United States
Environmental Protection
Agency

Office of Policy,
Planning, and Evaluation

EPA 230-R-95-008
September 1995

The Probability of Sea Level Rise

Library of Congress Cataloging-in-Publication Data
Titus, James G.
The probability of sea level rise/by James G. Titus, Vijay K. Narayanan.
p. cm.

Includes bibliographical references.
1. Sea level. 2. Greenhouse effect, atmospheric. 3. Climate Change, atmospheric.
I. Titus, James G., 1955- II. Narayanan, Vijay K, (Vijay Kumar), 1958- III. Title
GC89.T57 1995
551.4’58--dc20 95-15973
CIP

CHAPTER 7

RESULTS

If the experts on whom we relied fairly represent the breadth of scientific opinion, the odds are fifty-fifty that greenhouse gases will raise sea level at least 15 cm by the year 2050, 35 cm by 2100, and 80 cm by 2200.[1] Moreover, there is a one-in-forty chance that changing climate will raise sea level 35 cm by 2050, 80 cm by 2100, and 300 cm by 2200.

For the reader who skipped the chapters outlining our assumptions, we begin by outlining the key results from those chapters. Next, we present our estimates for the total rise in sea level resulting from climate change and compare them with the results of other recent assessments. We then estimate the extent to which emission policies might reduce the risk of sea level rise. We close the chapter with a brief analysis of the extent to which uncertainty might be reduced through a better understanding of some key processes.

[1]Because other factors also contribute to sea level, the total rise is likely to be significantly greater, as we see in Chapter 9.

Summary of Previous Chapters

We now summarize the highlights of the previous chapters on radiative forcing, global temperatures and thermal expansion, polar temperatures and precipitation, and the contributions to sea level from Greenland, Antarctica, and small glaciers (see Table 7-1).

Radiative Forcing. Our emission projections were based on IPCC (1992) scenarios A through F; and we used the assessment by Wigley & Raper (1992) for calculating the resulting concentrations of both greenhouse gases and sulfate aerosols. As a result, our scenarios for anthropogenic radiative forcing[2] are broadly consistent with other recent assessments.[3] Like those

[2]That is, the amount of additional radiation striking the Earth's surface as a result of human modification of the atmosphere.

[3]Our mean estimate of radiative forcing for the year 2100, 5.0 W/m^2, is only slightly less than the medium forcing estimate by Wigley & Raper (1992).

TABLE 7-1
IMPACT OF GREENHOUSE GASES ON KEY CLIMATIC VARIABLES BY THE YEAR 2100

	mean estimate	Probability that Value Will Not Be Exceeded						
		2.5%	10%	50%	90%	95%	97.5%	99%
Temperature Change (˚C)								
Greenland	3.1	0.0	0.6	2.5	6.3	8.1	10	14
Antarctic Ocean	1.2	0.0	0.16	0.86	2.5	3.3	4.0	5.0
Global Average	2.2	0.0	0.6	2.0	4.0	4.7	5.4	6.3
Sea Level Contribution (cm)								
Thermal Expansion	21	0.6	5.1	20	38	45	50	58
Small Glaciers	9.2	–1.8	1.0	8.7	18	21	24	26
Greenland	4.6	–0.4	0.22	2.9	10	14	19	27
Antarctica	–1.1	–27	–12	–1.5	11	16	21	30
Other Variables								
CO_2 Concentration (ppm)	738	462	511	680	1047	1204	1363	1614
Radiative Forcing (W/m^2)	5.0	2.3	3.0	4.9	7.2	7.8	8.2	8.7
Greenland Precipitation (mm/yr, sea level equivalent)	1.7	1.3	1.4	1.6	2.2	2.6	3.2	4.2
Rate of Melting, Ross Ice Shelf (m/yr)	0.7	0.22	0.25	0.37	1.3	2.1	3.2	6.2

assessments, we generally project smaller anthropogenic changes in forcing than assumed in some of the older assessments.

Our median projection is that, over the period 1990–2100, radiative forcing will increase by 4.9 watts per square meter (W/m^2), which is equivalent to increasing CO_2 concentrations from 350 parts per million (ppm) to 770 ppm. By contrast, the IPCC (1990) "Business-As-Usual" scenario projected an increase of 7.5 W/m^2; and IPCC (1992) projected 6.2 W/m^2 for Scenario A.[4] About 1 percent of our simulations have more forcing than the 8.5 W/m^2 IPCC (1992) estimated for Scenario E,[5] while about 20 percent have a forcing less than the 3.5 W/m^2 projected by IPCC (1992) for Scenario C. Our median estimate is that radiative forcing will increase by 4.4 W/m^2 (equivalent to a CO_2 doubling) by the year 2089, with a 10 percent probability that the doubling equivalent will occur by 2068.

Although we project less radiative forcing than early IPCC assessments, our assumptions are consistent with the IPCC (1994) report on radiative forcing. That report has adopted scenarios that are much closer to the Wigley & Raper (1992) assumptions on which our scenarios are based. Most important, the IPCC has lowered the projected CO_2 concentration from 800 ppm to about 730 ppm for the year 2100. Although IPCC has not yet endorsed a specific estimate of the average global forcing effect of sulfates, it has acknowledged that sulfates offset a large fraction of the historic greenhouse warming.

