CHAPTER 4

GREENLAND ICE SHEET

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

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

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

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

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

---

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

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

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

Ablation

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

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

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

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

$$\begin{aligned} b &= d\,(H_e - y) && \text{for} && y < H_e \\ &= 0 && \text{for} && y \geq H_e \end{aligned}$$

$$\begin{aligned} a &= 0.35 \text{ m/yr} && \text{for} && y > H_e \\ &= 0 && \text{for} && y \leq H_e, \end{aligned}$$

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

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

$$a = 0.35 \text{ m/yr} \quad \text{everywhere, and}$$

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

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

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

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

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

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

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

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

---

[3] We use different variable names than Bindschadler.

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

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

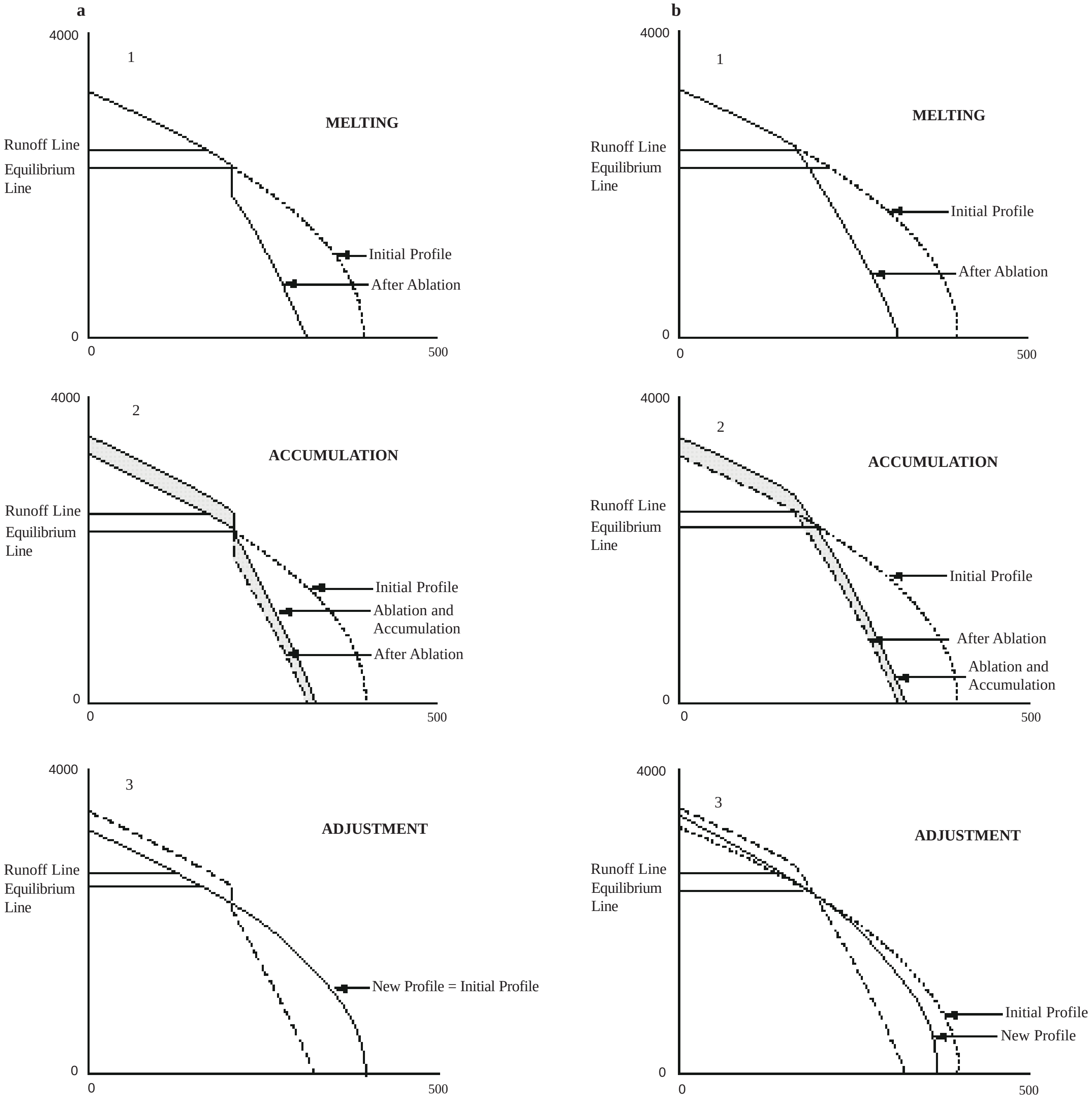

Figure 4-1. Two-Dimensional Schematic of the Greenland Ice Sheet. The profiles in (a) show the framework employed by Bindschadler; (b) shows our modification. In each case, the first diagram shows the initial profile (dotted) and a new profile (solid) after one period's melting. Note that the Bindschadler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

