CHAPTER 2

CONCENTRATIONS OF GREENHOUSE GASES

Anthropogenic Emissions

This analysis is based on the IPCC assumptions for emissions and concentrations, as updated by Wigley & Raper (1992). That analysis considers seven greenhouse gases (CO_2, CH_4, N_2O, CFC-11, CFC-12, HCFC-22, and HFC-134a) as well as three gases with important indirect effects on climate (SO_2, carbon monoxide, and volatile organic compounds). For all gases other than CFC-11, CFC-12, and HCFC-22, we characterize (anthropogenic) emission rates through the year 2100 using lognormal distributions, with the geometric means and standard deviations calculated from the six emission scenarios from IPCC (1992). For the two CFCs, we used the IPCC scenarios directly.[1]

Figure 2-1 compares our probability density function for CO_2 emissions with that of Nordhaus & Yohe (1983). For the year 2100, Nordhaus & Yohe have a median of about 14 gigatons (Gt) per year of carbon and a geometric mean of 19 Gt/yr, while both our median and geometric means are 16 Gt/yr. Our 68 percent confidence interval (σ range) extends from 8 to 34 Gt/yr, while the 68 percent limits for Nordhaus & Yohe are 7 and 31 Gt/yr. Our 1, 5, and 10%-high scenarios are 88.5, 53.6, and 41.3 Gt/yr, respectively. Nordhaus & Yohe found similar uncertainty. Although the highest 7 percent of their simulations are reported at around 52 Gt/yr, this estimate presumably reflects a truncation of the distribution; their 10th percentile is approximately 43 Gt/yr. Edmonds et al. (1985) found even more uncertainty: Their 5%-high scenario is 80 Gt/yr, roughly equal to our 2%-high scenario; and their 25%-high scenario of 28 Gt/yr is almost as great as our 16% (σ-high) limit. Figure 2-2 compares our projections of CO_2 emissions with the six IPCC emissions scenarios for the years 1990 to 2100.

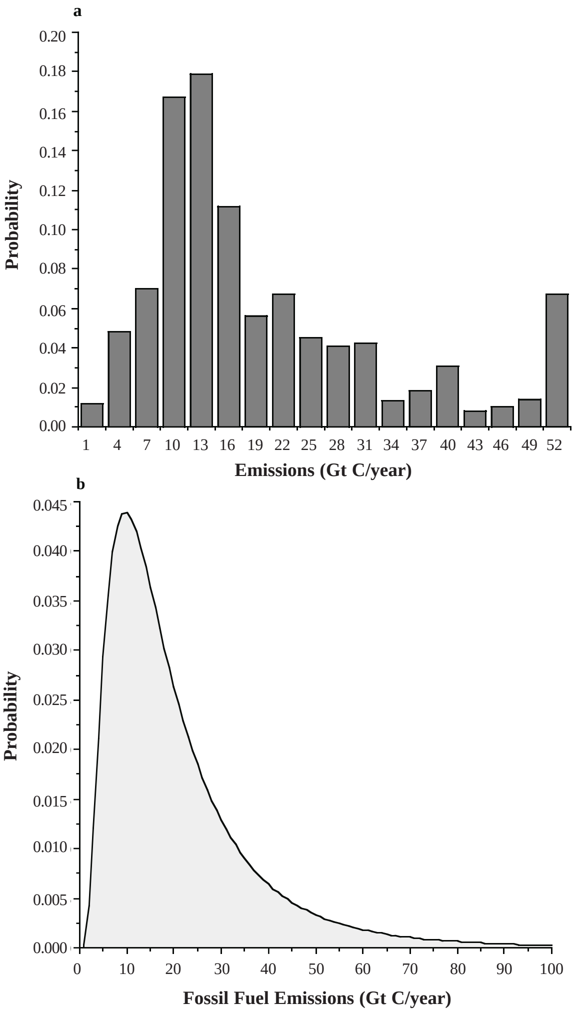

Figure 2-1. **Probability Density of CO_2 Emissions in the Year 2100.** (a) Nordhaus & Yohe (1983); (b) this analysis.