Global Warming. The reviewer assumptions imply that there is a 90 percent chance that the next century will see more than the 0.5˚C warming experienced in the last century, a 50 percent chance that the Earth will warm more than 2˚C, and a 3 percent chance that our planet will warm 5˚C, which is more than it has warmed since the last ice age. Although a 2˚C warming is most likely by the year 2100, there is a 7 percent chance that it will occur by 2050. Even if emissions are constant after 2100, temperatures are likely to rise about 0.15˚C per decade throughout the 22nd and 23rd centuries.

[4]These estimates are equivalent to increasing CO_2 by factors of 3.4 and 2.8, respectively. Note that IPCC (1990) also estimated that radiative forcing increased by about 2.5 W/m^2 through the year 1990, compared with the preindustrial level.

[5]About 20 percent of our simulations, however, have more forcing than the 6.6 W/m^2 estimated by Wigley & Raper (1992) for Scenario E.

Thermal Expansion. As global temperatures rise, the various layers of the ocean will warm and expand. Especially in the long run, thermal expansion depends on the extent to which the heat is able to penetrate into the intermediate and deep layers of the ocean. For example, a decline in deepwater formation would slow upwelling, allowing heat to penetrate farther, and thereby increase thermal expansion. Differences in opinions regarding ocean circulation changes led to a 10 percent variation among the reviewers regarding likely expansion. By the year 2100, the most likely expansion is 20 cm, but there is a 2 1/2 percent chance that expansion will exceed 50 cm. Although global temperatures are projected to rise 25 percent less during the 22nd century than in the 21st, thermal expansion is likely to be 20 to 40 percent more, due to the delayed response of expansion to higher temperatures.

Greenland Climate. The likely contribution of Greenland to sea level will depend on the magnitude of increases in precipitation and melting, both of which would increase at higher temperatures. Particularly if the Gulf Stream weakens due to a shutdown in North Atlantic deepwater formation, Greenland may warm less than the global average warming—or perhaps even cool. Nevertheless, most of the reviewers expect Greenland temperatures to eventually warm by more than the global average. Thus, we estimate that there is a 50 percent chance that Greenland will warm at least 2.5˚C between 1990 and 2100, a 25 percent chance of a warming greater than 4˚C, and a 2 1/2 percent chance that the warming will exceed 10˚C. By contrast, Wigley & Raper (1992) projected a best-guess warming of 3.8˚C.

All but one of the reviewers expect Greenland precipitation to increase about 8 percent per degree (C), which is equivalent to a sea level drop of 0.1 mm/yr per degree. In light of the projected warming of Greenland, there is a 50% chance that by 2100 Greenland precipitation will increase 20 percent, and a 5% chance that it will double. At the low end of the spectrum, there is a 10% chance that precipitation will increase by less than 5 percent.

Greenland Contribution. Our median estimate is that Greenland will contribute 2.9 cm to sea level by the year 2100. Our 95 percent confidence range is –0.37 cm to 19 cm. For 2200, we estimate a median contribution of 12 cm, but a 10 percent chance of a 50 cm contribution. At the low end of the range, we estimate a 5 percent chance that Greenland will have a negative contribution to sea level through 2100. Mostly because our temperature estimates are lower, our median is less than the 7.5, cm projected by Wigley & Raper (1992).

Antarctic Climate. Antarctic air temperatures are likely to rise by approximately 2.5˚C in the next century, largely as a result of reduced sea ice. For each degree (C) of warming, Antarctic precipitation is likely to increase approximately 8 percent, equivalent to a 0.4 mm/yr drop in sea level.

Unlike Greenland, Antarctica is colder than freezing even during summer; so warmer *air* temperatures will not cause significant glacial melting. Warmer *water* temperatures, by contrast, could potentially increase melting of the marine-based West Antarctic Ice Sheet and adjacent ice shelves. The reviewers generally agreed, however, that any warming of the circumpolar ocean is likely to lag behind the general increase in global temperatures by at least fifty years, and perhaps by a few centuries. Thus, we estimate that Antarctic ocean temperatures are most likely to warm 0.86˚C by the year 2100. Although a 3˚C warming is likely by 2200, there is only a 6 percent chance that such a warming will occur by 2100.

Antarctic Contribution. Warmer ocean temperatures have about a 50 percent chance of doubling the average rate at which the underside of the Ross Ice Shelf melts, from 0.17 m/yr to 0.35 m/yr, by the year 2100. Although a doubling may seem significant, most previous studies have suggested that the rate of melting would have to increase to at least 1 m/yr to have a significant impact on sea level. The reviewer assumptions imply that there is only about a 10 percent chance of such an increase in the next century. We also estimate that there is a 5 percent chance that by 2100 the Ross Ice Shelf will be melting 2 m/yr, which is similar to the melt rate that prevails today beneath the George VI Ice Shelf.

Even with a large rate of shelf-melting, the Antarctic contribution to sea level may be negligible. Because ice shelves float and hence already displace ocean water, shelf-melting would raise sea level only if it accelerates the rate at which ice streams convey ice toward the oceans. Several models suggest, however, that shelf-melting will not substantially accelerate ice streams—and even the models that project such an acceleration generally suggest a lag of a century or so. Thus, through the year 2100, we estimate a 60 percent chance that the sea level drop caused by increased Antarctic precipitation will more than offset the sea level rise caused by increased ice discharge; this probability declines to 50 percent by 2200.

Our analysis suggests that if Antarctica is going to have a major impact on sea level, it will probably be after the year 2100. Even by 2200, the median contribution is negligible; but the reviewer assumptions also imply a 10 percent chance of a contribution greater than 40 cm, as well as 3 and 1 percent chances that the contribution could exceed 100 and 200 cm, respectively.

