CHAPTER 6

SMALL GLACIERS

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

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

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

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

Note that the equilibrium condition is

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

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

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

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

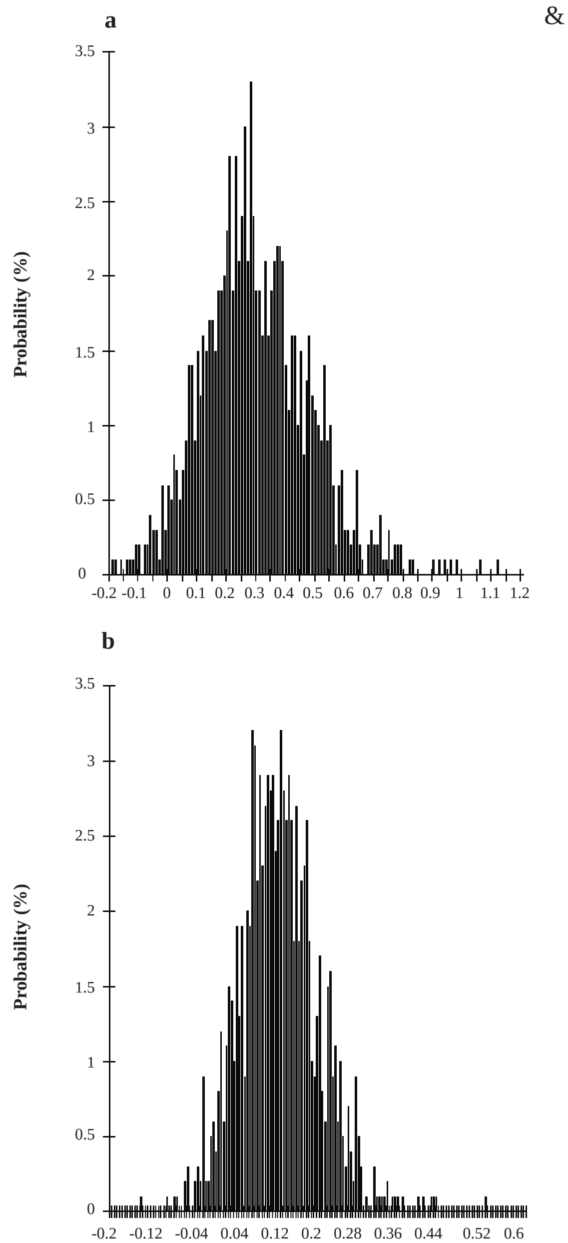

Figure 6-1. Probability Density of Assumed Small-Glacier Sensitivity to Global Warming. Distribution of β based on (a) IPCC/Raper et al. (1990); and (b) scaled by Oerlemans & Fortuin estimate.

