CHAPTER 3

CLIMATE CHANGE

Given the concentrations of greenhouse gases and resulting radiative forcings during particular years, projections of sea level rise require two types of climatic information: (1) estimates of the downward penetration of heat for calculating the thermal expansion of ocean water; and (2) estimates of polar air temperatures, water temperatures, sea ice, and precipitation changes for calculating the glacial contribution to sea level.[1]

Following the general convention, we use a one-dimensional ocean model to simultaneously calculate transient air temperatures and thermal expansion of ocean water. We then employ subsidiary equations to estimate changes in sea ice and polar temperatures. After summarizing the results from our initial draft assumptions, we present the assumptions suggested by the expert reviewers and the resulting estimates. Because a different set of reviewers commented on our equations for polar precipitation, we present those assumptions and results separately at the end of this chapter.

PART A: TEMPERATURE AND THERMAL EXPANSION

The Use of 1-D Ocean Models to Estimate Global Temperature and Thermal Expansion

Although three-dimensional models are generally used to estimate equilibrium responses to greenhouse gases, their cost is too great for undertaking analyses that require many runs of a given model. Hoffert et al. (1980) first proposed a one-dimensional upwelling-diffusion model for analyzing global warming during specific years; numerous studies have employed that model and its descendants. The most widely used of these descendants is the model by Wigley & Raper (1987, 1992), which has been used to produce the official temperature and sea level scenarios of the Intergovernmental Panel on Climate Change. *See e.g.*, IPCC (1990, 1992). To be consistent with IPCC, we used the Wigley & Raper model as well.[2] The model requires us to supply coefficients for (1) the equilibrium average surface warming[3] for a CO_2 doubling (ΔT_{2X}); (2) vertical mixing/diffusion (**k**); (3) upwelling velocity (**w**); and (4) the ratio of the warming of newly formed (polar) bottom water to warming of surface water (π).

Like IPCC and Wigley & Raper, we ran the model using historic concentrations of greenhouse gases from a representative preindustrial starting point (*i.e.*, 1765) to the present. This procedure ensures that when we project the model into the future, the resulting estimates of thermal expansion and warmer temperatures reflect the delayed impact of past emissions as well as the impact of future emissions. While a single historic simulation might be preferable,[4] we follow the convention of IPCC and Wigley & Raper by simulating the model over the historic data for each of our simulations. Figure 3-1 compares actual temperatures with the projected temperatures using the Wigley & Raper model under various scenarios. The model projects a flattening out of the warming over the years 1955–70 because of the negative forcings associated with sulfates and CFC-related ozone depletion (*see* Chapter 2).

Unlike the original version by Hoffert et al. (1980), this model treats the two hemispheres sepa-

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[1] Ideally, we would also like to know whether the precipitation in polar areas is in the form of rain or snow. Because the models we use for Greenland and Antarctica assume that all precipitation is snowfall, this chapter does not address that question.

[2] Tom Wigley and Sarah Raper helped us adapt their model for our purposes.

[3] Since at least 1979, studies of the greenhouse effect have focused on the equilibrium impacts of a CO_2 doubling, that is, an estimate of how much the Earth's average temperature would rise if the concentration of atmospheric CO_2 doubled and then remained at the higher level indefinitely. *See e.g.,* NAS (1979).

[4] For the reader familiar with one-dimensional modeling, we note that this procedure may be analytically and computationally inferior to simply running the historical simulation to 1990 once and starting each of the 10,000 simulations at that point. For example, if we assume that temperature sensitivity is 4.5˚C, the model estimates much more historical warming than what actually occurred, which in turn implies a greater temperature difference between the mixed layer and the thermocline than actually exists. As a result, the model will overstate the downward penetration of heat and thermal expansion that ought to result from future greenhouse forcing. Conversely, for low values of ΔT_{2X}, the model understates thermal expansion.

A decline in upwelling also reduces the temperature difference between the surface and the thermocline. As a result, the net effect of simulating history each time is functionally similar to imposing a correlation between low values of ΔT_{2X} and declines in upwelling. *But see* Chapter 9, Notes 6 and 7.

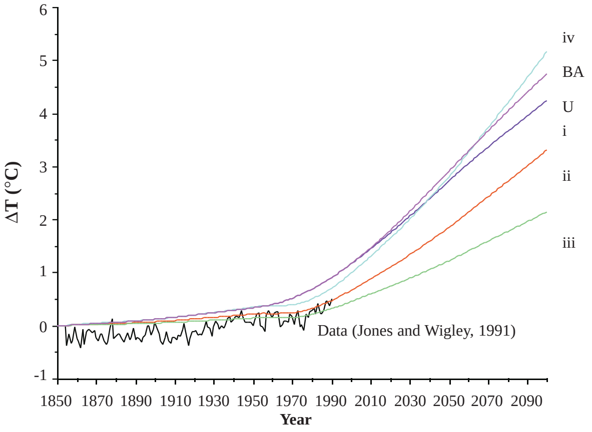

Figure 3-1. Comparison of Historic Temperatures and Projections of the Wigley & Raper Model. Curves (i) and (ii) use the medium assumptions and IPCC scenario IS92a emissions of greenhouse gases; (ii) also includes the offsetting forcings from sulfates and CFC-induced ozone depletion. Curves (iii) and (iv) are the same as (ii), except for ΔT_{2X} values of 1.5 and 4.5˚C. Curve BAU is the same as (i), except that it uses the IPCC (1990) "Business-as-Usual" emission scenario. The jagged curve that stops in the 1990s represents historic temperatures.

rately. Thus, it would be possible to supply the model with Northern and Southern Hemisphere values for **k**, π, and **w**. Nevertheless, we follow the convention of previous studies and run the ocean model based on the assumption that these parameters have the same values for both hemispheres.[5]

Previous assessments of sea level rise have assumed that the values of these parameters are fixed. In reality, however, the three-dimensional processes that π, **k**, and **w** approximate are all likely to change. The importance of allowing for such changes depends on the purpose to which the model is likely to be put, *e.g.*, whether the principal goal is to project transient surface temperatures or sea level. Regardless of the values of π, **k**, and **w**, the transient air temperature will eventually approach ΔT_{2X} if CO_2 is held fixed at twice its preindustrial concentration; those parameters merely determine how rapidly temperatures adjust to their equilibrium. IPCC (1990) showed that temperature is not extremely sensitive to these parameters, especially after the first few decades of a model run.

Sea level rise, by contrast, is very sensitive to these parameters, particularly in the long run. For a given rise in global surface temperatures, the oceanic expansion depends on the resulting rise in water temperatures at every depth. The upper (mixed) layer warms almost as much as the Earth's average surface temperature, but the bottom water only warms by π times that amount. Intermediate waters initially warm *less* than the bottom water, but eventually warm more than the bottom and less than the surface.[6]

Figure 3-2 illustrates the sensitivities of the Wigley & Raper model to a CO_2 doubling, holding **k** and **w** constant at the median values described below, for π=0, 0.2, and 1.0, and ΔT_{2X}=2.5˚C.[7] Surface temperature change is about 18 percent less for π=1 than for π=0 after the first 100 years, and 16 percent less after 500 years. Thermal expansion, however, is 40 percent *greater* after 100 years, 90 percent greater after 200 years, and over three times as great after 500 years. This difference occurs because even after 500 years, the deep ocean (*e.g.*, depth of 2 km) warms only 0.05˚C for π=0, while for π=1 it warms by approximately 1˚C. During the first century, most of the thermal expansion takes place in the mixed layer and upper thermocline, which warm by about the same amount for π=0 and π=1. During later centuries, however, the majority of expansion comes from the thermocline and deep ocean. Even though both the warming and the coefficient of expansion are much greater for the mixed layer than for the thermocline and deep ocean, there is far more water to expand in those lower layers; hence they ultimately contribute the majority of thermal expansion.