Small Glaciers. If all the small glaciers melted, sea level would rise approximately 50 cm. We estimate that a 9 cm contribution through the year 2100 is most likely, with a 5 percent chance that the contribution will be greater than 20 cm.

Total Contribution of Climate Change to Sea Level

The reviewer assumptions imply that there is a 1 percent chance that climate change will raise sea level 42 cm by the year 2050, 104 cm by 2100, and over 4 m by 2200. The most likely (median) contribution, however, is only about one-third as great: 15 cm by 2050, 34 cm by 2100, and 81 cm by 2200. Uncertainty increases over time: the ratio of our 1%-high scenario to our median scenario is 2.8 for 2050, 3.1 for 2100, and 5.1 for 2200. Figure 7-1 illustrates the cumulative probability distribution of the primary contributors to sea level for the year 2100.

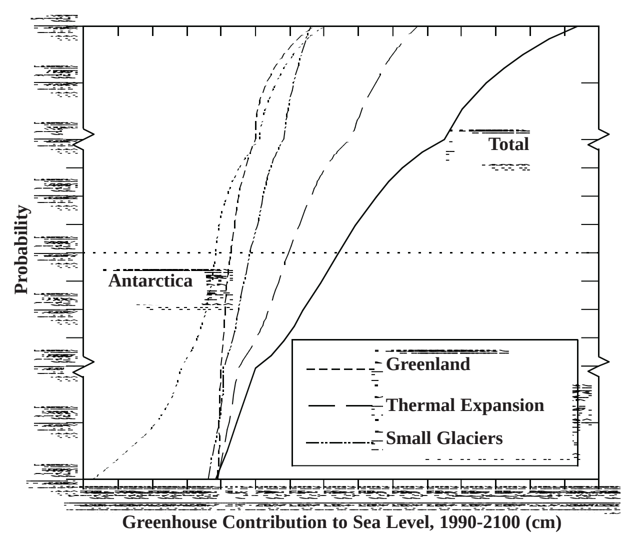

Figure 7-1. Greenhouse Contribution to Sea Level. The cumulative probability distributions show the contribution to sea level from thermal expansion, small glaciers, Greenland, and Antarctica for the period 1990–2100.

TABLE 7-2
YEAR BY WHICH VARIOUS THRESHOLDS ARE EXCEEDED[a]

THRESHOLD	Probability that Threshold Will Be Exceeded by a Given Year: 97.5%	90%	70%	50%	30%	10%	5%	2.5%	1%
Climate Contribution to Sea Level									
> 50 cm	>2200	>2200	>2200	2136	2108	2083	2074	2066	2059
> 1 meter	>2200	>2200	>2200	>2200	2180	2133	2118	2108	2097
Sea Level along U.S. Coast[b]									
> 1 ft	2169	2099	2069	2058	2049	2038	2034	2031	2027
> 3 ft	>2200	>2200	2194	2157	2131	2106	2097	2090	2083
> 5-ft contour on topographic maps	>2200	>2200	>2200	>2200	2180	2141	2127	2117	2107
Other Variables									
ΔForcing > 4.4 W/m^2	>2200	>2200	2103	2089	2064	2068	2066	2064	2062
CO_2 > 600 ppm	>2200	>2200	2117	2078	2077	2052	2048	2045	2042
ΔT > 1˚C	>2200	>2200	2069	2048	2034	2022	<2020	<2020	<2020
ΔT > 2˚C	>2200	>2200	2174	2099	2073	2052	2046	2041	2031

[a]Compared with 1990 levels.

[b]Based on rate of sea level rise at New York City, which typifies the Atlantic and Gulf Coasts of the United States. See Chapter 9 for further details.

(As we discuss in the final chapter, the rise in sea level along most of the U.S. Coast will be higher due to nonclimatic contributors to sea level.) Table 7-2 illustrates the year by which sea level and a few other key variables will exceed particular thresholds. Although a 2˚C warming is most likely to occur over the next century, for example, there is a one percent chance that such a warming could occur by the year 2031.

Figures 7-2 and 7-3 illustrate the cumulative and annual contributions of climate change to sea level for selected simulations. By the year 2100, climate change is most likely to add 4 mm/yr to sea level (implying a rate of more than 6 mm/yr along most of the U.S. coast). Moreover, there is a 10 percent chance that climate change will add 1 cm/yr, and a 1 percent chance that it will add 2 cm/yr, by the end of the twenty-first century.

The net effect of the reviewer assumptions is illustrated by Table 7-3, which compares our final reviewer-based estimates with the draft estimates. The final median estimates are approximately one-third lower than estimated in the draft report, primarily because the median estimate of warming over the next century was lowered from 3˚C to 2˚C. At the high end of the range, by contrast, the final results are only one-fourth lower for the year 2100—and they are actually higher for 2200, primarily because of the potential contribution from Antarctica. At the low end of the range, the final results are much lower than the draft results, for three reasons: (1) one reviewer expects global temperatures to rise only slightly, if at all; (2) another reviewer suggested that polar precipitation is very uncertain and could conceivably increase by 20 percent for a 1˚C warming; and (3) the factors that cause a lower median temperature also operate on the low end of the spectrum.