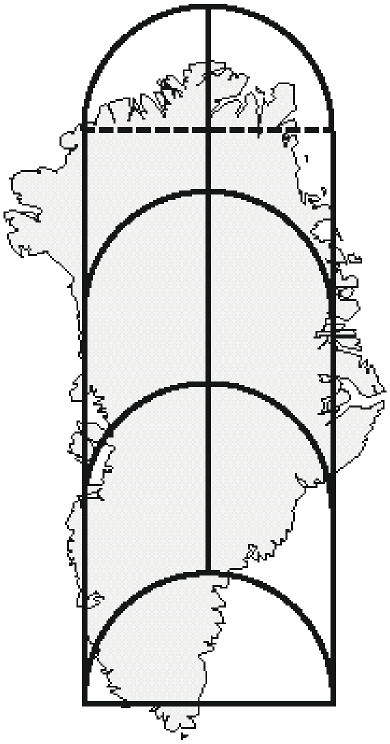

Figure 4-2. **Schematic of Bindschadler (1985) Model.** Extrapolating the 2-D model to three dimensions by a scaling factor of 5000 km is equivalent to assuming two parabolic cylinders back-to-back, with transverse (longitudinal) length of 2500 cm. Greenland is drawn to the same scale.

Scaling and Mass Constraint

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

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

Parameter Values

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

$$A = B + C;$$

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

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

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

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

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

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

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

---

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

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

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

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

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

Substituting our equation explaining the elevation of the runoff line,

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

into the previous equation, we have:

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

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

Refreezing

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

The Lag Due to Refreezing

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

---

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

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

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

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

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

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

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

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

Elevations Where All Melt Water Refreezes

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

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

---

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

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

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

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

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

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

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

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

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

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

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

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

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

Calving

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

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

Ice Sheet Dynamics and Changes in Profile

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

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

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

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

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

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

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

---

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

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

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

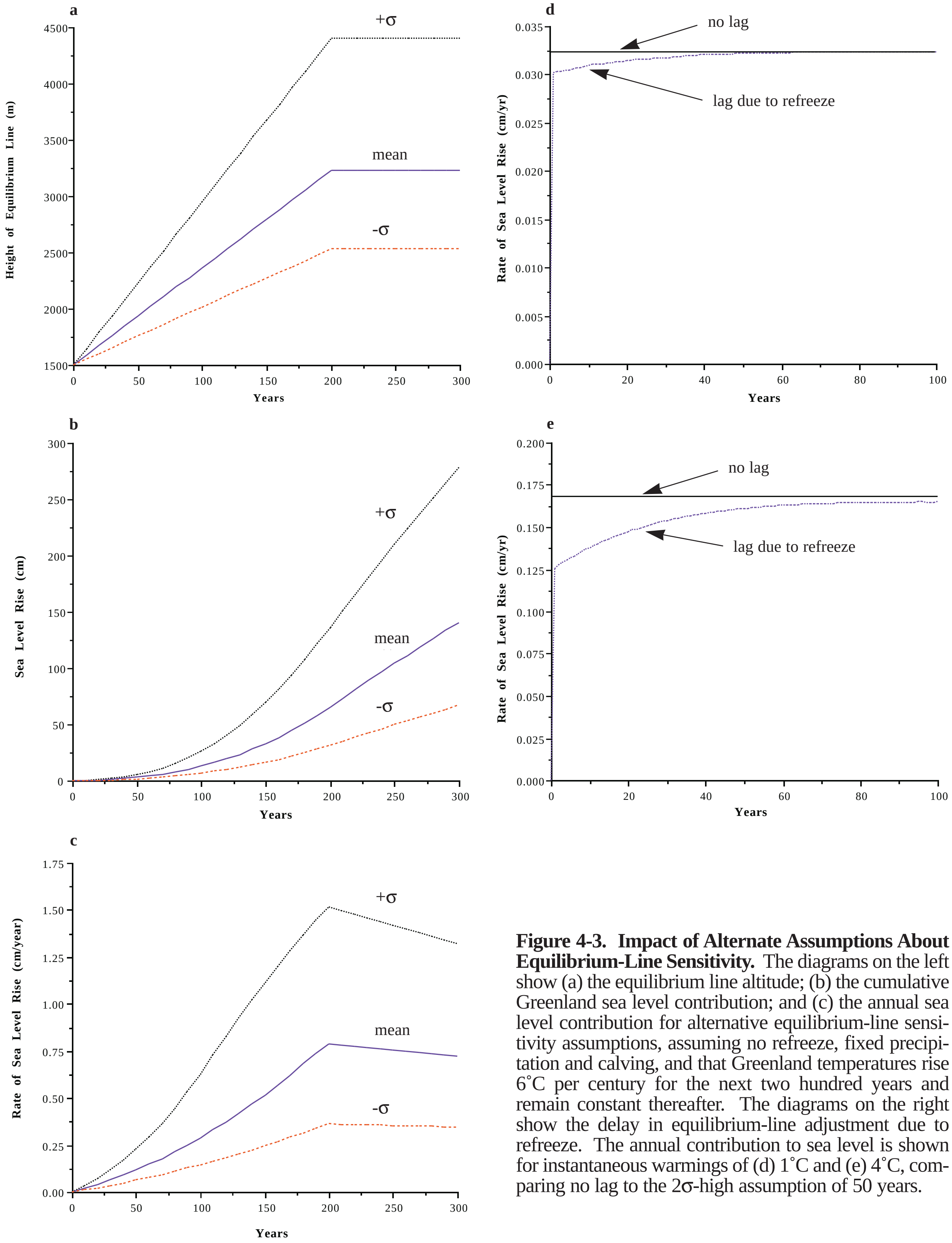

Figure 4-3. Impact of Alternate Assumptions About Equilibrium-Line Sensitivity. The diagrams on the left show (a) the equilibrium line altitude; (b) the cumulative Greenland sea level contribution; and (c) the annual sea level contribution for alternative equilibrium-line sensitivity assumptions, assuming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

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

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

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

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

Draft Results

---

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

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

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

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

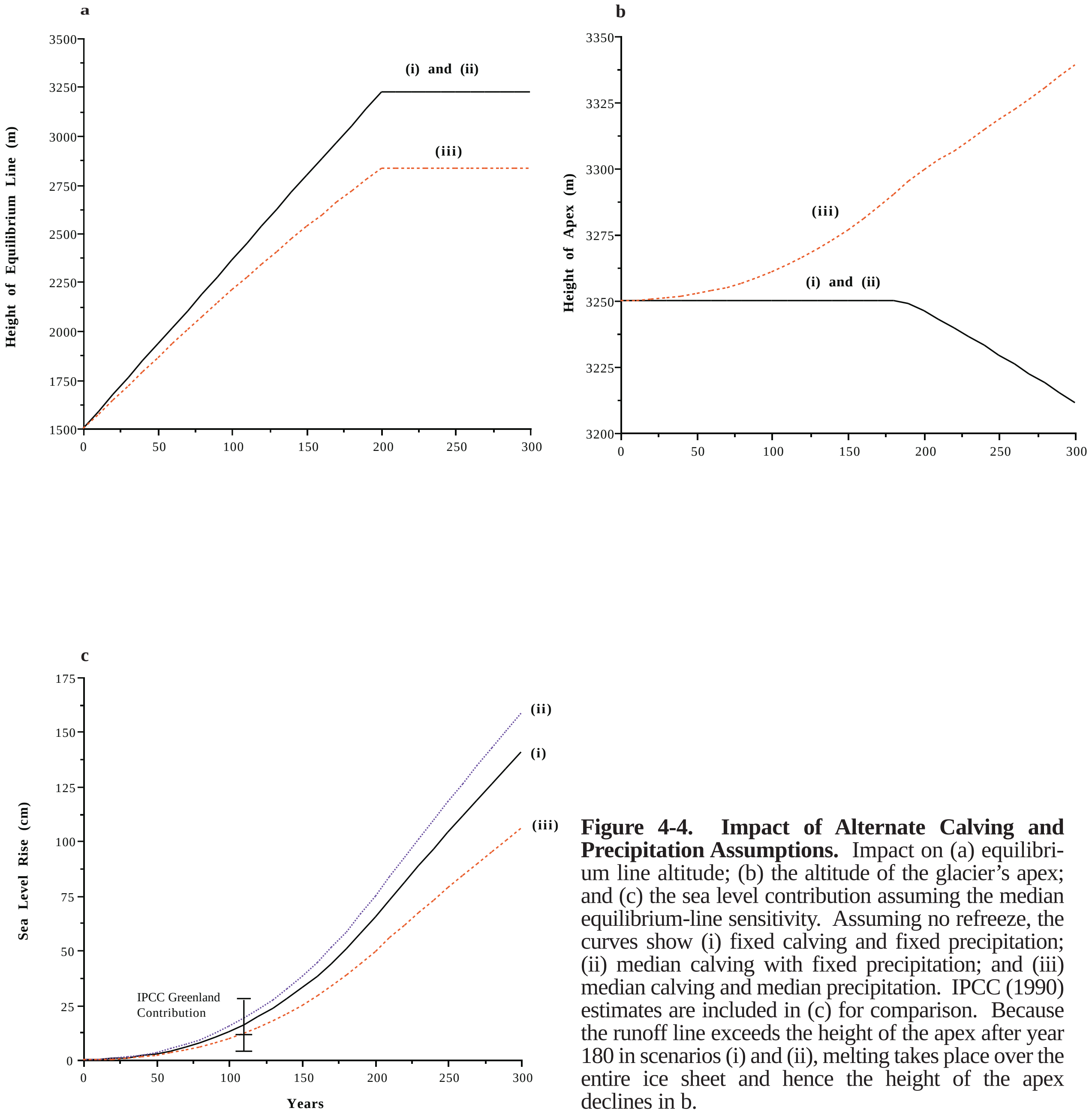

Figure 4-4. Impact of Alternate Calving and Precipitation Assumptions. Impact on (a) equilibrium line altitude; (b) the altitude of the glacier's apex; and (c) the sea level contribution assuming the median equilibrium-line sensitivity. Assuming no refreeze, the curves show (i) fixed calving and fixed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