Figure 3-2 also illustrates the impact of an instantaneous 50 percent decline in deepwater formation (**w**) with no change in greenhouse gas concentrations (the relevance of which is discussed below).[8] Such a change in ocean circulation would warm the thermocline (Figure 3-2b) substantially. Assuming that π=0.2, a 50 percent decline in deepwater formation would

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[5] We occasionally refer to hemisphere-specific values for these parameters as part of the conceptual justification for the global values that we use, but all model runs use the same values for both hemispheres.

[6] This model artifact probably does not correspond to reality. *See* Figure 3-5 and accompanying text, *infra*.

[7] The significance of these parameter values is described below. We remind the reader that the assumption π=1 implies that the water that sinks toward the bottom in polar regions warms as much as the global average warming; π=0 implies that the water sinks at the same temperatures as today. For a given amount of heat, warmer sinking water means that the water remaining at the surface is colder.

[8] The paramater literally represents the average rate of upwelling throughout all portions of the ocean other than those where downwelling occurs. Because the amount of deepwater formation is proportional to the upwelling velocity, we mean both "deepwater

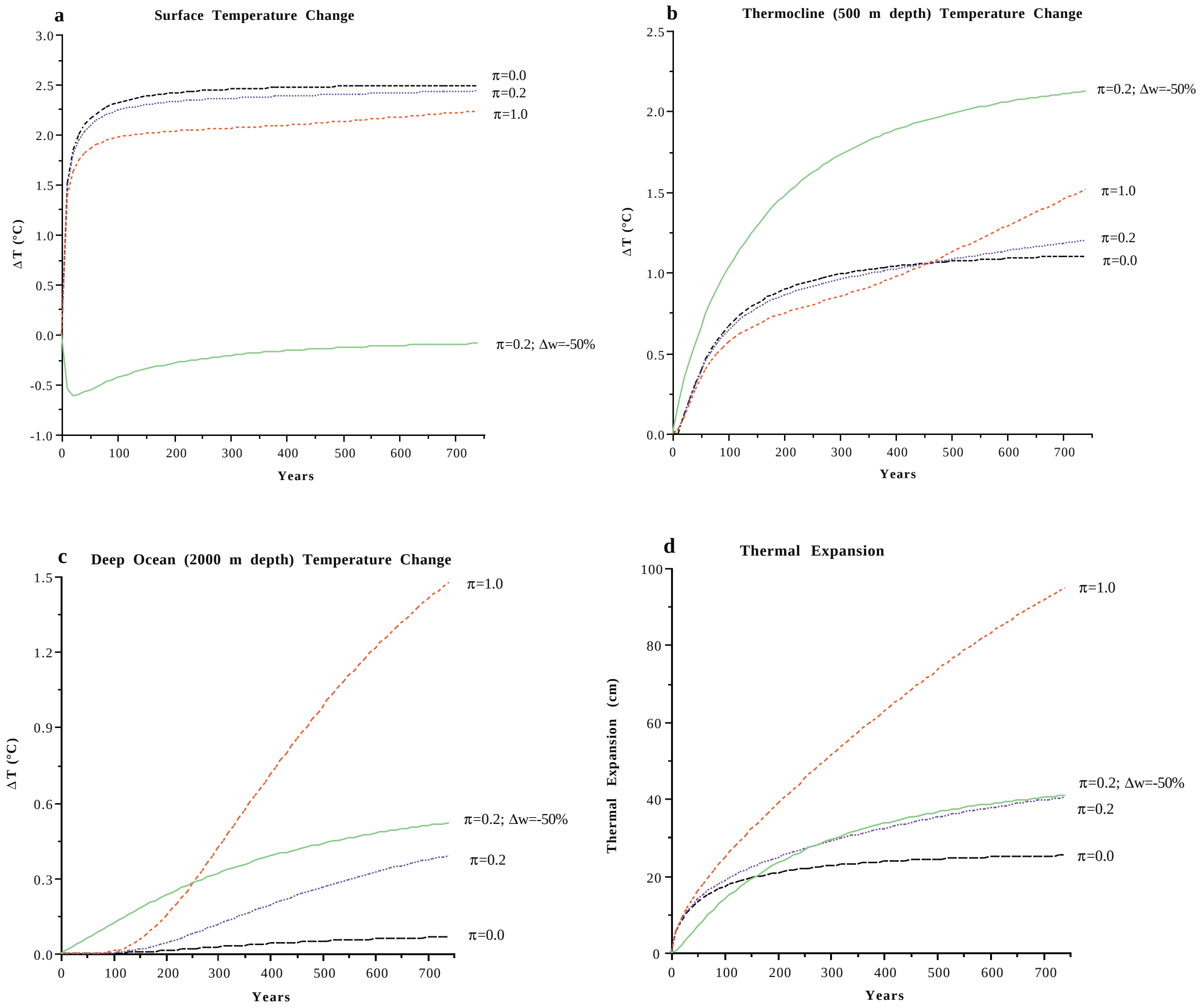

Figure 3-2. Impact of CO_2 Doubling or 50 Percent Reduction in Deepwater Formation: Evolution Over Time. Impacts on (a) surface temperature; (b) thermocline temperature at 520 m depth; (c) deep ocean temperature at 2020 m depth; and (d) ocean expansion, resulting from one-time doubling of CO_2 or halving of deepwater formation, with ΔT_{2X}=2.5˚C, as projected by the Wigley & Raper model. The first three curves assume a CO_2 doubling with climate sensitivity of 2.5˚C, with π equal to (i) 0, (ii) 0.2, and (iii) 1.0. The fourth curve (iv) holds greenhouse gases constant but cuts the upwelling velocity from 4 m/yr to 2 m/yr, with π=0.2.

raise sea level about as much as a CO_2 doubling (Figure 3-2d).

When using an upwelling/diffusion model to estimate thermal expansion, the sinking water amplification parameter π serves two purposes, which tend to suggest vastly different values. The direct function of the parameter is to indicate the rise in the temperature of *newly formed* deep water as a fraction of the warming of globally averaged surface temperature. For a given value of the upwelling velocity parameter **w**, however, π represents the equilibrium ratio of the warming of *all* deep water to the warming of the surface temperatures. Because the Earth will not warm enough to measure π for several decades, this parameter must be picked based on theory and judgment, not measurement. This judgment would be substantially helped, however, if three-dimensional modeling studies would report the temporal evolution of π—preferably for both hemispheres.

Previous assessments have generally picked **w** and **k** based on direct measurements and the fact that the existing temperature-depth profile is determined by a given ratio of **k**/**w**. By contrast, π cannot be measured directly; thus, it is picked so that the one-dimensional model has desirable properties. A value of π=1 allows the model to assume that, in equilibrium, the shape of the temperature-depth profile does not change; this assumption is a reasonable default because no one knows whether the difference between temperatures of deep and surface water will increase or decrease. A value of π=0 allows the model to reflect the fact that most deep water is formed by the creation of sea ice, which will always occur at the same temperature, unless sea ice changes substantially.[9]

The initial simulations we distributed to the reviewers were split evenly between runs in which we employed (a) fixed values of the three parameters and (b) those in which we allowed **w** to change in response to global temperatures.

<u>Fixed Parameters</u> (OM1)

One can pick π based on either (1) a reasonable assessment of the warming of polar sinking water or (2) on desired equilibrium properties of the model. Most deep water is formed by the freezing of surface sea water: The salt is separated from the ice, leaving a brine that is denser than surrounding sea water due to its higher salinity and perhaps its colder temperature as well. Because global warming will not change the temperature at which saltwater freezes, the deep water that is formed would logically be no warmer than it is today, implying that π=0. The assumption of π=1 is more reasonable for areas where deep (or intermediate) water is formed as a result of evaporation-driven salinity increases, as in the North Atlantic and Mediterranean regions. If one assumes that π_{SH}=0 for the 80 percent of bottom water formed through salt rejection in the Antarctic, but that π_{NH}=1 for the 20 percent that is formed from evaporation in the Northern Hemisphere, the average global value of π is 0.2.