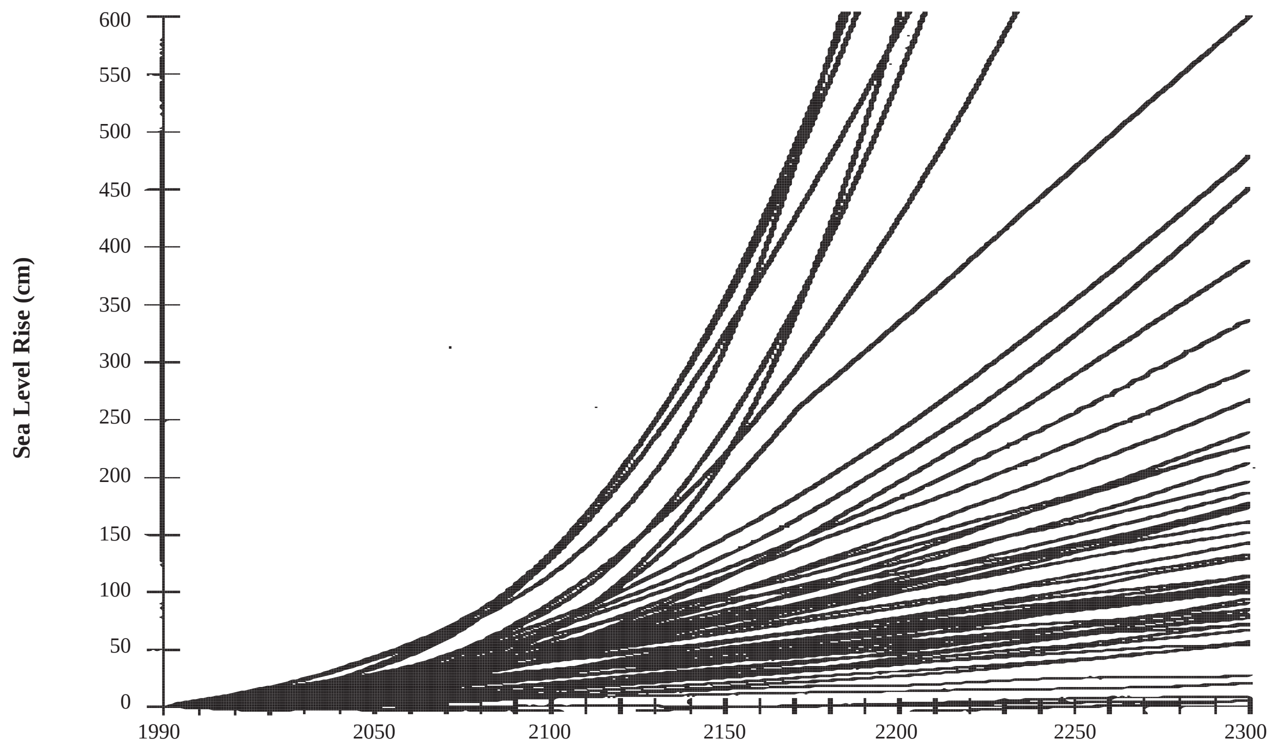

Figure 7-2. Cumulative Contribution of Climate Change to Sea Level: Selected Simulations.

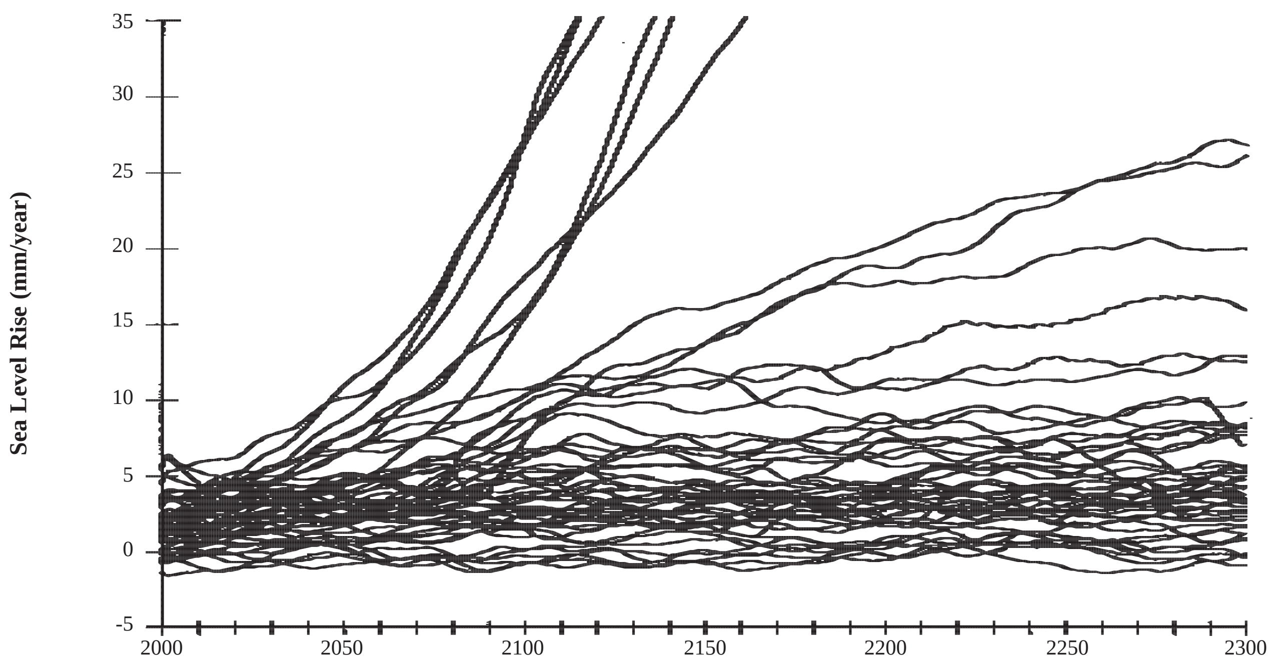

Figure 7-3. Annual Contribution of Climate Change to Sea Level: Selected Simulations. See Figure 2-5 and accompanying text for description of these and other spaghetti diagrams.