For simplicity, we assume that emissions for the various gases are perfectly correlated. This assumption allowed us to draw from only one distribution to calculate all emissions, rather than from one distribution for each gas. In effect, we assume that the IPCC scenarios were already designed to convey the combined uncertainty of future emission rates.[2] Moreover, because economic growth and policies on emissions reduction are the primary factors driving changes in emission rates, emissions are highly correlated.

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[1] For CFC-11 and CFC-12, three of the IPCC scenarios assume that emissions decline to zero. As a result, the geometric standard deviation cannot be calculated. Therefore, we follow the procedure outlined above for the three nonzero scenarios and draw from this distribution one-half of the time. The other half of the time we draw from one of the three zero-tending emissions scenarios. For HCFC-22, two of the IPCC scenarios assume that emissions decline to zero. Here again we follow a similar procedure, drawing from a distribution 2/3 of the time and from one of the two zero-tending scenarios 1/3 of the time.

[2] This assumption is not as unreasonable as it might seem at first glance. IPCC Scenario E, for example, which has the highest CO_2 emission rate, assumes less emissions of HCFCs and methane than assumed by Scenario F. Thus, assuming perfect correlation among the scenarios is unlikely to overstate total uncertainty of radiative forcing.

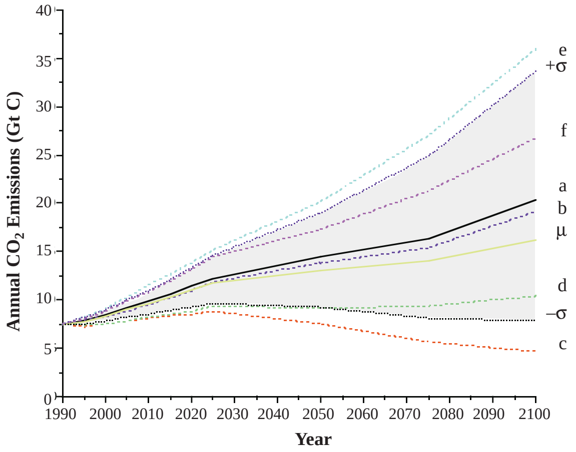

Figure 2-2. IPCC (1992) CO_2 Emissions Scenarios. a=IS92a,...f=IS92f. The shaded area shows the emissions rates bounded by our σ-low and σ-high scenarios. The scenario μ represents the geometric mean from our analysis.

The IPCC projections did not extend beyond the year 2100. While we would have liked to consider subsequent changes in emission rates, the available analyses after that year are rather sparse.[3] Therefore, our simulations assume that emissions are constant after the year 2100. Temperatures and sea level will continue to change, however, because the processes determining atmospheric concentrations, climate, thermal expansion, and glacial contributions each take several decades to reach equilibrium.

Concentrations and Radiative Forcing

Given the emission rates, we calculate concentrations using the same models as IPCC (1992), as modified by Wigley & Raper. For greenhouse gases other than CO_2, we explicitly consider uncertainties in atmospheric lifetimes (unlike IPCC and Wigley & Raper). Table 2-1 lists the atmospheric lifetimes employed by Wigley & Raper, along with the uncertainty as estimated by various studies. In each case, we treat the ratio of the high to the low value as representing the ratio between the σ-high and σ-low scenarios.

The fate of CO_2 is generally modeled as being more complex than the fates of other greenhouse gases. Wigley & Raper, for example, assume that there are four independent sinks, with lifetimes of 1.6, 30, 80, and 330 years, and that, even in equilibrium, about 13 percent of the CO_2 emitted remains in the atmosphere.[4] After one hundred years, only 1/e (37 percent) of the carbon emitted in a particular year remains, which is consistent with an atmospheric lifetime of one hundred years (*i.e.*, an annual decay rate of 1 percent). But after ten years, 25 percent of the carbon has been removed, implying a much more rapid adjustment at first; while after two hundred years, 27 percent still remains, implying a slower adjustment. Thus, the term "lifetime" when applied to CO_2 cannot be viewed as a shorthand for the entire atmospheric decay function, but only as an estimate of how long it takes for various sinks to absorb all but 1/e of the carbon emitted in a given year.