One consequence of using a low value of π in thermal expansion calculations is that most of the ocean is assumed to warm much less than the surface, even in equilibrium. As a result, total thermal expansion estimates are lower than would be the case if all of the ocean warmed uniformly, especially in the long run.[10] In the absence of a strong theoretical explanation for how the shape of the temperature profile might change, a reasonable default assumption might be to assume no change. Thus, for example, IPCC (1990) assumes that π=1; as Figure 3-3 shows, the temperature-depth profile flattens if π=0, while largely retaining its current shape if π=1.

A possible problem with π=1 is that such an assumption, at least superficially, implies that the newly formed polar bottom water warms 1:1 with the global average surface temperature. Many researchers find this assumption unlikely because of the role of sea ice; *see e.g.*, Wigley & Raper (1991). Others believe that, in the long run, the downwelling water could warm as much (and perhaps more) than the global average warming, but that initially the warming will be less because Antarctic warming will lag behind global warming. As a result, the initial value of π_{SH} is close to 0, but it gradually increases to (and perhaps even beyond) a value of 1.0.[11]

Schlesinger & Jiang (1991), for example, ran their coupled ocean/atmosphere model for twenty years, after which time polar ocean temperatures are projected to warm between 0.004 and 0.57 times the global average warming, with a depth-averaged value of 0.14. They suggested that with a longer run, the depth-averaged value would probably be closer to 0.4; accordingly, they suggested that it would be appropriate for analyses employing simpler models to assume that π=0.4.

The analogy between three-dimensional and one-dimensional models is less than perfect. Most importantly, π does not literally represent polar warming; a 1-D model does not even have latitude. Instead, π represents the amount of additional heat conveyed by downwelling to the deep ocean, expressed as a fraction of the amount of heat that would be conveyed if greenhouse forcing warmed the downwelling water by as much as it warms the average surface temperature. Therefore, $\pi=\Delta T_{polar}/\Delta T_{global}$ only if ΔT_{polar} is averaged only over the regions and seasons in which downwelling takes place. Because the Schlesinger & Jiang calculations do not refer directly to the warming of the downwelling region, their suggestion that π=0.4 is somewhat *ad hoc*, but it is probably as reasonable as other procedures for picking the value of π.

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[9] The relationship between π and seaice formation is described further, below.

[10] In the very long run, it is even theoretically possible for the bottom water to warm more than the surface—especially if bottom-water creation due to seaice formation were to decline.

[11] *See* **Expert Judgment**, *infra* for a discussion of the wide divergence of opinion on the value of π.

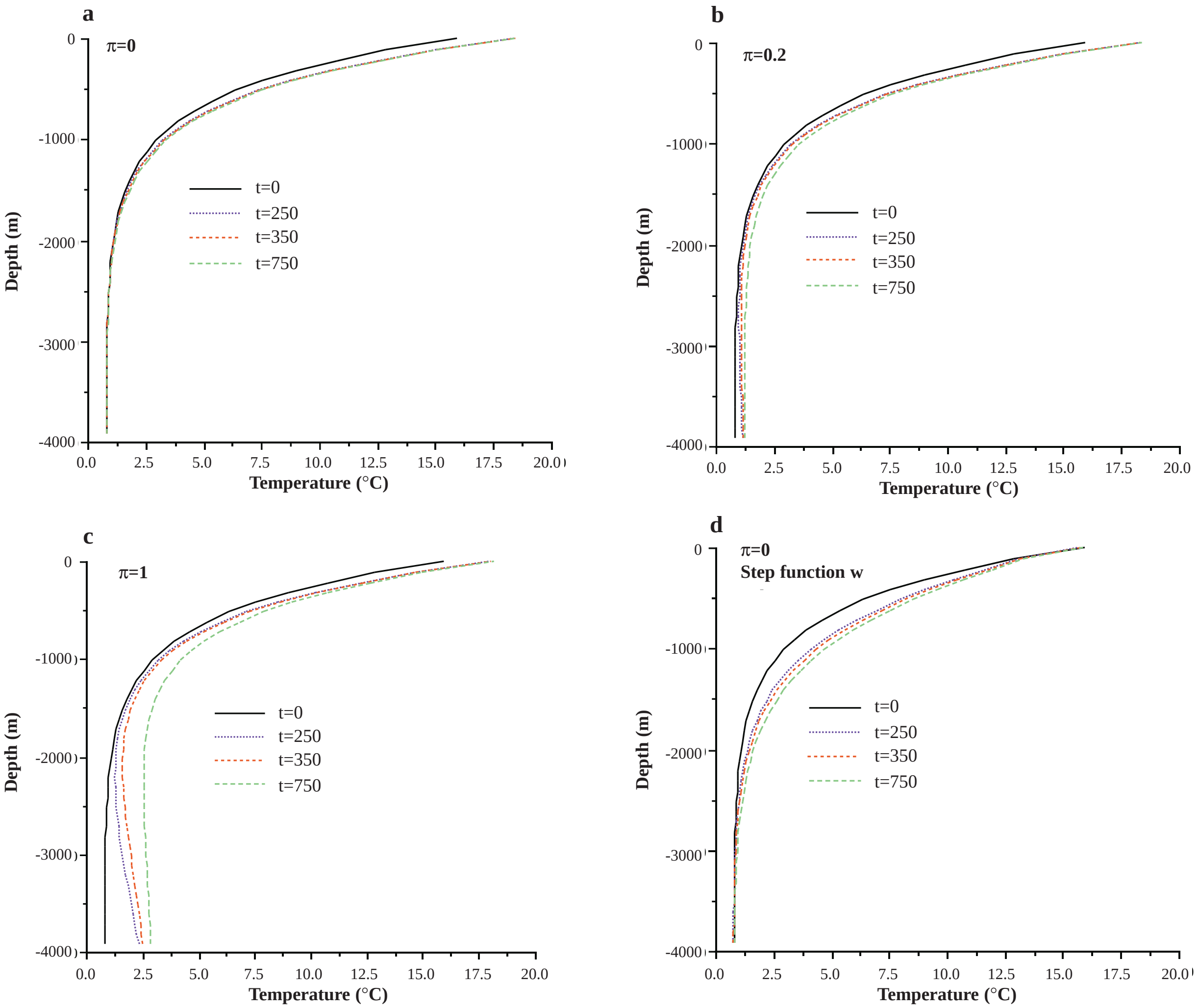

Figure 3-3. Impact of CO_2 Doubling or 50 Percent Reduction in Deepwater Formation: Depth-Temperature Profiles. These profiles correspond to Figure 3-2; *i.e.*, instantaneous CO_2 doubling in 1990 with (a) $\pi=0$, (b) $\pi=0.2$, and (c) $\pi=1.0$; and (d) no change in CO_2 but 50 percent reduction in upwelling velocity. Each box shows profiles for years 0, 250, 350, and 750.

An alternative approach is to pick the value of π that comes closest to duplicating temperature or thermal expansion estimates from a 3-D coupled ocean model. As we discuss below, for example, Figure 3-6 shows that a value of $\pi=0.6$ approximates the 25 cm of thermal expansion projected over a 95-year period by the GFDL model; a value of 0.13 approximates the Southern Hemisphere surface warming.