TABLE 7-3
CUMULATIVE PROBABILITY DISTRIBUTION OF THE
CONTRIBUTION OF CLIMATE CHANGE TO SEA LEVEL RISE

	Draft Results Sea Level Rise (cm)			Final Results Sea Level Rise (cm)			Rate of Rise (mm/yr)
Cumulative Probability	2030[a]	2100	2200	2050[a]	2100	2200	2100
1[b]	4.1	15	28	-1.2	-1.2	-0.8	-0.36
2.5[b]	—	—	34	0.4	1.7	3.5	0.03
5[b]	6.3	22	43	2.1	4.9	10	0.47
10	7.8	28	55	4.6	10	22	1.05
20	9.7	35	72	8.1	19	39	1.91
30	12	40	84	11	24	53	2.68
40	13	46	100	13	29	67	3.44
50	15	52	112	15	34	81	4.21
60	16	58	128	17	39	96	5.04
70	18	65	148	20	45	115	6.08
80	20	73	180	23	53	143	7.49
90	23	88	228	28	65	196	9.89
95	26	101	280	33	77	254	12.37
97.5	—	—	332	37	88	316	15.41
99	31	131	400	42	104	409	19.34
99.5[b]	—	—	452	46	115	498	23.05
Mean	—	—	—	16	37	99	5.04
σ				9	22	82	4.19

[a]Although the draft provided results for the year 2030, we subsequently decided that the year 2050 would be more useful for the purposes of this chapter. Budget constraints precluded us from recomputing the draft results for 2050.

[b]Included for diagnostic purposes only. Neither the reviewers nor the modeling efforts focused on the risk of a sea level drop. Therefore, the lower end of the uncertainty range is much less reliable than the upper end.

NOTE: Because nonclimatic factors also contribute to sea level rise, these results should not be used to project sea level in specific locations. See Table 9-1 for results better suited for that task.

Because the reviewers represent a cross-section of the scientific community, we have weighted the individual assessments equally.[6] Nevertheless, the variation of reviewer assessments may also be worth considering. Figure 7-4 shows the variation in sea level estimates resulting from the assumptions suggested by the various climate reviewers (see Chapter 3). Even though their estimates for global temperature change were similar, Schneider, Rind, and Hoffert projected much less warming for Greenland and Antarctica than did Manabe or MacCracken. As a result, the Manabe and MacCracken assumptions suggest a 1 percent chance of a 3 m rise by 2200; the Schneider, Rind, and Hoffert assumptions, by contrast, imply a 7 percent chance of a 3 m rise and a 1 percent chance of a 5 m rise over the next two centuries.

[6]Some Delphic studies have asked the reviewers to assign an appropriate weight to the opinions of each reviewer. We decided not to follow that approach, for reasons explained in Chapter 1. Among those reasons: (a) we would have had to double the number of questions asked of each reviewer; (b) the reviewers' expertise on individual physical processes does not necessarily imply an expertise to assess the merits of other reviewers' opinions; (c) the reviewers already self-selected out of parameters on which they had no expertise; (d) we wanted to keep this analysis "on the record," which would have been impossible if the reviewers had to rate the expertise of other scientists; and (e) we would still have to pick an appropriate weight for each reviewer's opinion of the other opinions. *See* Chapter 1, **Approach**.

TABLE 7-4
CONTRIBUTION OF CLIMATE CHANGE TO SEA LEVEL 1990-2100
COMPARISON BETWEEN IPCC (1990) AND OUR RESULTS

Scenario	Thermal Expansion	Small Glaciers	Greenland	Antarctica	Total
IPCC/low[a]	25.8	7.8	2.9	–7.6	29
1%	–0.8	–3.9	–0.8	–37	–1.2
10%	5.1	1	0.2	–11.7	10.3
IPCC/best[a]	38.7	18.5	11.6	–5.36	64
Median	19.7	8.7	2.9	–1.4	34.1
IPCC/high[a]	58	21.5	27.7	0	107.2
90%	38.1	18.3	10.3	11	65.1
99%	57.5	26.3	27.2	30	104

[a]IPCC results cited here are somewhat different from those of IPCC 1990 because they are with respect to a 1990 base, rather than IPCC's 1985 base. In addition, IPCC (1990) rounded some of its results.

NOTE: Because nonclimatic factors also contribute to sea level rise, these results should not be used to project seal level in specific locations. See Table 9-1 for results better suited for that task.

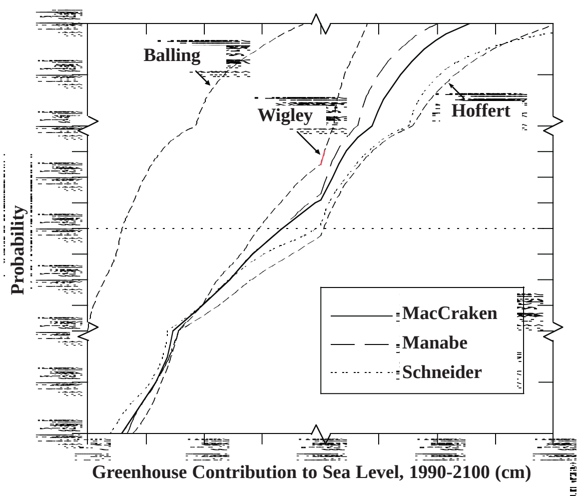

Figure 7-4. Greenhouse Contribution to Sea Level by Climate Reviewer. These cumulative distributions show the greenhouse contribution for the year 2200. Wigley & Raper provided assumptions for Greenland and Antarctica; otherwise, the displayed distributions combine the reviewer's climate assumptions with random samples of the assumptions suggested by the precipitation and Antarctica reviewers.

