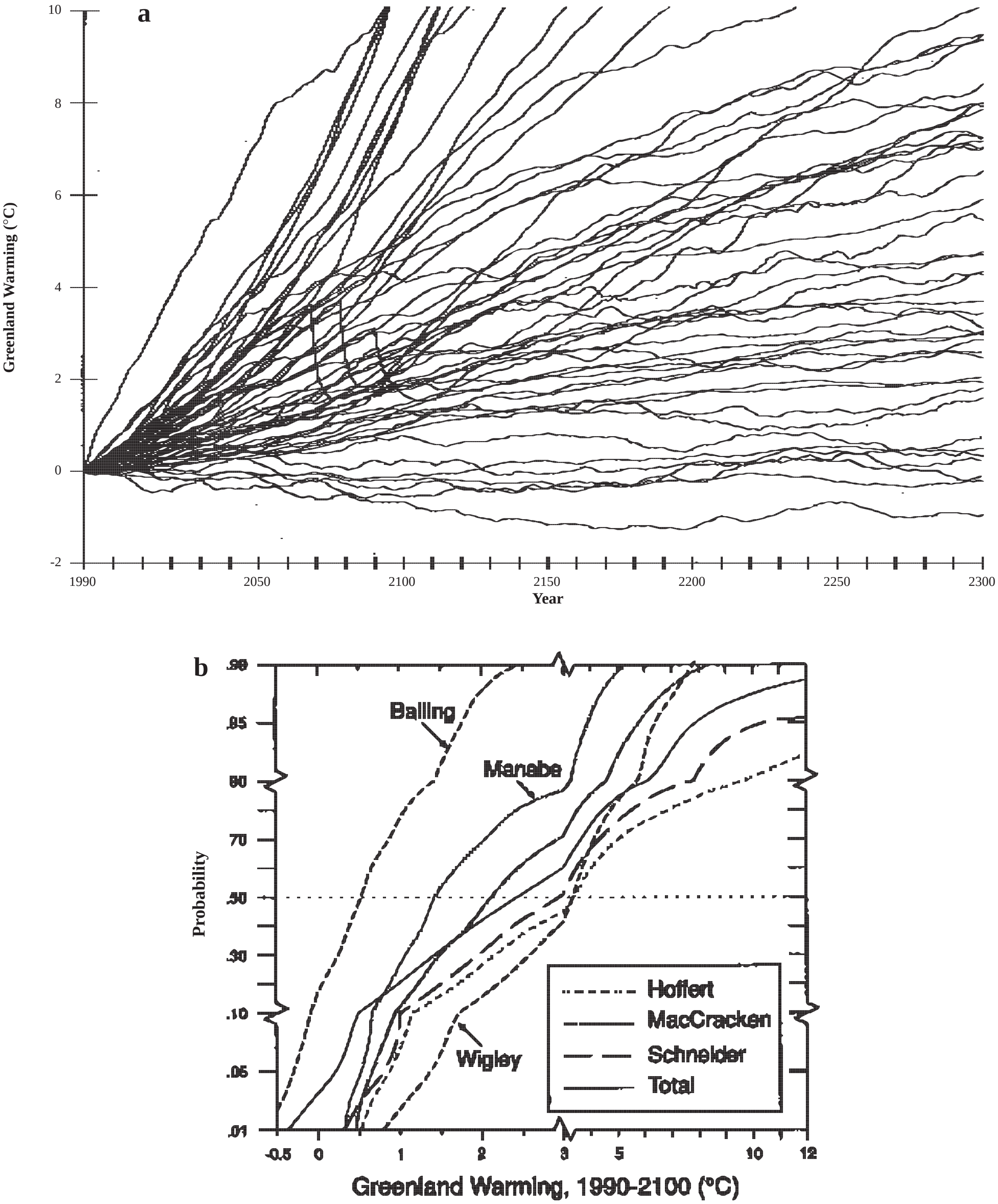


Figure 3-16. Greenland Warming. (a) Selected simulations for the period 1990–2300 and (b) cumulative probability distribution by the year 2100 for various reviewer assumptions.