Allowing **w** to Vary (OM2)[12]

As long as the three parameters are fixed, the value of π determines the amount of heat reaching the deep ocean. Thus, other than by sheer coincidence, it is impossible to pick a specific value of π that both (1) conforms to the narrow definition $\pi=\Delta T_{\text{polar sinking}}/\Delta T_{\text{global}}$ and (2) functionally represents a desired assumption regarding the long-term evolution of $\Delta T_{\text{surface}} - \Delta T_{\text{deep}}$. The approach endorsed by Wigley & Raper and Schlesinger & Jiang (1991) focuses on the former—which is at least arguably "measurable" from 3-D transient experiments—and accepts whatever result is

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[12] We remind the reader that by "fixed **w**," we mean that $\mathbf{w}=\mathbf{w}_0$ throughout a given simulation, not that all simulations use the same value for **w**.

implied regarding equilibrium deep ocean temperatures (and thus thermal expansion). The approach followed by IPCC (1990), by contrast, (a) constrains the calculations to a reasonable default assumption that in the long run the middle and deep oceans warm as much as the surface, and (b) accepts the implied assumption that the bottomwater-formation temperature rises by ΔT_{global}, even though the freezing point of water stays relatively constant.[13]

If one allows **w** to vary over time, by contrast, one can assume that sea water will continue to freeze at the same temperature, without having to assume that, in equilibrium, there will be a large increase in the temperature difference between bottom and surface waters; by contrast, when π=0 and **w** is fixed, this assumption is unavoidable. Thus, our second approach is to assume that in the Southern Hemisphere, π=0, but that $\mathbf{w}_{SH}$ declines in proportion to the decline in annual Antarctic seaice formation that accompanies warmer temperatures. Because Northern Hemisphere deep water is generally not formed by freezing, we assume that π_{NH}=1. This case also assumes that w_{NH} declines, albeit for a different reason: increased precipitation prevents salinity in the Gulf Stream from rising as much as today, thereby reducing downwelling in the North Atlantic. *See* Manabe & Stouffer (1993).

Figure 3-4 compares the (OM2) case where π=0.2 and w declines geometrically by 15 percent per degree Celsius (C) of surface warming, with three OM1 cases (fixed **w**) where π is set to 0, 0.2, and 1.0. The figure illustrates warming at (a) the surface and depths of (b) 520 m and (c) 2000 m, as well as (d) thermal expansion. Radiative forcing is based on the IPCC (1990) "Business-as-Usual" scenario through the year 2100, and constant thereafter, with ΔT_{2X}=2.5. For the first century, the surface temperature of the OM2 (variable-**w**) case is within 1 percent of the OM1 (π=1) case, while thermal expansion is somewhat less. During subsequent centuries, thermal expansion diverges markedly.

The rough equivalence in thermal expansion estimates is largely coincidence. Given the similarity of surface temperatures, both cases have about the same amount of expansion in the mixed layer. In the variable **w** case, however, the thermocline (Figure 3-4b) warms more rapidly due to the declining rate at which colder bottom water upwells to this depth. The deeper layers of the ocean warm much more rapidly in the π=1.0 case because, by definition, the very bottom warms as much as the surface. With **w**=4 m/yr, a depth 200 m above the bottom receives water that downwelled fifty years previously. Warming at this depth by the year 2100 is equal to the 2050 surface warming, ignoring any diffusion from the surface (which is negligible at this depth). Thus, the cases differ in that the declining **w** allows more downward diffusion over time, while the π=1 allows for a gradual warming of the deep ocean by directly replacing the coldest remaining layer in each time step with water that has warmed as much as the surface.

The variable-**w** case is more realistic than π=1 in many ways. As Figure 3-5 shows, the one-dimensional model with π=1 yields an odd depth pattern of temperature changes: Not only do deep layers warm more than the surface and intermediate layers (Figure 3-5g), but a fairly substantial inversion also results (Figure 3-5c). This odd result stems from the fact that the model assumes that all downwelling conveys water to the very bottom (as opposed to distributing this water to various layers). By 2100, the bottom (4000 m) reaches a temperature of 2.8˚C, compared with the 1.2˚C that prevails at 3000 m; by 2500, the bottom reaches 5.0˚C, compared with 3.1˚C at 2000 m. By contrast, in the variable-**w** case, the inversion is trivial even after 500 years: 1.36˚C at 4000 m and 1.33˚C at 3000 m. This anomaly should not lead one to automatically disregard the relatively high thermal expansion estimates of π=1; the inversion probably *diminishes* the thermal expansion estimates. A more sophisticated 1-D model might avoid the inversion by distributing the additional heat due to downwelling at various depths. Because these warmer depths are accompanied by higher expansion coefficients, the resulting sea level rise would be somewhat greater.

Nevertheless, the variable-**w** assumption creates a number of risks. Like setting π_{SH} at zero in the fixed-**w** case, allowing **w** to decrease may satisfy a narrow criteria: the parameter in the one-dimensional model corresponds to reasonable expectations of how the 3-D variable would change. But it may do so at the expense of causing unintended dynamic model properties. Furthermore, intended reasonable "default" properties may not in reality be correct, or they may be overwhelmed by other changes that we cannot foresee. For example, a decrease in seaice formation would seem to imply less bottom water and hence a decline in **w**. Yet the 1-D models were

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[13] At prevailing salinities, the freezing point is typically about –1.9˚C. Although lower salinity would raise the freezing point somewhat, it cannot warm by more than 1.9˚C, and even that would require an unrealistic 99.9% decline in ocean salinity. Thus, for any significant value of ΔT, $\Delta T_{polar\ sinking}$ will be well below ΔT, unless the deep water is formed by a process other than seaice creation.