The assumptions of Wigley & Raper and Balling, by contrast, suggest that the risk of a large rise is much smaller. Because Wigley & Raper assumed a narrower range of possible temperature projections than the other "mainstream" reviewers, their range of sea level projections is also narrower. Finally, Wigley & Raper provided their own assumptions for the ice sheet contribution to sea level—assumptions that suggest lower risk than was suggested by the glacialogy reviewers of Chapters 4 and 5. Their median projection is also somewhat lower because their ocean model assumptions did not imply as much downward penetration of heat as the assumptions favored by the other reviewers. Given Balling's assumption that global temperatures are not sensitive to greenhouse gases, his low projections of the sea level contribution are not surprising. Nevertheless, he allowed for random fluctuations in climate and accepted the other models used in this report. As a result, his relatively optimistic assumptions still imply that there is a 1 percent chance that changing climate will add 90 cm to sea level over the next two centuries.

Comparison with IPCC (1990)

For the last several years, the most widely cited estimates for future sea level rise have been those reported by IPCC (1990). As this report went to press, the IPCC was revising its projections for a report to be released later in 1995. Although we hope that this report satisfies the special information needs of coastal planners and engineers, it seems reasonable to assume that more general assessments of the climate change issue will continue to use IPCC estimates. Therefore, we briefly compare our results with those of IPCC (1990), as well as Wigley & Raper, whose periodic assessments have often provided useful interim indications of the direction in which scientific opinion is headed.

Table 7-4 compares our projections for the year 2100 with those of IPCC (1990). Although our median estimate of 34 cm is fairly consistent[7] with the Wigley & Raper (1992) estimate of 48 cm, it is substantially lower than the IPCC "best-guess" estimate of 64 cm. Our downward revision (compared with IPCC's medium estimate) is primarily driven by the lower temperature estimates, which in turn resulted from lower estimates of radiative forcing (*i.e.*, lower concentrations of greenhouse gases and inclusion of the offsetting effect of sulfate aerosols).

Our draft results, however, show that the median sea level estimate would have been lower than the IPCC (1990) estimate even if our temperature estimates had been as high as those of IPCC (1990). The draft and IPCC (1990) both assumed a warming of about 3˚C over the 1990–2100 period, but the draft projected a sea level contribution of only 51 cm. About half of this downward revision (compared with IPCC) resulted from lower thermal expansion estimates, which stemmed from changes in ocean modeling assumptions.[8] Our nonlinear model of the Greenland contribution, combined with explicitly considering increased precipitation, resulted in a much lower estimate of this ice sheet's sensitivity to a warming of a few degrees (C). Finally, we incorporated recent work suggesting that small glaciers are less sensitive to global temperatures than previously thought.

Although our median projection is a downward revision compared with IPCC (1990), it is more difficult to say whether our estimates of the entire range also constitute a downward revision. The terms "low scenario" and "high scenario" have no precise meaning. The IPCC (1990) high scenario, for example, involved a coincidence of high temperature sensitivity and high values for the sensitivity of Antarctic, Greenland, and small glaciers; but it was based on best-guess estimates of future concentrations and ocean mixing (although those assumptions are both at the high end of the range we use here). Our results, by contrast, do not explicitly include a coincidence of all parameters reaching their "high values," both because we randomly selected the parameter values and because the normal and lognormal distributions do not have fixed upper bounds.

Nevertheless, given the interpretation of "high" and "low" as "worst-case" and "best-case" scenarios, our final results reflect far more uncertainty than the IPCC results. More than 40 percent of our simulations project less sea level rise than IPCC's low scenario of 30 cm by 2100; 15 percent of the simulations suggest that climate change will contribute even less than Wigley & Raper's (1992) estimate of 15 cm. At the upper end of the range, about 0.75 percent of our simulations suggest more sea level rise than IPCC's high scenario (110 cm). Thus, while IPCC's high scenario was 1.7 times its "best-estimate" scenario for the year 2100, approximately 16 percent of our simulations are more than 1.7 times our median estimate; and our 1%-high estimate is 3.1 times our median scenario.

The Implications of Alternative Emission Rates

The preceding results were based on a mix of emission scenarios. To the coastal decisionmaker, future emission rates are but one of many sources of uncertainty and are functionally no different from the various climatic and glacial process parameters. To the climate policymaker, however, emission rates are (in theory) a variable that can be fixed by policy. As a result, climate policymakers may be more interested in the *conditional* probability distribution of sea level rise for a given emissions scenario, and the implications of policies to reduce emissions.

Table 7-5 summarizes the results for a variety of alternative emission scenarios. The left side of the table compares the impacts of IPCC Scenarios A and E. We also examine the potential benefits of freezing emissions in the year 2025 or 2050, rather than 2100. These scenarios use the full distribution of emission sce-

[7]As discussed in Chapter 9, if one assumes that the historic sea level rise has been 1.8 mm/yr, then our median estimate of the total rise in sea level (including nonclimatic contributors) by the year 2100 is 45 cm.