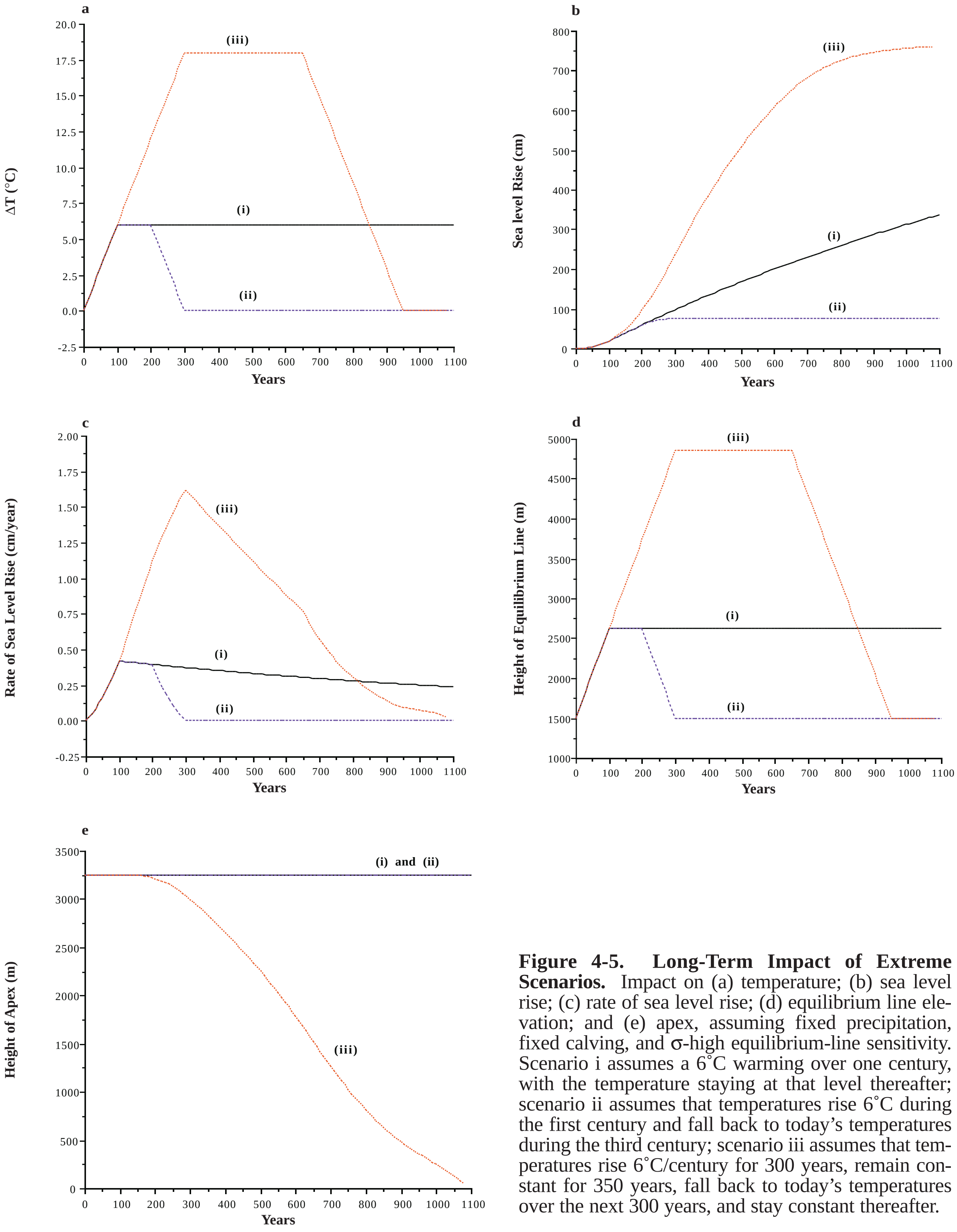

Figure 4-5. Long-Term Impact of Extreme Scenarios. Impact on (a) temperature; (b) sea level rise; (c) rate of sea level rise; (d) equilibrium line elevation; and (e) apex, assuming fixed precipitation, fixed calving, and σ-high equilibrium-line sensitivity. Scenario i assumes a 6°C warming over one century,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