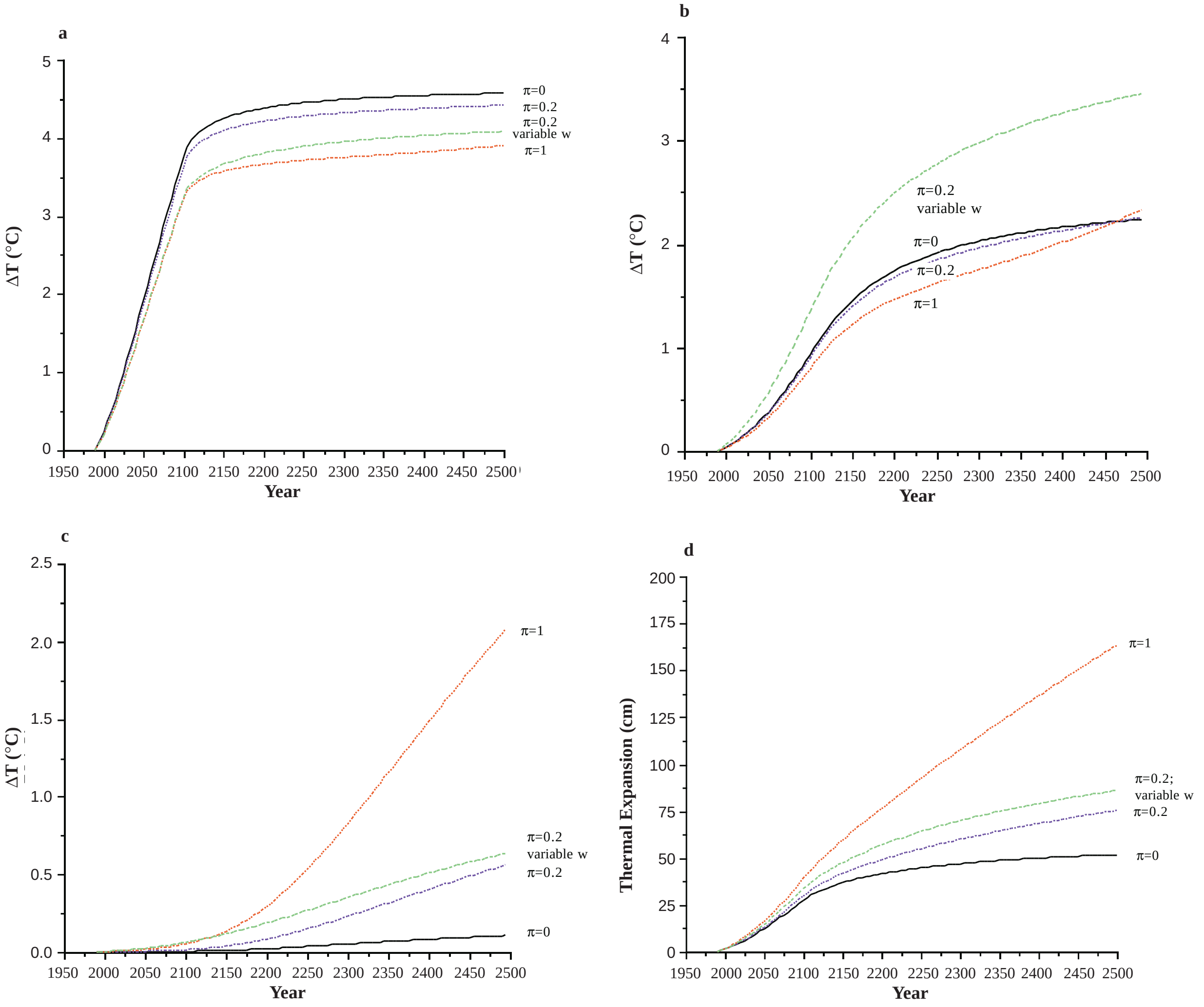

Figure 3-4. Impact of IPCC Business-as-Usual Scenario Over Time. Impacts on (a) surface temperature; (b) thermocline temperature at 520 m depth; (c) deep ocean temperature at 2020 m depth; and (d) ocean expansion, assuming that greenhouse gas concentrations increase through 2100 as projected by the IPCC (1990) Business-as-Usual scenario, and remain constant thereafter. The first three graphs assume that climate sensitivity is 2.5˚C for a CO_2 doubling, and that π equals (a) 0, (b) 0.2, and (c) 1.0; (d) also assumes that π=0.2, but that upwelling velocity (**w**) declines 15 percent per degree (C) of surface warming. In all cases, the initial 1990 conditions are derived by running the model from 1765 to 1990 using historic concentrations.

designed and calibrated to deal with the way the ocean circulates today; there is no guarantee that either (1) Antarctic bottomwater formation will change in proportion with the reduction in seaice formation or (2) that a decline in bottomwater formation will change thermocline temperatures in the same fashion as a 1-D model would suggest.

Although these uncertainties caution us against taking any of the results too seriously, they do not necessarily imply that the resulting thermal expansion estimates are less reliable than for the (OM1) case where $\mathbf{w}=\mathbf{w}_0$ and $\pi=0.2$ ($\pi_{SH}=0$). For example, if sea ice declines and deepwater formation does not decline or declines less than proportionately, it seems reasonable to assume that the downwelling water must be significantly warmer, which would imply a relatively high value for π. Presumably in this case, deep water formed by processes *other* than salt rejection must (at least partly) offset the reduction in bottom water formed by sea ice, and such downwelling

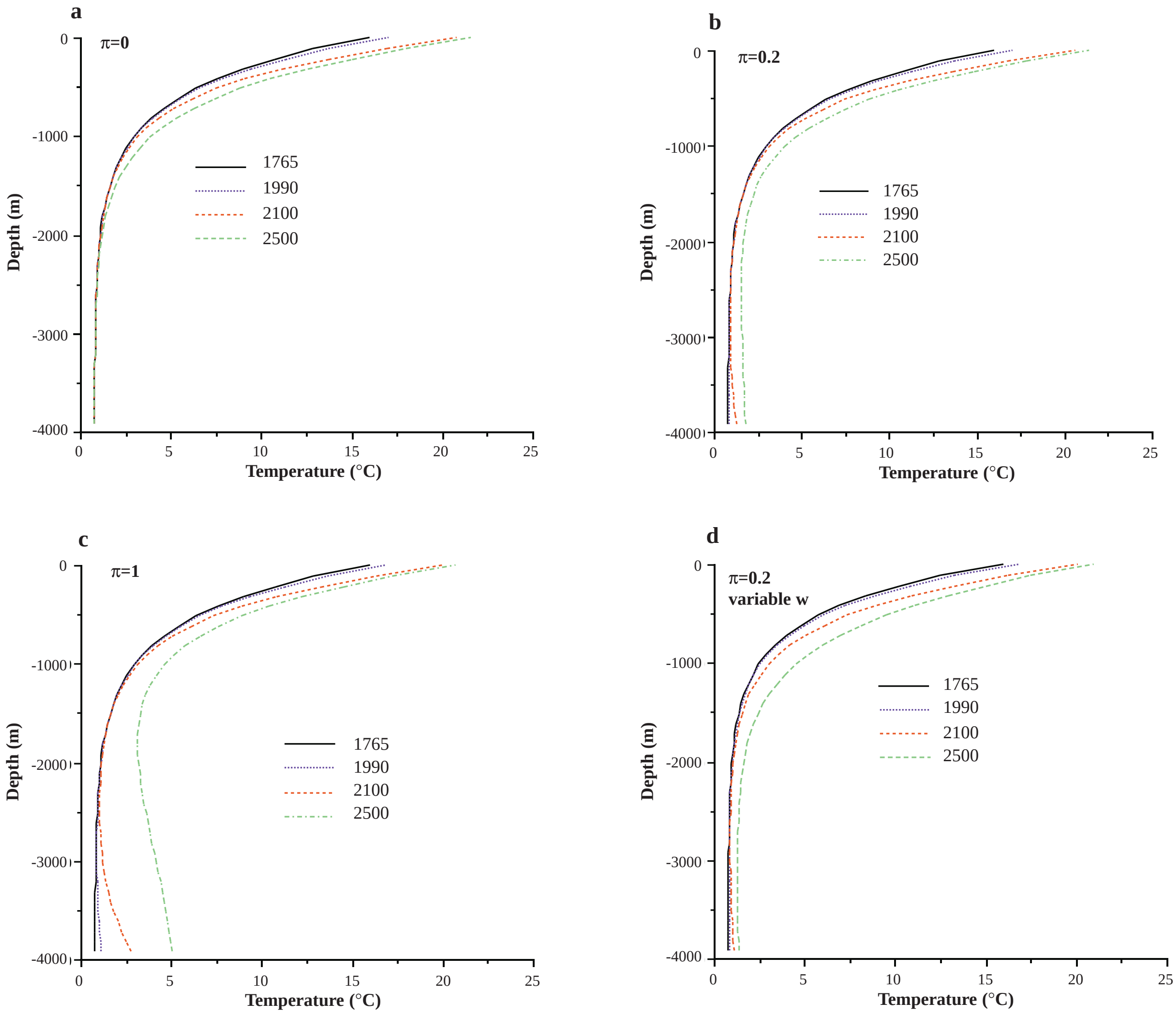

Figure 3-5. Impact of IPCC Business-as-Usual Scenario on Temperature-Depth Profile. These profiles correspond to Figure 3-4; *i.e.*, IPCC (1990) increases in greenhouse gas concentrations with (a) π=0, (b) π=0.2, (c) π=1.0; and (d) π=0.2 along with upwelling velocity declining 10 percent per degree (C) of surface warming. Absolute tem-