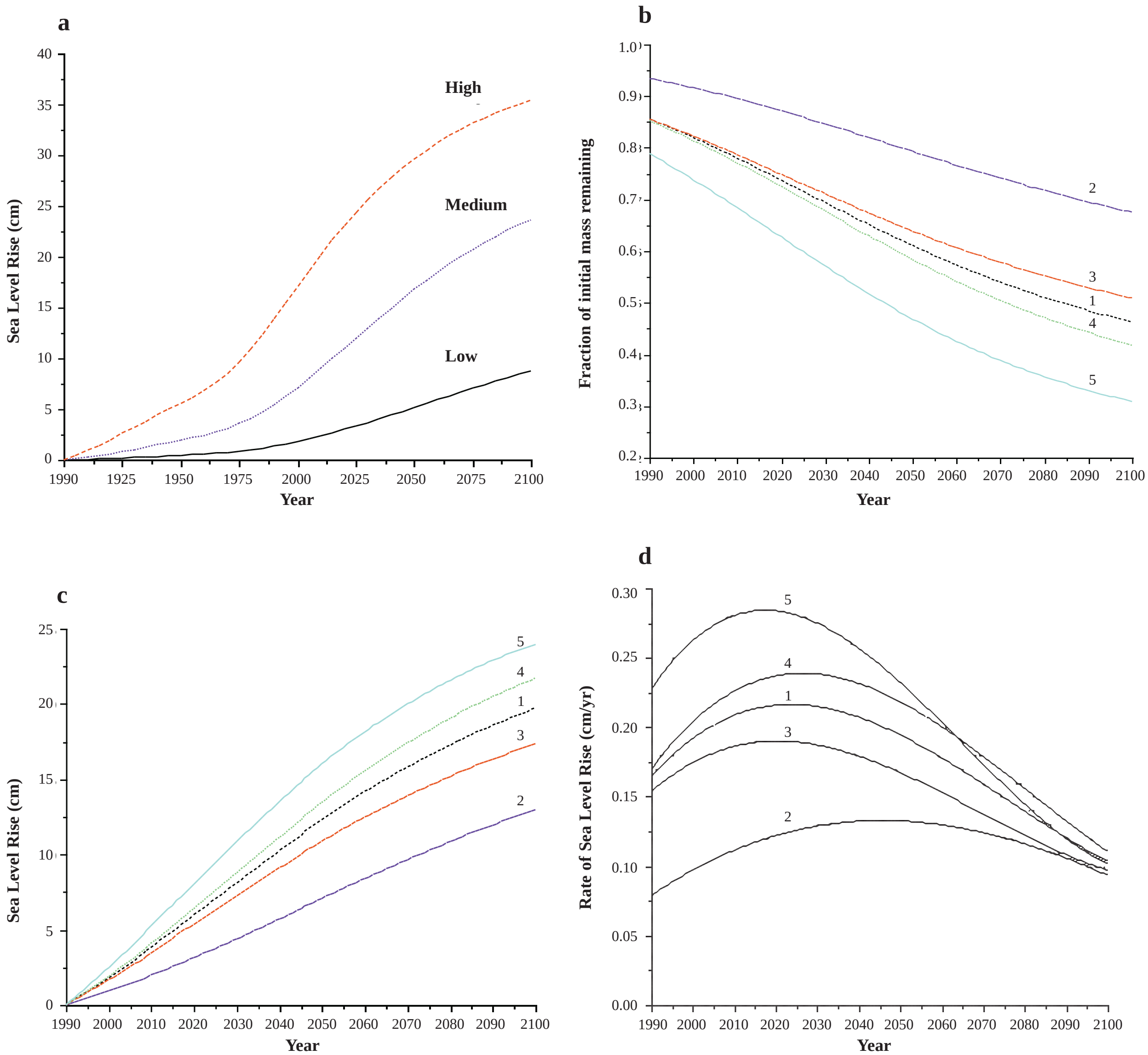

Figure 6-2. Characteristics of the Raper et al. Model of the Small Glacier Contribution. Sensitivity runs using Raper et al. (IPCC) model and IPCC 1990 "Business-as-Usual" forcing, showing (a) IPCC (1990) estimates of the historic and future small glacier contribution; and projections over the period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