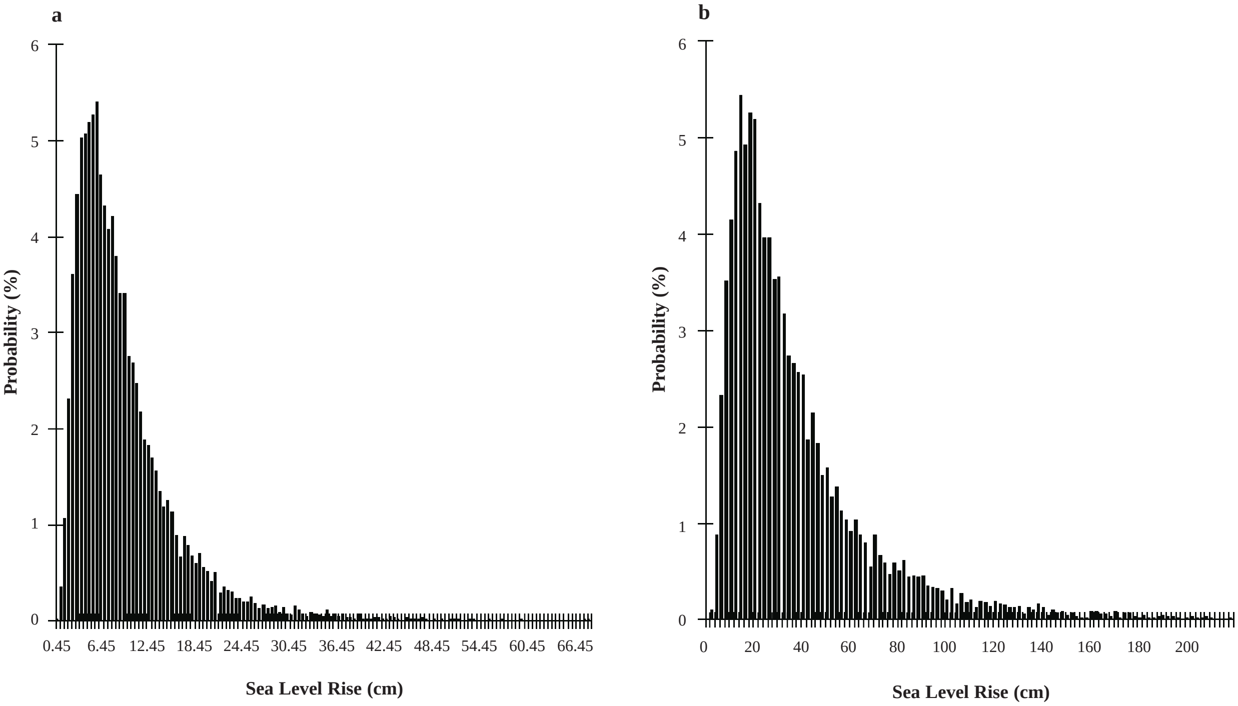

Figure 4-6. Probability Density of the Greenland Contribution to Sea Level: Draft Report. Contribution between 1990 and (a) 2100 and (b) 2200.

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

Expert Judgment

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

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

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

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

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

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

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

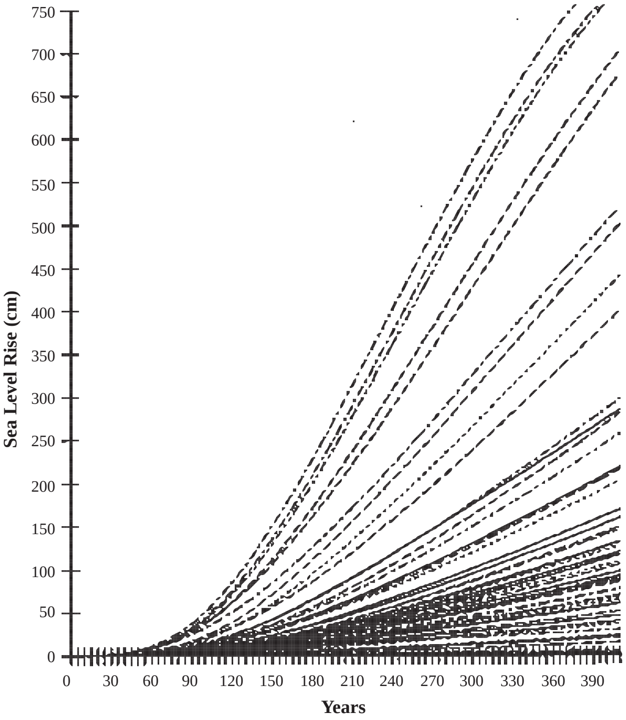

Figure 4-7. Draft Greenland Contribution for Selected Simulations, 1990-2400. See Figure 2-5 and accompanying text for description of these simulations.