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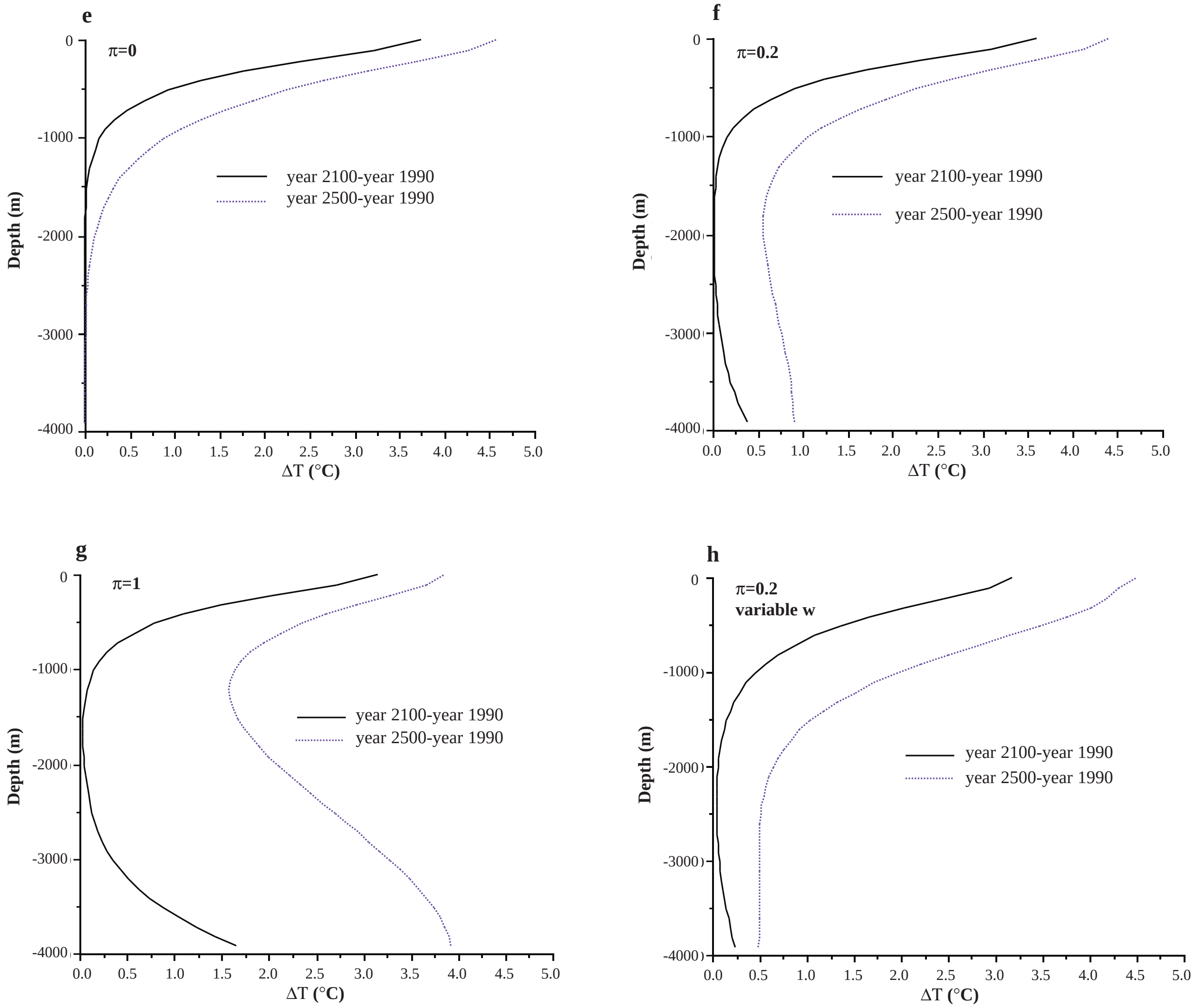
generally would take place at a higher temperature.

One theory for expecting downwelling not to decline as sea ice declines is that thermohaline circulation is driven by equatorial upwelling, as well as polar downwelling. To this extent, elimination of seaice formation need not lead to a proportional reduction in the forces that cause water to downwell. Moreover, increased evaporation in the tropics might further increase the tropical force contributing to downwelling. Because the circumpolar ocean is 3˚C warmer than the *in situ* freezing point of sea water and may be warmer in the future, the replacement downwelling water would presumably be at least 3˚C warmer than the bottomwater formed by sea ice. Thus, if the assumption that **w** declines in proportion with the decline in sea ice is an overestimate of the actual decline in **w**, we also are underestimating π_{SH} by assuming it to be zero—it could be much higher, implying that π could be closer to one.

How should we pick the rate at which **w** changes? Just as π can be picked either to satisfy expected changes in polar water temperatures or to satisfy desirable long-term dynamic properties, so can **w** be picked based either on estimates of circulation changes or to satisfy



peratures are shown for the years 1765, 1990, 2100, and 2500. Note that the inversions in box c for 1990 and 2100 are unreported results from IPCC (1990). The post-1990 *changes* in temperatures corresponding to boxes a-d are shown in boxes e-h, respectively, for the years 2100 and 2500.

dynamic properties. In the case of **w**, the literature offers both (a) estimates of how seaice formation might respond and (b) 3-D model estimates of total changes in circulation. The most obvious dynamic property to watch is the ability of the model to duplicate thermal expansion estimates from 3-D models.

Figure 3-6a compares projected thermal expansion over a 95-year period using the 1-D model for various sensitivities of π and **w**, with the results from the Geophysical Fluid Dynamics Laboratory (GFDL) model reported by Manabe et al. (1991). For a value of π=0, **w** must decline by slightly more than 25 percent per degree (C) to duplicate the 25 cm of thermal expansion; if π=0.2, **w** declines 15%/˚C; if π=0.4, **w** declines about 5%/˚C; and if π=0.6, a fixed **w** slightly overpredicts the GFDL estimate of thermal expansion. Figure 3-6b shows the surface warming for the same combinations of π and **w**. All of the combinations that provide good fits for thermal expansion underestimate the 2.7˚C Southern Hemisphere warming projected by the GFDL model, with the high values of π (which are accompanied by low sensitivities of **w**) coming closer. As Figure 3-6c shows, the GFDL coupled ocean model