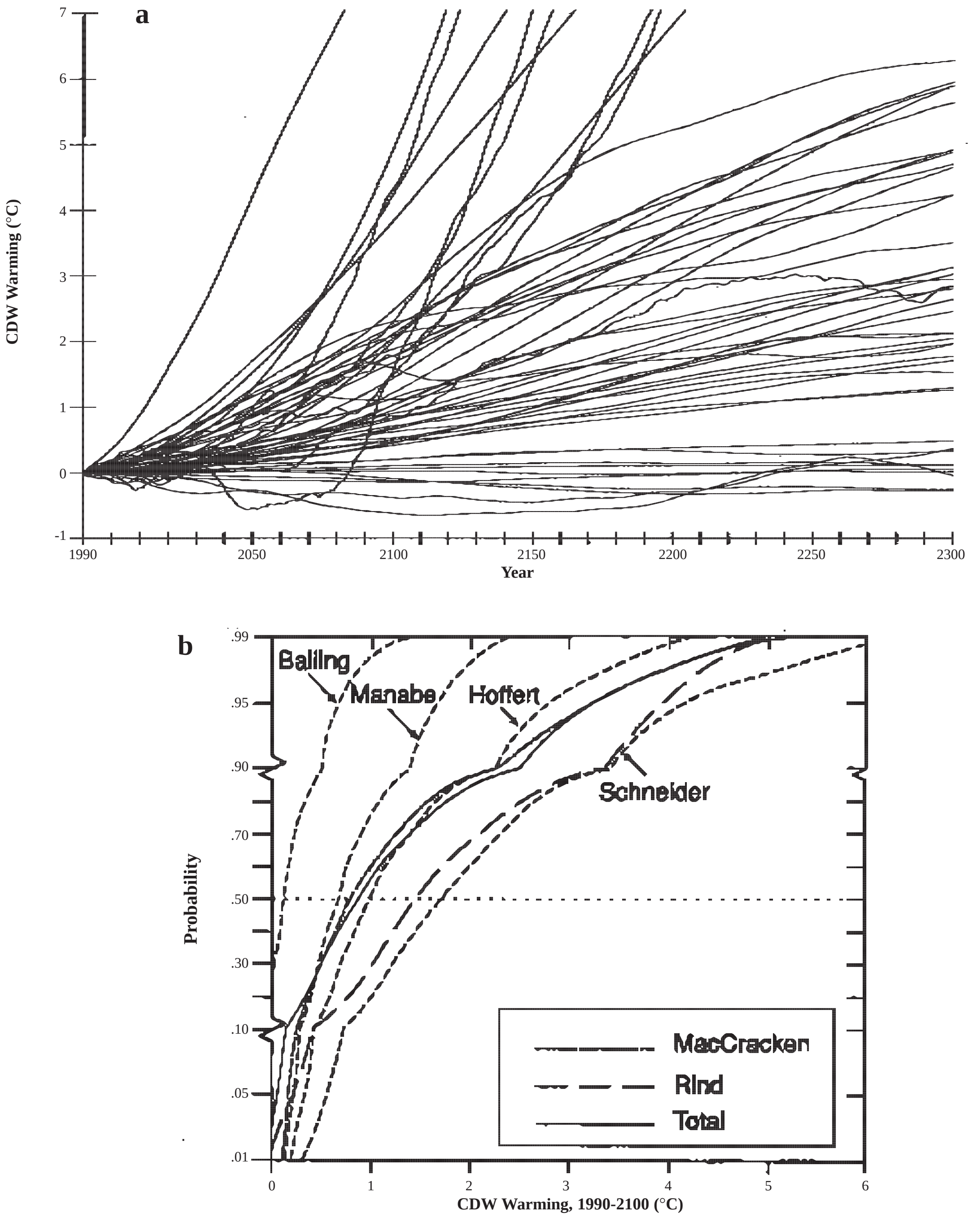


Figure 3-17. Circumpolar Ocean Warming. (a) Selected simulations for the period 1990–2300 and (b) cumulative probability distribution of circumpolar ocean warming by the year 2100 for various reviewer assumptions.