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

$$d\mathrm{SL}_{\mathrm{Greenland}}/dt = \beta_G\ \Delta \mathrm{T}_{\mathrm{Greenland}},$$

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

Final Results

---

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

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

TABLE 4-2
EXPERT REVIEWERS OF CHAPTER 4

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

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

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

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

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

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

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

---

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

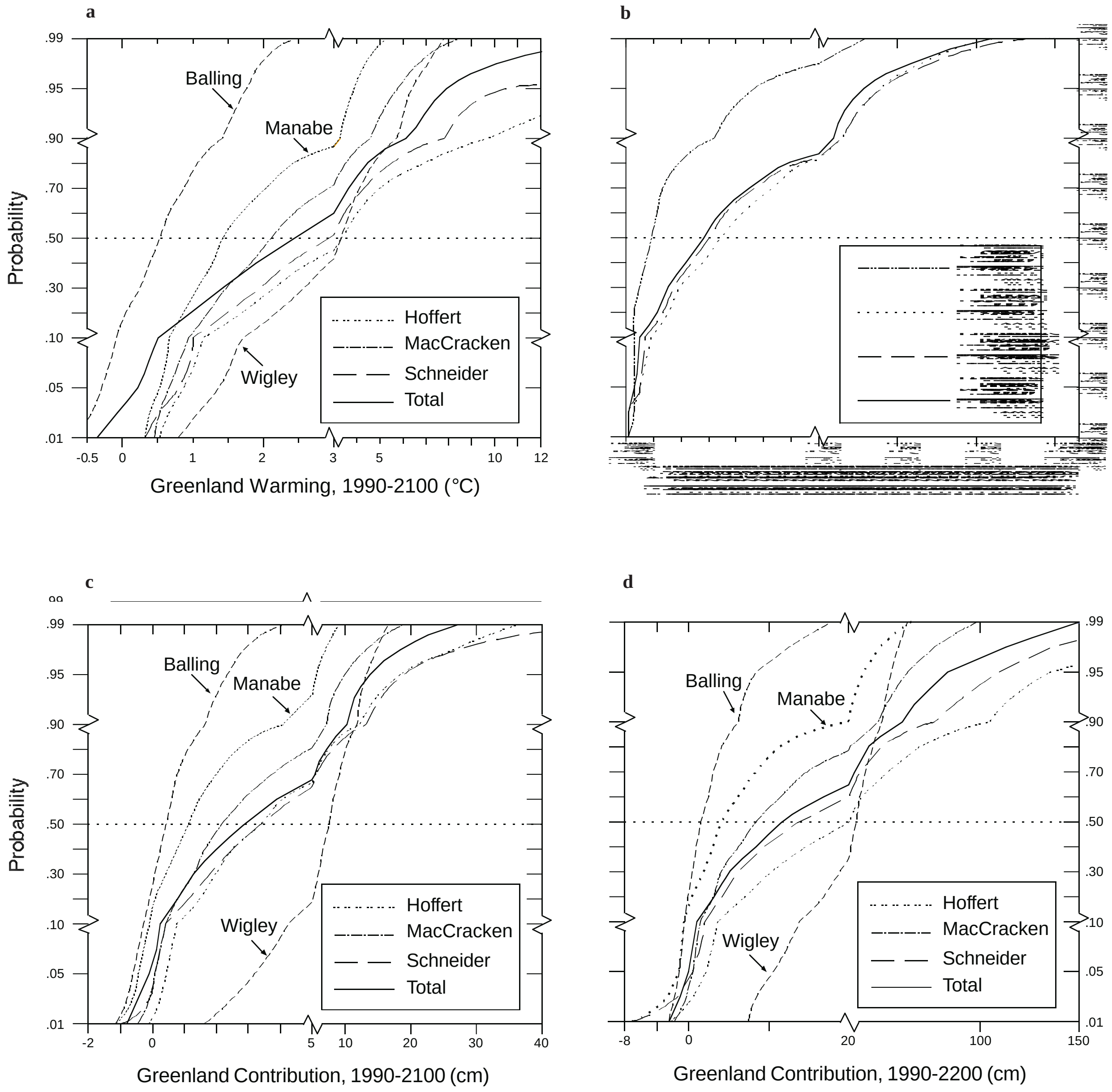

Figure 4-8. **Climate Change in Greenland.** Cumulative probability of (a) warming by the year 2100; (b) sea level equivalent of annual precipitation in 2100, assuming that the current rate is 1.33 mm/yr; and Greenland contribution to sea level through the years (c) 2100 and (d) 2200. The Rind, MacCracken,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