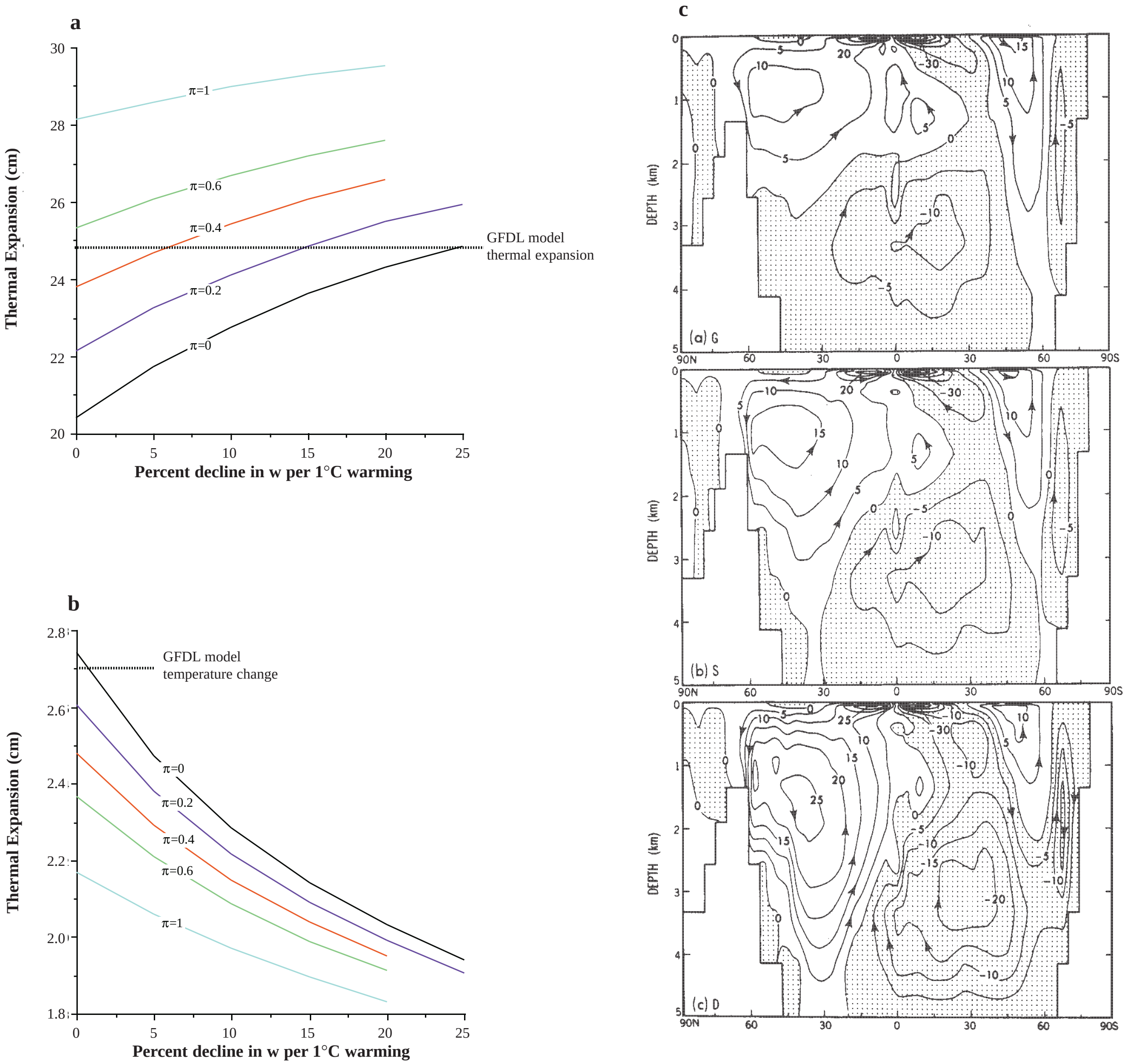


Figure 3-6. Using the GFDL Coupled Atmosphere-Ocean Model to Derive a Reasonable Value of How Upwelling Velocity Responds to Global Warming. Given various values of π, (a) shows thermal expansion as a function of the upwelling sensitivity. The GFDL estimates of thermal expansion can be duplicated by combinations in which upwelling sensitivity is approximately equal to 0.25–π/2, at least for 0<π<0.6. Unfortunately, these combinations do not duplicate Southern Hemisphere temperatures, as shown in (b). Nevertheless, the derived value of **w**-sensitivity is further supported by (c) GFDL's estimate of the change in stream functions over a seventy-year period: A one-third decline in circulation is evident between the S (baseline) and G (CO_2 doubling) simulations; similarly, a 50 percent reduction in CO_2 would increase mixing by about 1/2, as shown in the D-simulation.

SOURCES: Manabe et al. (1991) for three-dimensional results; see text for 1-D results.

suggests approximately a one-third reduction in overall upwelling after seventy years (by which time global temperatures rise 3˚C).

The impact of warming on annual seaice formation also is an indicator of changes in downwelling. Parkinson & Bindschadler (1982) estimated a 50 percent reduction in Antarctic seaice formation for a 5˚C warming in Antarctic air temperatures, which corresponds to a decline of 14.8%/˚C. Although the sensitivity in that analysis referred to Antarctic (rather than global) temperatures, the implied sensitivity is broadly consistent with that suggested by comparing 1-D with 3-D models.

Parameter Distributions for the 1-D Model in the Draft Report

We now present our reasoning behind the initial set of parameter distributions employed in the draft Monte Carlo analysis that was circulated to the reviewers. As discussed below, the reviewers used these initial distributions as a starting point in selecting the distributions used in the simulations.

Climate Sensitivity (ΔT_{2X})

Since the 1979 National Academy of Sciences report *CO_2 and Climate: A Scientific Assessment*, the consensus estimate has been that a CO_2 doubling will warm the Earth's average surface temperature 1.5 to 4.5˚C in equilibrium. That report and a second panel (NAS 1982) stated that 3˚C was the most likely value. Subsequent reports such as NAS (1983) and IPCC (1990) concluded that the most likely value is 2.5˚C. Wigley & Raper (1991) employed their one-dimensional model to estimate that historic warming is consistent with a value of about 3.3˚C. They have subsequently concluded that they may have overestimated the impact of historic aerosols, which would imply a sensitivity closer to 2.5˚C. On the other hand, their analysis assumed that π=0.2 and that **w** remains constant; allowing **w** to decline or a higher value of π would result in a higher sensitivity estimate. Overall, their analysis does suggest that the historic record thus far is consistent with the consensus estimate of ΔT_{2X}.

Nevertheless, this range has not met with universal acceptance. Patrick Michaels, the State of Virginia's climatologist, estimated that the warming is likely to be about 1˚C (Michaels et al. 1992); and Sherwood Idso of the U.S. Agricultural Research Service in Tempe, Arizona, has long argued that the warming is likely to be much less than the consensus assumes. Idso & Balling (1991), for example, estimated a sensitivity of only 0.35˚C. At the other end of the spectrum, Lashof (1989) estimated that the warming could be as high as 8 to 10˚C, particularly if the anthropogenic doubling induces biological feedbacks to release additional greenhouse gases.[14]

The combined picture that these studies paint is that our uncertainty is a skewed distribution that can be roughly described as lognormal. The draft report assumed that ΔT_{2X} is lognormally distributed with a geometric mean of 2.6˚C and σ limits of 1.5 and 4.5˚C. This distribution has a mean of 3.0˚C and a 2 percent chance of exceeding Lashof's 8˚C estimate, as well as a 5 percent chance of falling below Michael's 1˚C.

Diffusivity (**k**) and Initial Upwelling Velocity ($\mathbf{w}_0$)

The parameters **k** and **w** determine how rapidly the ocean reaches its new equilibrium. Diffusivity (**k**) represents the rate at which heat is transported from the relatively warm surface layers of the ocean downward to the colder thermocline and deep ocean. The parameter represents conduction and local-scale mixing, as well as the diffusion that its name suggests. Sarmiento et al. (1976) used measurements of the distribution of radium and radon isotopes to estimate upper and lower bounds for **k** as a function of depth. IPCC (1990) accepted the Hoffert et al. (1980) calculations that the depth-averaged value of **k** implied by Sarmiento et al. is between 1000 and 3000 m^2/yr, and used the intermediate value of 2000 m^2/yr.

The upwelling velocity parameter **w** can be literally interpreted as the speed at which ocean water flows upward, averaged over the entire ocean except for those areas where ocean water is sinking. Because the total water that sinks must equal the total water flowing upward, and because the region over which ocean water sinks is relatively small, this parameter is estimated as the ratio of global deepwater formation divided by the area of the ocean.

In picking the current upwelling velocity $\mathbf{w}_0$, a primary consideration is to ensure that when combined with the value for **k**, the ocean model duplicates

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[14] Both Michaels et al. and Lashof included nonclimatic factors in their estimates. Michaels et al. included the expected correlative increase in aerosol concentrations; Lashof included possible biological feedbacks that might increase natural greenhouse gas emissions.

today's temperature-depth profile. IPCC assumed that $\mathbf{k}/\mathbf{w}$=500 m, implying that $\mathbf{w}$=4 m/yr. This value is consistent with existing literature: Perry & Walker (1977) estimated the total bottomwater formation to be 35 to 55 million cubic meters per second. Averaged over the entire (nonbottomwater-forming) area of the ocean, this range implies an average upwelling velocity of 3.3 to 5.2 m/yr.

We used a lognormal distribution for $\mathbf{k}$ and $\mathbf{w}_0$ to avoid negative values. As a result, we had to choose between using the IPCC values as the medians of our distribution and using the ranges derived from previous studies; we opted for the former.[15] Thus, the draft assumed that $\mathbf{k}$ has a median of 2000 m^2/yr with 2σ limits of 1333 and 3000. Given the assumption for $\mathbf{k}/\mathbf{w}$, $\mathbf{w}_0$ had a median of 4 m/yr with 2σ limits of 2.67 and 6.0; the σ limits of 3.3 and 4.9 m/yr were thus consistent with the Perry & Walker estimates.[16]

Probability that Upwelling Velocity Changes

Under OM1, the ocean model treats $\mathbf{w}$ as fixed and draws π from a distribution described below. For OM2, by contrast, the ocean model allows $\mathbf{w}$ to change over time. Lacking analysis favoring one model over the other, the draft assumed that each of these cases were equally likely; that is,

$$\text{Prob(OM1)} = \text{Prob(OM2)} = 0.5.$$

Thus, half of the simulations assumed that $\mathbf{w}=\mathbf{w}_0$ and half assume that $\mathbf{w}$ changes.

Values of π in the Fixed-$\mathbf{w}$ Case

Under OM1, the draft used a lognormal distribution for both hemispheres, with 2σ limits of 0.2 and 1. The high end is justified by its use in IPCC (1990) and by the fact that, without additional information, the simplest assumption is that in equilibrium the various layers of the ocean warm by the same amount. The low end is justified by its use in Wigley (1992) and the fact that without additional information it might be reasonable to assume that the temperature at which the nonfreezing bottom water (20 percent) forms would rise by the global average, while the water forming due to freezing (80 percent) would continue to occur at the same temperature.