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

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

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

Draft Results

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

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

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

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

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

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

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

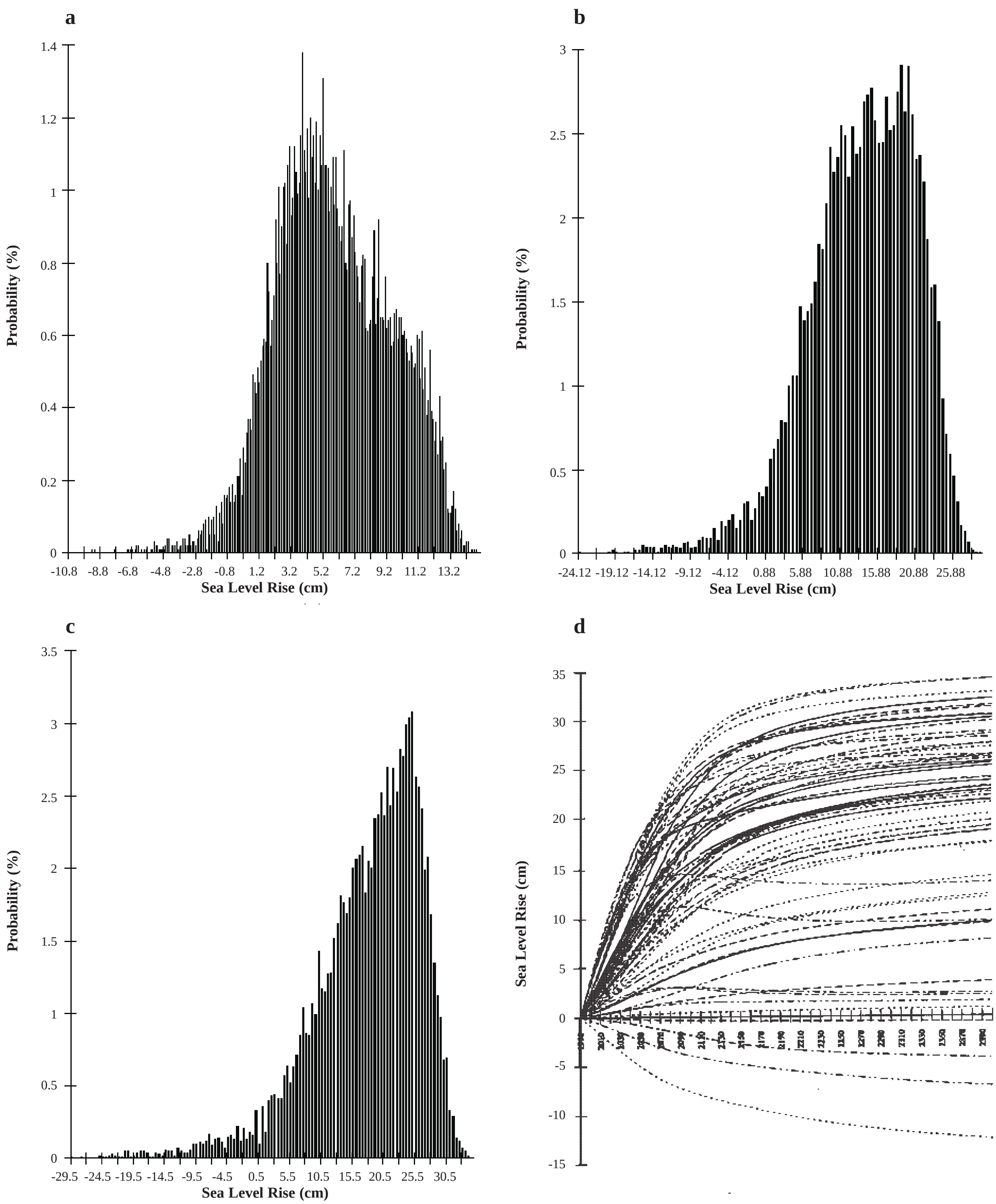

Figure 6-3. Small Glacier Contribution: Draft Report. Probability densities for the periods (a) 1990–2030, (b) 1990–2100, and (c) 1990–2200, along with (d) a spaghetti diagram of cumulative small glacier contributions to sea level: See Figure 2-5 and accompanying text for explanation of the scenarios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

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

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

Changes Made in the Final Version

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

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

[4]Both the Greenland and the small glacier specifications used in this report impose a mass constraint to prevent the sea level contribution from exceeding the amount of ice that exists. The Greenland specification suffers from the assumption that altitude is the sole reason that some parts contribute more than others; in fact, differences in latitude are also important. A good aspect of that model, however, is that it is capable of assuming that increased precipitation over a given area builds up at first, but that as warmer temperatures expand the ablation zone, that area may begin to lose mass. A consideration of the fraction of precipitation falling as rain would improve this aspect.

By contrast, the mountain glacier equation implicitly assumes a variation in latitude: As temperatures rise, higher latitudes fall within the net annual ablation zone. The model assumes that the equilibrium impact increases at a decreasing rate with temperature, which is consistent with the idea that because there is, for example, less land between 75–80˚N than between 70–75˚N (or for that matter, less land at 3000 m elevation than at 2000 m), each additional degree of warming brings less alpine snow within the net ablation area. The primary problem with the specification is that the equilibrium condition $z/z_0=\beta^*\Delta T/(1+\beta^*\Delta T)$ appears to have no theoretical or empirical basis. It is hardly self-evident, for example, that it should take 5.44 times as much warming to melt the second 17 cm as it takes to melt the first 17 cm, yet the Raper et al. equation imposes that assumption for all values of β.

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

Cumulative Probability (%)	2050	2100	2200
0.1[a]	–6.6	–10.9	–19.1
0.5[a]	–3.7	–5.7	–9.3
1.0[a]	–2.6	–3.9	–6.5
2.5[a]	–1.2	–1.8	–2.5
5[a]	–0.4	–0.3	–0.3
10	0.4	1.0	1.6
20	1.7	3.3	5.2
30	2.7	5.3	8.1
40	3.7	6.9	10.7
50	4.8	8.7	13.2
60	5.9	10.5	15.7
70	7.2	12.4	18.5
80	9.0	14.8	21.7
90	11.5	18.3	25.8
95	13.8	21.1	29.0
97.5	15.8	23.6	32.8
99	18.0	26.3	34.2
99.5[a]	20.2	27.8	35.6
99.9[a]	26.3	32.2	38.6
Mean	5.4	9.2	13.5
σ	4.5	6.7	9.2

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

Final Results

Given these changes, Table 6-2 summarizes the cumulative probability distribution for the small glacier contribution to sea level. The median estimate is one-third lower than in the draft version because of (a) the lower historic glacial sensitivity and (b) the lower temperature estimates.[5] Nevertheless, small glaciers still

[5]Excluding the Balling temperature estimate, our median temperature estimate by the year 2100 is a warming of 2.25˚C, rather than 2.02˚C. This higher warming results in a median mountain glacier contribution of 10 cm.