Table 2-1 suggests that the lifetime for CO_2 is less certain than the lifetime for the other greenhouse gases. Nevertheless, we omit any consideration of this uncertainty and simply adopt the set of parameters used by Wigley & Raper. The complexities that we would have to address are beyond the scope of this analysis for two reasons: (1) there are many ways to alter the carbon cycle model to convey the fourfold uncertainty regarding the "lifetime" of CO_2, and none could be readily justified[5]; and (2) changes in temperatures, oceanic circulation, and ecosystems are likely to alter the underlying carbon cycle in ways that are not adequately captured by any carbon cycle model that could be readily adapted for our purposes.

The uncertainty surrounding future radiative forcing is less than the uncertainty surrounding emissions, for two reasons. First, concentrations represent the cumulative impact of all past emission rates; thus, they respond with a long lag to emission rates. For example, the impact of a doubling or a halving of emission rates after ten years would increase or decrease concentrations of CO_2 by less than 10 percent; thus, our uncertainty about what emissions will

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[3] Cline (1992b) discusses results from the Nordhaus model. He reports that the model projects about a 25 percent increase in emissions during the 22nd century, but this scenario is based on the assumption that per capita economic growth is only 0.1 percent per year. When Cline modifies the model to allow for a 1 percent annual economic growth, he finds that emissions could approximately double during that time period.

[4] Concentrations respond to emissions of a unit of CO_2 as follows: $\text{Mass}(t) = 0.13 + 0.22e^{-t/330} + 0.26e^{-t/80} + 0.29e^{-t/20} + 0.01e^{-t/1.6}$.

[5] The most obvious way would have been to assume fourfold uncertainty in all of the lifetimes, but such a result would imply fourfold uncertainty for the initial response (*e.g.*, first decade) when, in fact, the short-term uncertainty is much smaller. We considered arbitrarily assuming that the two slower reservoirs of 80 and 330 years have fourfold uncertainty, but Tom Wigley convinced us that such an assumption would probably be worse than ignoring carbon cycle uncertainty.

TABLE 2-1
PROBABILITY DISTRIBUTIONS OF ATMOSPHERIC LIFETIMES
OF GREENHOUSE GASES USED IN THIS REPORT
(years)

Gas	Wigley Point Estimate	Range	Source	Uncertainty ($\sigma_{high}/\sigma_{low}$) in simulations[a]
N_2O	132	110–168	WMO	1.53
CFC-11	55	42–66	WMO	1.57
CFC-12	116	104–113	WMO	1.09
HCFC-22	15.8	13.5–17.7	WMO	1.31
HFC-134a	15.6	N.A.	WMO	1.31[b]
CH_4	11.8	10–14	Vaghjiani (1991)	1.4
CO_2	100	50–200	IPCC (1990)	1.0

[a] Calculated as the ratio of the high to low estimate under "Range."

[b] Lacking a published estimate of uncertainty, we assume that the uncertainty for HCFC-134a is the same as that of HCFC-22.

NOTE: In all cases other than CH_4 and CO_2, the simulations use the Wigley & Raper point estimate for the median and "Uncertainty" for the geometric standard deviation. In the case of CH_4, the Vaghjiani & Ravishankara estimates of 10 and 14 years are treated as σ limits; *i.e.*, the Wigley & Raper value is not used. In the case of CO_2, we ignore uncertainties in the adjustment period.

do in the next decade has little impact on our uncertainty regarding concentrations ten years hence. Second, radiative forcing is proportional to the *logarithm* of CO_2 concentration, a functional specification that inherently reduces uncertainty.

Figure 2-3 illustrates our draft estimates of the increase in radiative forcing by the years 2030 and 2100. Our median estimate of 6.2 watts per square meter (W/m^2) by the year 2100 was similar to the IPCC (1992) estimate for radiative forcing under Scenario A, but much less than the 7.5 W/m^2 estimated by IPCC (1990).