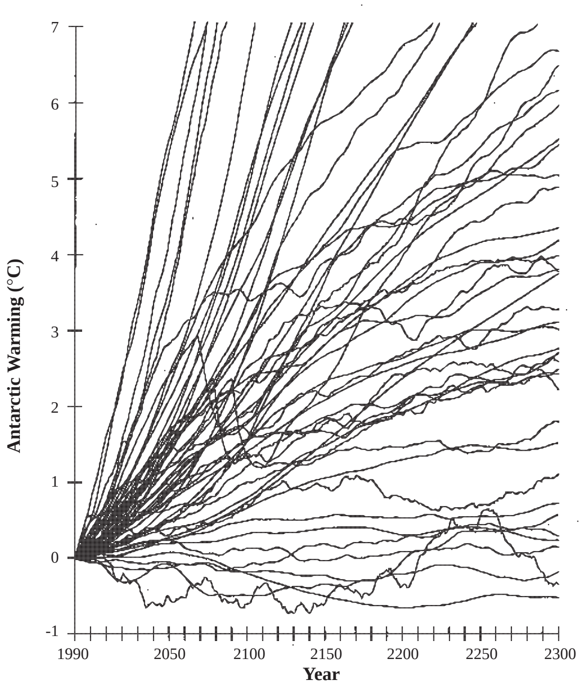


Figure 3-18. Spaghetti Diagram of Antarctic Air Temperatures. Selected simulations showing the change in Antarctic air temperatures for the period 1990–2300. See Figure 2-5 and accompanying text for additional explanation of the scenarios selected.

those simulations representing the Rind assumptions.[36]

PART B: CHANGES IN POLAR PRECIPITATION

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

Greenland

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

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

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

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

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

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

where V'=*d*V/*d*T.

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

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

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

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

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

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

SOURCE: Fortuin & Oerlemans (1990).

TABLE 3-9
ANTARCTIC PRECIPITATION BASINS EMPLOYED IN THIS REPORT

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

SOURCE: Fortuin & Oerlemans (1990).

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

Antarctica

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

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

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

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

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

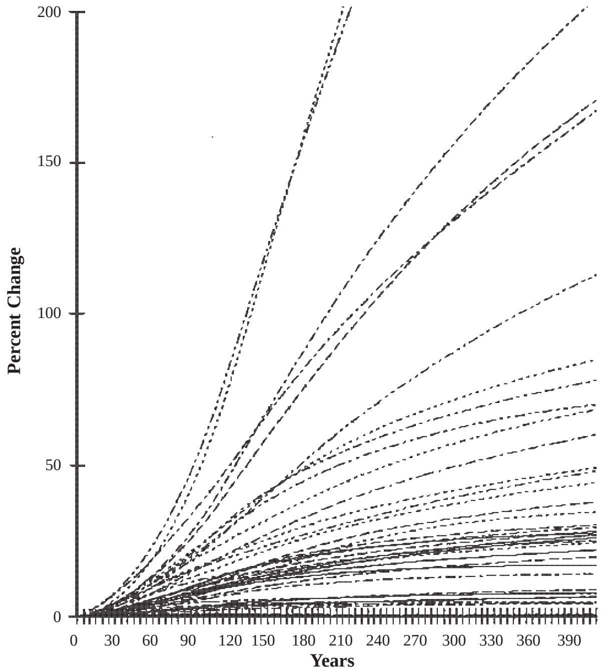

Figure 3-19. Antarctic Precipitation for Selected Scenarios in the Draft Analysis. A doubling of precipitation would lower the rate of sea level rise by 4.2 to 5.6 mm/yr, holding everything else constant.