[8]The most important changes were lower values of the parameter π and a correction in the Wigley & Raper model regarding how expansion was calculated.

TABLE 7-5
IMPLICATIONS OF ALTERNATIVE EMISSIONS SCENARIOS

Assumptions									
Emission Scenarios:	E	A	All[a]	All	All	All	All	All	All
Emissions Fixed After:	2100	2100	2100	2050	2025	2100	2100	2050	2025
Climate Sensitivity[b]:	1.0-4.4	1.0-4.4	1.0-4.4	1.0-4.4	1.0-4.4	2.6 fix	4.0 fix	4.0 fix	4.0 fix
Increased Forcing, 1990–2100 (W/m^2)									
median	6.6	5.5	4.9	4.4	4.0	4.9	4.9	4.4	4.0
10%-high	6.6	5.5	7.2	5.8	4.9	7.2	7.2	5.8	4.9
1%-high	6.6	5.5	8.7	7.0	5.9	8.7	8.7	7.0	5.9
Warming, 1990–2100 (˚C)									
median	2.6	2.3	2.0	1.9	1.7	2.4	3.3	3.1	2.9
10%-high	4.5	4.0	4.0	3.6	3.3	3.3	4.8	4.2	3.8
1% high	6.7	6.0	6.3	6.0	5.6	4.4	8.1	6.9	6.3
Warming, 1990–2200 (˚C)									
median	4.9	4.0	3.3	2.9	2.7	4.0	5.8	5.0	4.6
10%-high	9.0	7.4	7.4	5.8	5.2	5.6	8.3	6.6	5.8
1%-high	13.8	11.5	12.8	9.9	9.0	7.4	10.5	8.1	7.1
Sea Level Contribution, 1990–2100 (cm)									
median	40	36	34	33	31	38	53	50	48
10%-high	71	66	65	62	59	53	73	70	67
1%-high	110	103	104	102	101	84	118	113	110
Sea Level Contribution, 1990–2200 (cm)									
median	108	91	81	71	66	97	140	124	114
10%-high	237	200	195	166	152	162	236	205	191
1%-high	447	385	409	357	347	308	455	403	366
Annual Greenhouse Contribution to Sea Level by 2100 (mm/yr)									
median	6.2	4.8	4.2	3.6	3.2	4.9	7.1	5.9	5.3
10%-high	12.0	9.7	9.9	8.2	7.3	8.1	11.7	9.8	8.9
1%-high	21.2	17.8	19.3	17.4	15.3	15.2	22.1	19.5	17.3

[a]The column shows the result for the final analysis discussed throughout this report.

[b]The σ range is 1.0-4.4 rather than 1.5-4.5, due to the downward effect of the Balling assumptions.

narios from the baseline analysis. The third, fourth, and fifth columns in Table 7-5 use a range for the climate's sensitivity to a CO_2 doubling, while the last three columns use the relatively high value of 4.0˚C suggested by many three-dimensional general circulation models.[9]

The results suggest that if emission Scenario E is likely to unfold, the *initial* benefit of emissions policies would be modest. Moving society down to the scenario A trajectory would decrease the median sea level contribution from 40 cm to 36 cm; freezing emissions in the year 2050, which is roughly equivalent to IPCC Scenario D, would reduce the sea level contribution to 33 cm—only 17 percent less than what would occur under Scenario E. Over the next two centuries, however, freezing emissions by 2050 would reduce the expected rise in sea level by 35 percent (71 cm compared with 108 cm).

Using the uncertainty range developed in Chapter 2, freezing emissions by 2050 would only reduce the next century's sea level rise by about 3 percent, compared with freezing emissions in 2100; freezing emissions by 2025 would reduce the rise by about 10 percent. These results do not necessarily mean that stabilizing emissions is not worthwhile, only that the benefits of doing so would accrue over a long period of time. The median *rate* of sea level rise would be one-sixth lower by 2100 if emissions were frozen in 2050, and 25 percent lower if emissions were frozen in 2025. The median cumulative greenhouse contribution to sea level through the year 2200 would be reduced by 12 and 18 percent, respectively, if emissions are frozen in 2050 and 2025; the 10%-high estimates would be reduced by 15 and 25 percent.

Sensitivity Analysis of Variation

Given the large number of parameters used in this analysis, one might reasonably ask: Which of these parameters are superfluous and which contribute significantly to our uncertainty? Although a complete analysis of this question is beyond our current resources, we briefly discuss four of the most important processes: emissions, climate sensitivity, the response of polar temperatures to global temperatures, and the response of ice-shelf melting to changes in Antarctic ocean water temperatures. We fix the parameter(s) controlling these processes at roughly their median values and examine the extent to which uncertainty declines.

As Table 7-6 shows, the climate sensitivity parameter accounts for the most uncertainty, especially at first. For the year 2100, fixing this parameter reduces the standard deviation of sea level rise projections by 35 percent. Fixing the polar-temperature parameters or the ice-shelf-melt parameters, by contrast, each reduces the standard deviation by about 4 percent; and fixing emissions equal to Scenario A reduces the uncertainty by about 0.5 percent. For the year 2200, however, fixing climate sensitivity only reduces the standard deviation by 21 percent, while fixing polar-temperature and ice-shelf-melt sensitivities reduces the standard deviation by 10 and 16 percent, respectively.