Expert Judgment

Because of the extensive review of the IPCC scenarios, we did not develop reviewer-based probability distributions for this chapter in the manner undertaken for the next three chapters. Nevertheless, we did make some changes due to the reviewer comments.[6]

The draft, like the IPCC (1990) and (1992) reports, ignored the negative effects of sulfates and ozone depletion. Several reviewers told us to include those offsetting effects and we have done so, based on the Wigley & Raper (1992) sulfate scenarios. CFC emissions cause a long-term depletion of stratospheric ozone, a greenhouse gas; this delayed effect eventually offsets the warming from CFC emissions.[7]

Figure 2-4 illustrates the resulting estimates of radiative forcing. Part (a) compares our uncertainty for radiative forcing with the IPCC scenarios. Ignoring the uncertainty in atmospheric lifetimes, our σ limits for the year 2100 are 3.9 and 7.1 W/m^2, slightly above the range implied by IPCC (1992) scenarios C and E. Figure 2-4b shows that including the uncertainty surrounding non-CO_2 atmospheric lifetimes expands this range to 3.6 to 7.5 W/m^2 in the unlikely event that high and low lifetimes correspond with high and low emission rates. The figure also shows that the sulfates reduce radiative forcing by about 8 percent in the median scenario.

The results also include the biological feedback suggested by Wigley & Raper (1992). The draft had used the same version of the carbon cycle model as used by IPCC (1992), which resulted in a CO_2 con-

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[6] Subsequent chapters present the model as originally presented by the reviewers, followed by the reviewer changes. Because the reviewer changes are straightforward, this chapter only presents the postreview version of our assumptions.

[7] On the other hand, CO and VOC emissions can result in reduced atmospheric OH, which could in turn slow the rate at which methane leaves the atmosphere.

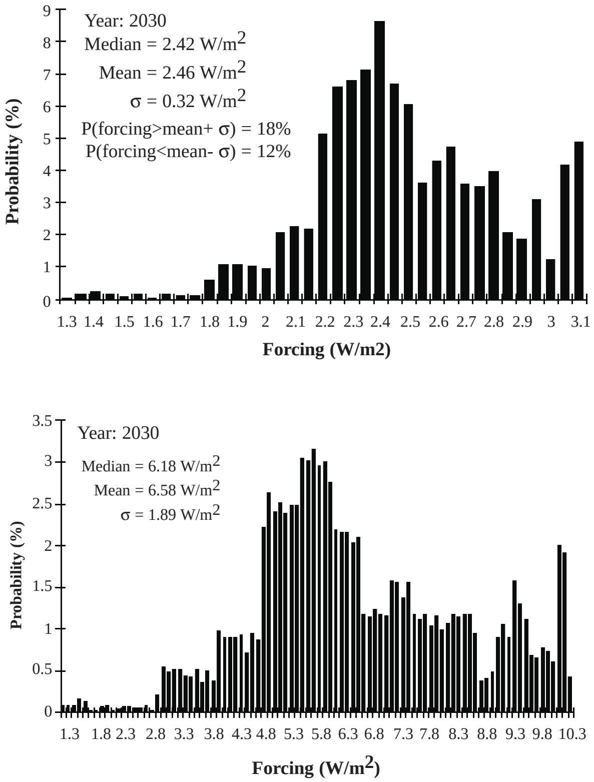

Figure 2-3. Increase in Radiative Forcing: Draft Report. Probability density function for the years 2030 and 2100. Note that the 6.2 W/m^2 median is well below the 7.5 W/m^2 from the IPCC 1990 Business-as-Usual Scenario.

centration of 800 ppm by the year 2100. The "feedback" version of the model, by contrast, results in a CO$_2$ concentration of about 730 ppm.

The reviewer comments also led us to change the shape of the emission distribution. The draft had used the shape of the distribution implied by the Nordhaus & Yohe (1983) results. The reviewers suggested that a lognormal distribution would be more appropriate; so we adopted that functional specification.