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

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

Expert Judgment

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

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

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

TABLE 3-10
REVIEWERS OF PRECIPITATION ASSUMPTIONS

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

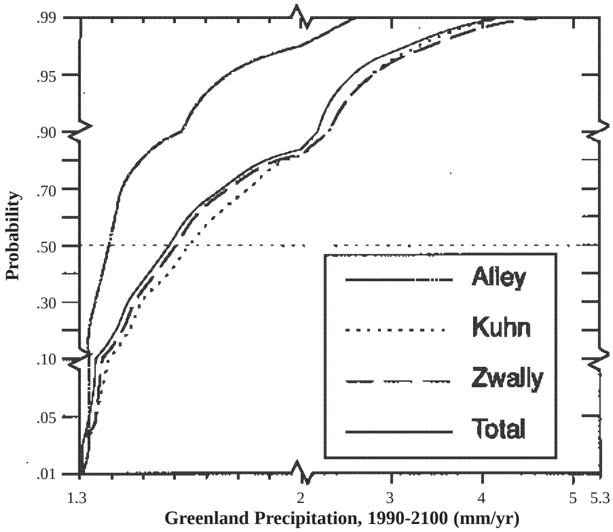

Figure 3-20. Changes in Greenland Precipitation, Sea Level Equivalent. Cumulative probability distribution for the year 2100, assuming that the current rate is 1.33 mm/yr; the Rind, MacCracken, and Schneider precipitation assumptions were essentially the same as those of Kuhn.

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

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

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

Final Results

The combined assumptions imply a 50 percent

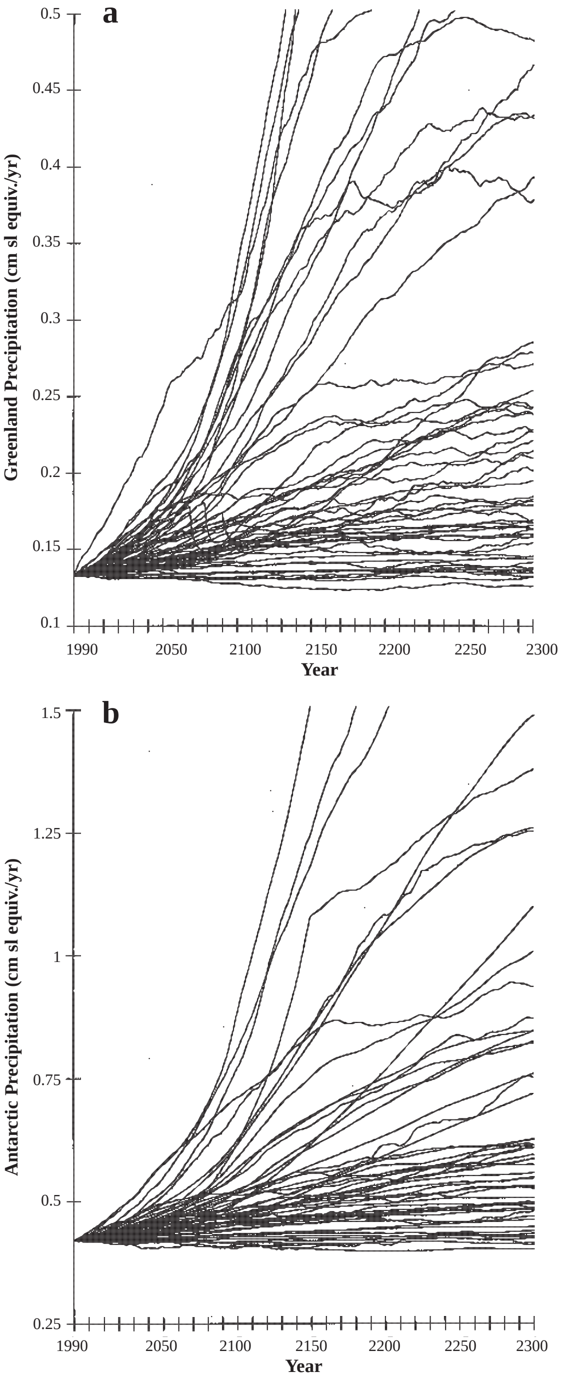

Figure 3-21. Spaghetti Diagram for Polar Precipitation, Sea Level Equivalent. Changes in (a) Greenland and (b) Antarctic precipitation for selected simulations, 1990–2300. Current rates of precipitation lower the rate of sea level rise by 1.3 and 4–5 mm/yr for Greenland and Antarctica, respectively.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

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

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