The contributions of polar amplification and shelf-melt sensitivity to total uncertainty is greater for the year 2200, primarily because the contributions of Antarctica and Greenland to sea level are likely to be much larger during the 22nd century than during the 21st century. Fixing temperature sensitivity or polar temperature amplification reduces the standard deviation for the Greenland contribution by about one-third. For Antarctica, however, the ice-shelf-melt sensitivity accounts for about half of the uncertainty; polar temperature amplification accounts for about 25 percent of the uncertainty; and climate sensitivity accounts for about 7 percent. The differences are even greater when one focuses on the 1%-high projections: fixing the shelf-melt sensitivity reduces the 1%-high estimate of the Antarctic contribution by more than two-thirds.

Numerical Error of the Monte Carlo Alogorithm

As discussed in Chapter 1, we chose to calculate the probability distribution of future sea level rise using the basic Monte Carlo algorithm. The Latin Hypercube algorithm generally provides more precise estimates of the tails of a distribution for a given number of simulations, but implementing it would have required additional work. We decide that the increased numerical accuracy was not worth the extra effort.

As a rough check to ensure that we had run enough simulations, we divided our sample into eight subsets, representing the first 1250 runs, the second 1250 runs, and so on. For the climate contribution to sea level (1990–2100), the 1%-high generally ranged between 101

[9] We include the scenario where climate sensitivity is fixed at 2.6˚C here for the reader interested in the resulting temperature projections, which are not displayed in Table 7-6.

TABLE 7-6
ANALYSIS OF VARIANCE: CUMULATIVE PROBABILITY DISTRIBUTION OF SEA LEVEL CONTRIBUTION WHEN CERTAIN PARAMETERS ARE FIXED AT THEIR MEDIAN VALUES

	PARAMETER FIXED				
	None (Baseline)	Emissions	Climate Sensitivity	Polar Temperatures	Ice Shelf Melt Rate
Parameter Set To:		Scenario A	2.6˚C	Median Values	Median Values
Greenland Contribution, 1990–2200 (cm)					
1% low	–2.7	–3.2	2.5	1.5	—
10% low	0.1	1.2	3.7	2.5	—
median	12.0	15.0	14.7	12.8	—
10% high	50.0	53.3	39.8	39.3	—
1% high	150.0	149.1	130.6	105.2	—
mean	21.0	23.3	23.7	18.3	—
σ	29.8	29.4	19.7	19.4	—
Antarctic Contribution, 1990–2200 (cm)					
1% low	–90.0	–88.7	–80.7	–88.3	–92.5
10% low	–25.0	–24.4	–15.4	24.2	–24.1
median	0.0	–0.1	9.7	–0.2	–0.3
10% high	43.0	46.0	47.8	35.7	25.2
1% high	206.0	206.4	152.7	139.0	62.7
mean	8.0	8.9	22.4	6.1	4.2
σ	47.0	45.6	44.0	38.1	23.4
Total Greenhouse Contribution, 1990–2100 (cm)					
1% low	–1.0	–1.0	7.0	–1.0	–1.0
10% low	10.0	12.0	21.0	10.0	9.0
median	34.0	36.0	38.0	33.0	33.0
10% high	65.0	66.0	53.0	62.0	62.0
1% high	104.0	103.0	84.0	102.0	98.0
mean	37.0	39.0	40.0	36.0	36.0
σ	22.3	22.2	14.6	21.5	22.0
Total Greenhouse Contribution, 1990–2200 (cm)					
1% low	–1.0	–1.0	26.0	–1.0	–2.0
10% low	22.0	28.0	5.0	22.0	23.0
median	81.0	91.0	97.0	76.0	77.0
10% high	196.0	200.0	162.0	180.0	171.0
1% high	409.0	385.0	308.0	309.0	293.0
mean	99.0	108.0	111.0	92.0	90.0
σ	82.4	83.9	65.5	73.8	69.2
Annual Greenhouse Contribution by the Year 2100 (mm/yr)					
1% low	–0.36	–0.27	0.48	–0.21	–0.17
10% low	1.05	1.54	2.20	1.05	1.06
median	4.20	4.84	4.90	3.96	4.07
10% high	9.89	9.70	8.10	9.19	9.34
1% high	19.34	17.82	15.21	16.62	16.18
mean	5.04	5.43	5.42	4.69	4.77
σ	4.19	3.79	2.95	3.52	3.71

and 107, with a mean of 104 and a standard deviation of 2.7 cm (*see* Appendix 1). Thus, the standard deviation of our estimate of the 1%-high estimate is 0.99 cm.[10]

For the purposes of this study, a standard numerical error of 1 cm for the 1%-high is acceptable. This result is not surprising, given that the 1%-high estimate represents one hundred observations. Had our intent been to characterize the one-in-a-million risk common in environmental risk assessments, or even the one-in-ten-thousand risk considered in the Dutch flood control system, the use of algorithms that capture the tails of a distribution would have been more important. We determined at the outset, however, that our models and assumptions were not suited for such unlikely risks.

References

Intergovernmental Panel on Climate Change. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge and New York: Cambridge University Press.

Intergovernmental Panel on Climate Change. 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge and New York: Cambridge University Press.

Intergovernmental Panel on Climate Change. 1994. *Climate Change 1994. Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*. Cambridge and New York: Cambridge University Press.

Wigley, T.M.L., and S.C.B. Raper. 1992. "Implications for Climate and Sea Level of Revised IPCC Emissions Scenarios." *Nature* 357:293-300.

[10]Recall from elementary statistics that the standard deviation of an estimate of the mean is equal to the standard deviation of a sample, divided by the square root of the sample size. In this case, the "mean" refers to the average value of the 1%-high of various data sets, and the sample size is 8.