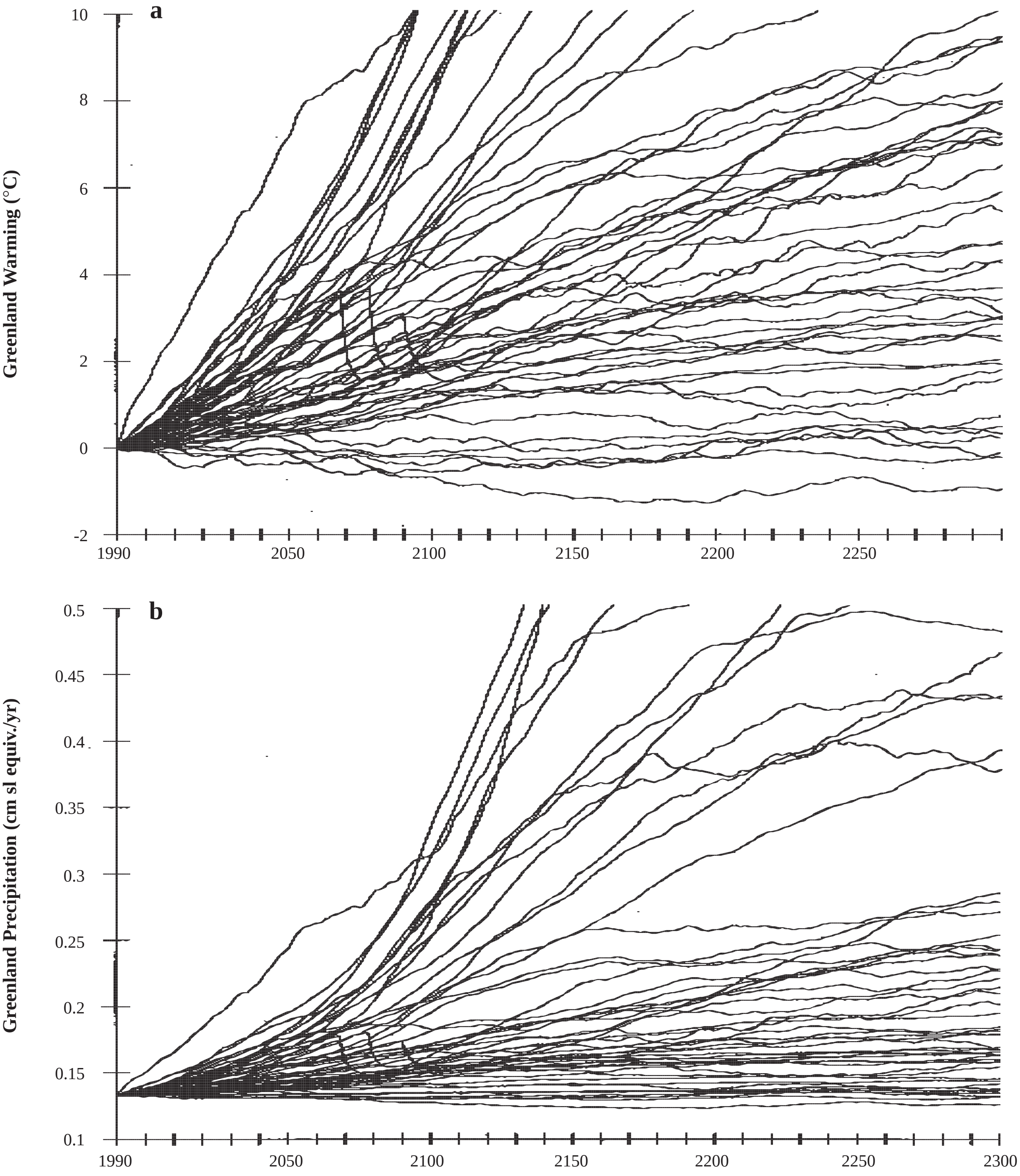

Figure 4-9. Spaghetti Diagram of Change in Greenland Climate. Increase in (a) temperatures and (b) precipitation over the Greenland Ice Sheet.