Several reviewers commented on our assumptions for the post-2100 period. David Rind felt that emissions are likely to keep changing. Tom Wigley also disagreed with the assumption that emissions would stay constant, believing that such a continuation could not be sustained by the available *reserves*; moreover, the effects of global warming would probably lead nations to limit emissions even if reserves

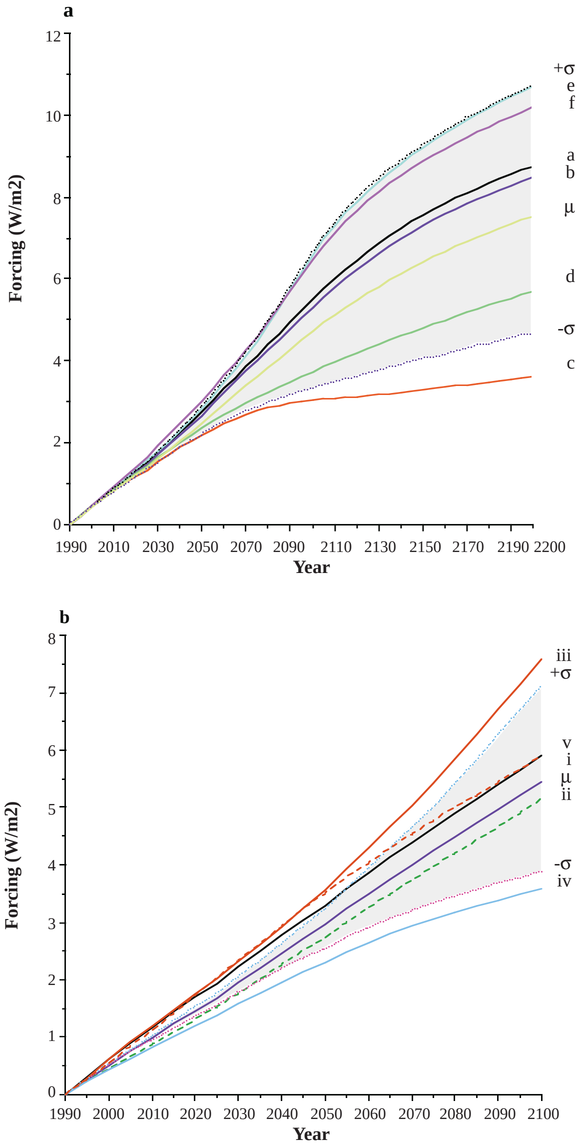

Figure 2-4. Increase in Radiative Forcing: Final Report. (a) Scenarios based on the median atmospheric lifetimes from our analysis, with median (μ) and σ limits (shaded) for emissions, are compared with (a) the six IPCC scenarios and (b) scenarios with (i) high atmospheric lifetime and median emissions; (ii) low atmospheric lifetime and median emissions; (iii) high lifetimes and high emissions; (iv) low lifetimes and low emissions; and (v) median emissions and median lifetimes with the negative impact of sulfates removed.

were sufficient. Jae Edmonds, by contrast, stated that available coal and shale oil *resources* are sufficient to sustain the Edmonds et al. (1985) 5th percentile estimate (80 Gt/yr) for at least a few centuries.

William Cline suggests that the few available studies imply that emissions could continue to rise after the year 2100. Cline (1992a) reports that Alan S. Manne believes that a linear extrapolation of emission rates is reasonable, which implies that the Manne & Richel (1990) estimates of CO_2 emissions would increase by about 0.6 percent per year from 27 Gt/yr in 2100 to 712 Gt/yr in 2275. Cline (1992b) shows that the Nordhaus (1992) model implies that emissions would increase from 20 Gt/yr in 2100 to more than 50 Gt/yr by 2275.

Both of those estimates focus on median scenarios; it seems less likely that the 88 Gt/yr implied by our 1%-high scenario would also continue at such a growth rate. Yet, to assume that high emission rates are more likely to stabilize or decline than the median scenario implies that there is less uncertainty surrounding emissions for the year 2200 than for the year 2100. This counterintuitive assumption should be used, in our view, only if there is a physical or economic constraint in the available supply of fossil fuels.