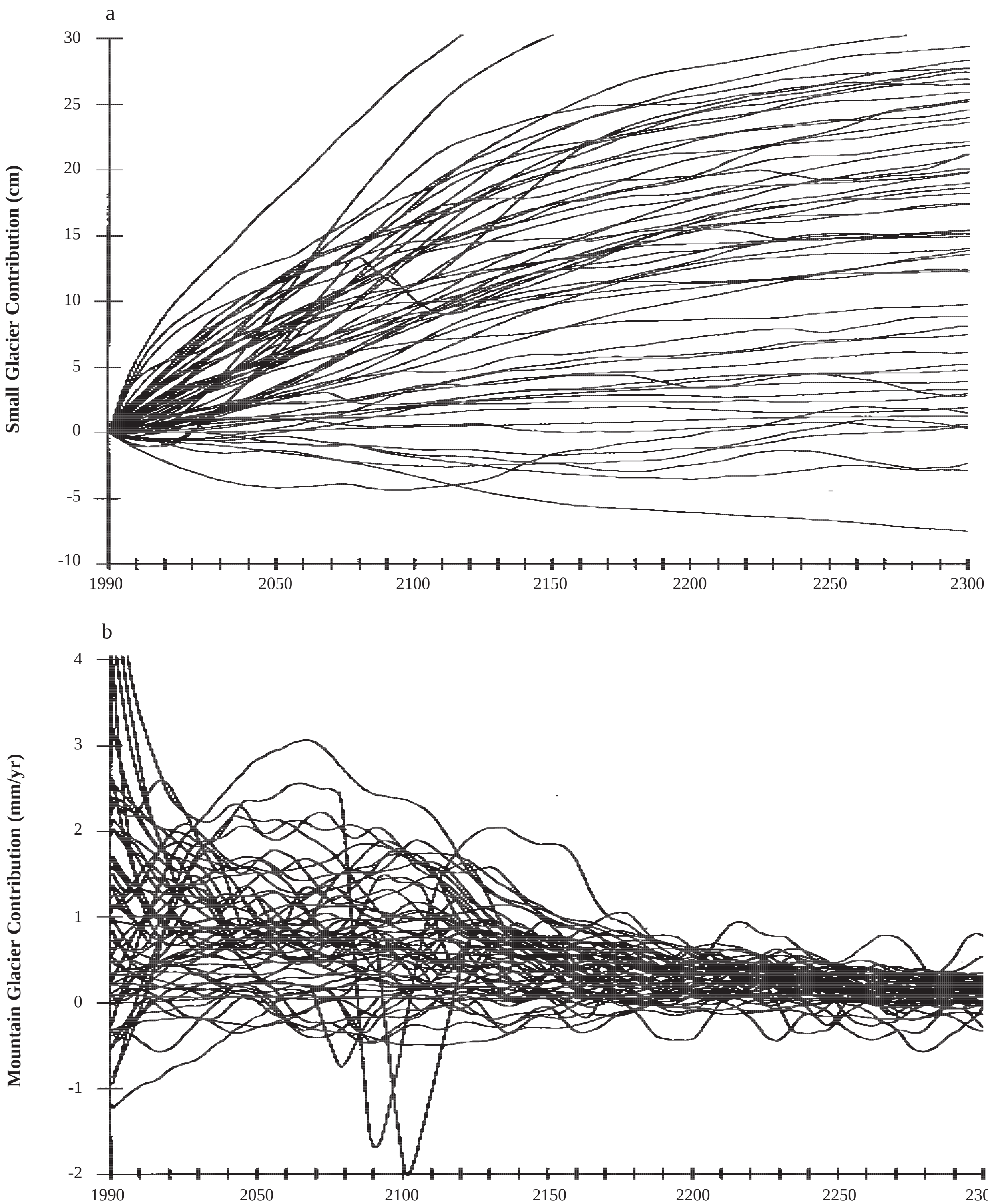

Figure 6-4. Spaghetti Diagrams of the Small Glacier Contribution: Final Results. Selected simulations for (a) cumulative and (b) annual small glacier contribution. See Figure 2-5 and accompanying text for explanation of scenarios selected.

would contribute 0.8 mm/yr—more than four times the historic contribution estimated by Fortuin & Oerlemans.

Unlike the median estimate, the final 1%-high estimate (26.3 cm) is actually higher than the 25.7 cm estimated in the draft report. The higher estimate results primarily from our downward correction of the historic contribution—and thus an upward correction in the current mass of small glaciers—in those scenarios that assume a high degree of global warming.

Figure 6-4 displays spaghetti diagrams for the total and annual contributions of small glaciers to sea level. Unlike other potential contributors to sea level rise, the annual alpine contribution is likely to decline after the next century as the glacial ice available for melting is consumed. In the case of some of the outlier scenarios, where the alpine contribution in the next decade is estimated to be over 4 mm/yr, the current contribution is unlikley to be sustained for more than the next 10–20 years.

The spaghetti diagrams suggest a declining uncertainty in the annual contribution to sea level. In percentage terms, however, the uncertainty does not decline. Even in absolute terms, the decline in uncertainty is an artifact of the model's assumption regarding the relationship between temperature and equilibrium glacial mass.

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