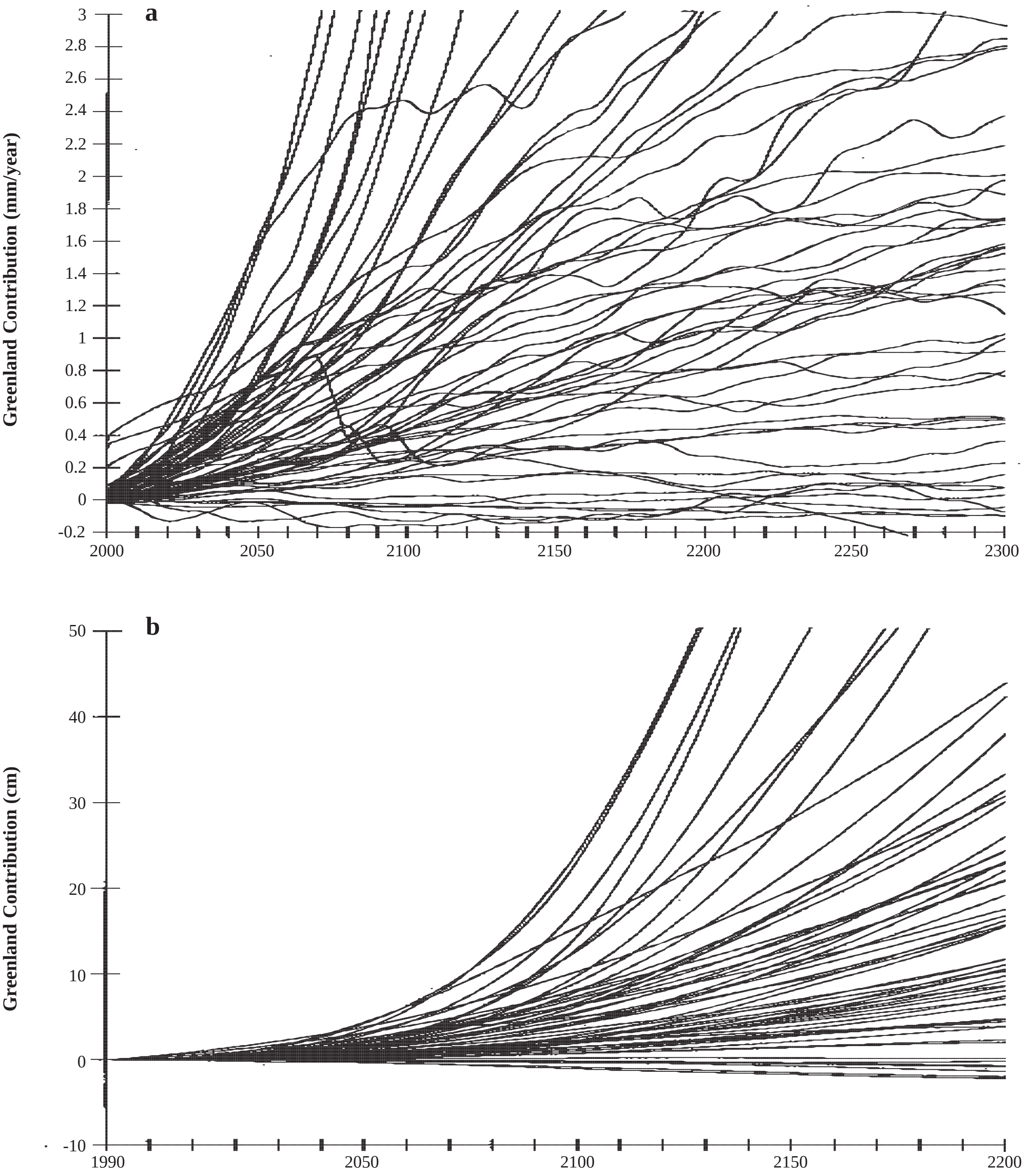

Figure 4-10. Spaghetti Diagram of Greenland Contribution to Sea Level. Selected simulations of (a) the rate of sea level contribution 1990–2300 and (b) total contribution 1990–2200. See Figure 2-5 for additional explanation on the scenarios chosen for this and other spaghetti diagrams.

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

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

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

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

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

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

References

Ambach, W,. and M. Kuhn. 1989. “Altitudinal Shift of the Equilibrium Line in Greenland Calculated from Heat Balance Characteristics.” In: Oerlemans, J. (ed). *Glacier Fluctuations and Climatic Change*. Kluwer (Dordrecht).

Bindschadler, R.A. 1985. “Contribution of the Greenland Ice Cap to Changing Sea Level: Present and Future.” In: Meier, M.F. et al (eds). 1985. *Glaciers, Ice Sheets, and Sea Level*. Washington, DC: National Academy Press.

Hollin, J.T. and R. G. Barry. 1979. “Empirical and Theoretical Evidence Concerning the Response of the

---

[31] In addition to precipitation exceeding melting, global and hence Greenland temperatures cool in a few cases.

Earth's Ice and Snow Cover to a Global Temperature Increaase." *Environmental International* 2:437-44.

Huybrechts, P.A, A. Letreguilly, and N. Reeh. 1991. "The Greenland Ice Sheet and Greenhouse Warming." *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)* 89:399-412.

Intergovernmental Panel on Climate Change. 1990. *Climate Change: The IPCC Science Assessment*. Cambridge: Cambridge University Press.

Karl, T.R., R.W. Knight, G. Kukla, and J. Gavin. 1995. "Evidence for Radiative Effects of Anthropogenic Sulfate Aerosols in the Observed Climate Record." In: Charlson, R,. and J. Heintzenberg (eds). *Aerosol Forcing of Climate.* Dahlem Konferenzen: John Wiley and Sons.

Ohmura, A., and N. Reeh 1990. New Precipitation and Accumulation Maps for Greenland. *Journal of Glaciology* 37(125):140-8.

Pfeffer, W.T., M.F. Meier, and T.H. Illangasekare. 1991. "Retention of Greenland Runoff by Refreezing: Implications for Projected Future Sea Level Change." *Journal of Geophysical Research* 96:C12:22,117-24.

Sikonia, W.G. 1982. Finite Element Glacier Dynamics Model Applied to Columbia Glacier, Alaska. *U.S. Geological Survey Professional Paper, 1258-B.*

Chapter 4