For purposes of our high scenario, such a constraint does not seem likely. Edmonds et al. (1985) estimate that there is 5000 to 18,000 Gt of coal that can be mined at $85/ton. If 70 percent is emitted as carbon, this estimate implies that our 1%-high scenario could be sustained for 40 to 150 years at a price of $85/ton. Because we are focusing on the high end of the range of possible emission rates, the high end of the available reserves is more relevant than the low end. Given the lower emission rates likely to prevail during the twenty-first century, the high scenario could be sustained until at least the year 2200. Prices greater than $85/ton, moreover, would increase the available coal and could also make oil shale economical. Finally, new discoveries and better technologies would increase the amount of fuels available at a given price. Therefore, we conclude that there is no physical constraint rendering it impossible to sustain the high scenario for the period of this analysis.

In light of the lack of knowledge regarding future emission rates, it still seems most reasonable to keep emissions fixed at the year 2100 level. Arguments can be made for increasing or decreasing the median scenario and for expanding or narrowing the range of uncertainty for subsequent years. The assumption of fixed emissions after the year 2100 is easier to understand, allows us to avoid manipulating the IPCC (1992) emissions scenarios, and at least in the narrow sense enables us to avoid additional speculation.[8]

Final Results

Table 2-2 illustrates our results for the increase in radiative forcing for the period 1990 to 2100. Largely because we included sulfates and the biological CO_2 feedback, our final estimates of radiative forcing are lower than reflected in previous IPCC assessments, as well as our draft report. IPCC's (1992) scenario A was about 6.2 W/m^2 and IPCC's (1990) business-as-usual scenario was 7.5 W/m^2, whereas our median is only 4.9 W/m^2.[9] About 1 percent of our simulations have higher forcing than the 8.5 W/m^2 that IPCC (1992) estimated for Scenario E,[10] while about 20 percent have a forcing less than the 3.5 W/m^2 projected for Scenario C. The table also shows our estimates for the year by which radiative forcing will increase by 4.4 W/m^2—the equivalent of a CO_2 doubling—over the 1990 level; the median estimate is the year 2089, with a 10 percent chance that the doubling equivalent will occur before 2068.

Our scenarios for radiative forcing are broadly consistent with recent assessments. Our *mean* estimate of radiative forcing (5 W/m^2) is only slightly less than the forcing estimate reported by Wigley & Raper (1992). Although IPCC (1992) had a higher forcing, the recent IPCC (1994) report on radiative forcing has adopted scenarios that are much closer to the Wigley & Raper estimates. Most importantly, the IPCC has lowered the projected CO_2 concentration from 800 ppm to about 730 ppm by the year 2100. *See also* Wigley (1993). Although IPCC (1994) did not endorse a specific estimate of the average global forcing effect of sulfates, it did acknowledge that sulfates have been offsetting global warming.[11]

We also show a selected set of 61 scenarios, which we follow throughout the course of this report.

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[8] In the broader and more realistic sense of the word, to assume no change in a changing world is highly speculative. Nevertheless, the convention of deeming such an assumption as not speculative is well established. *See e.g.*, IPCC (1990) (assuming that the contribution of groundwater and Antarctic ice sheet changes to sea level will be zero because the process is too difficult to model).

[9] Even though our analysis is based on Wigley & Raper (1992), our median is less than their estimate for Scenario A (5.3 W/m^2), because Scenario A's emissions are greater than the geometric mean of the six emission scenarios.

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

[11] As this report went to press, the IPCC was considering whether and how the effect of sulfates should be incorporated into global temperature projections for the comprehensive assessment due to be published at the end of 1995.

TABLE 2-2
CUMULATIVE PROBABILITY DISTRIBUTION FOR THE CHANGE IN CARBON DIOXIDE AND RADIATIVE FORCING

			Year by Which	
Cumulative Probability (%)	Forcing 1990–2100 (W/m^2)	CO_2 by 2100 (ppmv)	CO_2 Exceeds 600 ppmv	Doubling Equivalent for all Gases[a]
0.1[b]	1.3	405	>2200	>2200
0.5[b]	1.8	427	>2200	>2200
1.0[b]	2.0	439	>2200	>2200
2.5[b]	2.3	462	>2200	>2200
5.0[b]	2.6	482	>2200	>2200
10	3.0	511	>2200	>2200
20	3.6	554	2131	2151
30	4.0	591	2103	2117
40	4.4	633	2088	2099
50	4.9	680	2078	2089
60	5.4	729	2070	2081
70	5.8	792	2064	2077
80	6.4	878	2059	2073
90	7.2	1047	2052	2068
95	7.8	1204	2048	2066
97.5	8.2	1363	2045	2064
99	8.7	1614	2042	2062
99.5[b]	9.0	1775	2040	2061
99.9[b]	9.4	2364	2037	2059
Mean	5.0	738	N.A.	N.A.
σ	1.6	242	N.A.	N.A.

N.A. = Not applicable.

[a] "Doubling equivalent" refers to the year by which radiative forcing increases by 4.4 W/m^2 over 1990 levels, which is the radiative forcing from a doubling of CO_2.

[b] 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.

Figure 2-5 shows a "spaghetti diagram" of radiative forcing for these scenarios for the years 1990 to 2300. We selected these scenarios by ranking all the scenarios according to the amount of sea level rise for the year 2200. Figure 2-5 and all other spaghetti diagrams in this report illustrate (from highest to lowest) the following simulations: 1, 2, 5, 10, 50, 100, 200, 400, 600...9400, 9600, 9800, 9901, 9951, 9991, 9996, 9999, 10000. Thus, the top and bottom seven simulations should be viewed as extreme (1 percent) scenarios; otherwise, the simulations shown represent equal levels of probability. We show a disproportionate amount of extreme scenarios because (a) if unintended model calculations are taking place, they are most likely to occur and/or become noticeable in the extreme scenarios; (b) risk assessments inherently must focus on extreme scenarios; and (c) as a practical matter, extreme scenarios tend to be more widely spaced than the more typical scenarios, which makes them more legible.

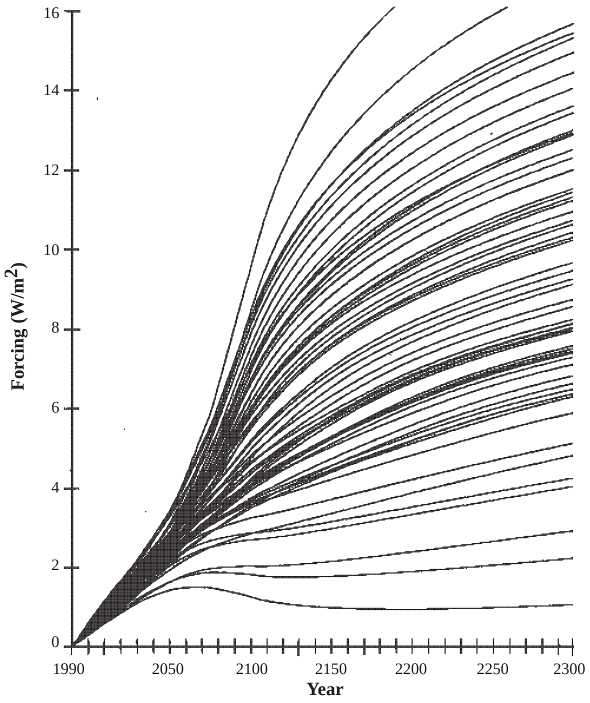

Figure 2-5. Projections of Greenhouse Forcing: Selected Simulations. This and all other spaghetti diagrams illustrate simulations 1, 2, 5, 10, 20, 50, 100, 200, 400, 600,..., 9400, 9600, 9800, 9901, 9951, 9981, 9991, 9996, 9999, 10000, where 1 and 10000 represent the simulations with the highest and lowest estimates of sea level rise for the year 2200.

The uncertainty in radiative forcing is fairly small for the next 50 years, with virtually all scenarios showing an increase between 2 and 3 W/m^2. After the year 2050, however, IPCC scenarios C and D assume that CO_2 emissions decline or remain constant, while other scenarios assume a continuing increase. As a result, the range increases to about 2.5 to 8.0 W/m^2 by 2100 and 2.6 to 13 W/m^2 by 2200. The effect of Scenario C's declining emissions can be seen in the bottom two curves, which decline after around 2070. Even though emissions are assumed to remain constant after the year 2100, radiative forcing continues to increase during the following two centuries for all but a few of the scenarios, due to the long atmospheric lifetime of CO_2.

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Chapter 2