Values of π and $\mathbf{w}$ in the Variable-$\mathbf{w}$ Case

Ideally, we would treat the two major sources of deepwater formation differently: (a) in the North Atlantic, where bottom water is caused by evaporation, we would assume that π=1 and allow $\mathbf{w}$ to change as indicated in various studies reporting declines in North Atlantic bottomwater formation[17]; (b) in the Southern Hemisphere, where bottom water is created by freezing, we would assume that freezing still occurs at the same temperature (*i.e.*, π_{SH}=0), but that it (and thus $\mathbf{w}_{SH}$) declines as described below.

Because the Wigley & Raper one-dimensional model does not fully account for heat transfer between the hemispheres, we must run the model using global values for $\mathbf{w}$ and π. Thus, we set π=0.2, which is consistent with the assumption that π_{NH}=1.0 and π_{SH}=0.0.

The literature provides two possible ways to estimate how $\mathbf{w}$ might change as temperatures rise: (1) assume a direct relationship between global (or Antarctic) temperatures based on coupled-ocean models; and/or (2) estimate the decline in seaice formation resulting from warmer temperatures and assume that $\mathbf{w}_{SH}$ declines proportionately. The GFDL coupled-ocean model run reported by Manabe et al. (1991) projects about a 30 percent decline in deepwater formation by the time global temperatures rise 3˚C. As described above, the Wigley & Raper model most closely approximates the thermal expansion estimates generated by GFDL when $\mathbf{w}$ declines 5 and 15 percent per degree (C) of surface warming, for π=0.4 and 0.2, respectively. Parkinson & Bindschadler (1985) estimated that a 5˚C uniform Antarctic warming would cause a 50 percent decline in sea ice, which would decrease $\mathbf{w}$ by 40 percent (because 80 percent of deep water is formed in Antarctica).

At first glance, the estimates from seaice reduction and 3-D modeling results are fairly consistent. However, the Manabe et al. projections coincide with a warming of only about 1˚C in Antarctica, implying a sensitivity three times greater than that implied by Parkinson & Bindschadler.

The draft assumed that both $\mathbf{w}$ and sea ice decline as temperatures warm. We define the parameter θ to describe how w changes:

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[15] With 2σ limits of 1000 and 3000, a normal distribution implies a median (mean) of 2000, but a lognormal distribution implies a median (geometric mean) of 1732.

[16] We remind the reader that $\mathbf{k}/\mathbf{w}$=500 m refers to the current situation. Thus, in the cases where w declines as temperatures rise, we have to pick an initial value for $\mathbf{w}_{1765}$ such that when the simulation reaches the year 1990, $\mathbf{w}=\mathbf{w}_0$.

[17] Seaice formation in the North Atlantic is relatively minor. Although seaice formation in the Arctic Ocean is significant, the mixing between the Arctic and the other oceans is sufficiently small for it to be safely ignored in a one-dimensional model.

$$\mathbf{w} = \mathbf{w}_0\ \theta^{\Delta T}.$$

The draft assumed that θ has a lognormal distribution with a median of 0.85, consistent with the results shown in Figure 3-6. To allow for some possibility of increased upwelling, the draft assumed that the σ limits for θ are 0.85^2 (*i.e.*, 0.72) and 1.0.

Polar Climate: Subsidiary Equations

The one-dimensional model estimates only one of the components of sea level rise directly: thermal expansion. As we discuss in Chapter 6, the models for projecting the alpine contribution to sea level rise are simple enough to require only a projection of global temperature change, which is also provided by the 1-D model. But 99 percent of the world's land-based ice rests on the polar ice sheets of Antarctica and Greenland. Thus, for estimating future sea level rise, the impact of greenhouse gases on polar climate could be as important as its impact on the worldwide average change in temperatures.

Early climatic assessments (*e.g.*, NAS 1979) suggested that polar temperatures were likely to warm two to three times as much as the global average. This result was based on both paleoclimatic evidence and the results of mixed general circulation models. Because of these projections, the relationship between global and polar temperatures is commonly known as the "polar amplification parameter." As Table 3-1 shows, many general circulation model studies with mixed-layer oceans suggest a considerable polar amplification. On the other hand, more recent studies (with deep-ocean models coupled to atmospheric models) suggest that the polar amplification may be less than 1.0.

Moreover, the annual average change in temperatures is not the best indicator for the impact of climate change on these ice sheets. Greenland is tens of degrees below freezing during winter, so a winter warming would not induce melting; the impact on summer temperatures is far more important. Antarctica is so cold that surface melting is trivial throughout the year. Ice flows gradually toward the oceans in the form of ice streams that are buttressed in part by floating ice shelves, most of whose bases are melting. If warmer climate is going to induce a significant contribution of Antarctic ice, it may do so through warmer water intruding beneath the ice shelves. Such warm intrusions could be enhanced either by warming the circumpolar ocean or by reducing the amount of sea ice. Finally, warmer temperatures could increase precipitation in polar areas, offsetting the potential contribution to sea level. Because most polar precipitation occurs during the warmer months, summer temperatures are more important than winter temperatures.[18]

TABLE 3-1
GREENLAND WARMING ESTIMATED BY VARIOUS CLIMATE MODELS

			Warming (°C)	
Model	Year	Season	Greenland	Global
Coupled Ocean				
GFDL	60–80	winter	3–5	2.3
GFDL	60–80	summer	1.0–1.5	2.3
GFDL	60–80	annual	3–4	2.3
MPI	56–65	annual	2–5	1.3
NCAR	31–60	annual	1	0.5
UKMO	65–75	annual	1–2	1.7
Equilibrium Mixed-Layer Ocean				
GFDL	$2XCO_2$	winter	8–18	4.0
GFDL	$2XCO_2$	summer	2–6	4.0
CCC	$2XCO_2$	winter	4–8	3.5
CCC	$2XCO_2$	summer	2–6	3.5
UKMO	$2XCO_2$	winter	0–4	5.2
UKMO	$2XCO_2$	summer	2–4	5.2

SOURCE: IPCC 1990, 1992.

Although several studies have reported the likely equilibrium impact of a CO_2 doubling on polar air temperature changes, relatively few have reported time-dependent projections. Fewer still have examined the likely changes in polar ocean temperature changes. Therefore, the draft used the simplest procedure: assume that (1) in equilibrium the temperature change is a constant times the global change, but that (2) at least in the Southern Hemisphere, the polar temperature change lags behind the global change.

This section describes the draft report's assumptions for polar temperature and seaice changes. Because different reviewers were involved, we defer discussion of precipitation changes until the final section of this chapter. Conceptually, our projections require two tasks: (1) estimating the relationship between global warming and equilibrium polar temperatures; and (2) specifying the dynamics and adjustment times by which polar temperatures respond

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[18] See Chapters 4 and 5 for more details on Greenland and Antarctica.

to global warming.

Equilibrium Polar Warming

Our projections of the equilibrium conditions toward which polar temperatures would tend required us to specify parameters for Antarctic air temperatures, Antarctic water temperatures, and Greenland air temperatures.

Antarctic Air Temperatures. The draft report assumed that, in equilibrium, the summer surface air warms P_1 times the global average surface warming. P_1 was lognormally distributed with a median of 1.0 and 2σ limits of 0.67 and 1.5, based on IPCC (1992).

The draft assumed that winter temperatures would be more sensitive. (As Table 3-1 shows, most modeling studies have reached this result as well.) Sea ice would decline as a result of the increased radiative forcing from greenhouse gases, even if temperatures did not warm; summer warming also reduces sea ice. Where sea ice is removed, air temperatures will be much warmer during winter because the exposed ocean can keep the air at around the freezing point, rather than tens of degrees below freezing. Because seaice retreat will allow these warmer areas to advance inland, temperatures over the coastal portions of the continent will be warmer as well. We assumed that, in equilibrium, the winter surface air warms P_2 times the global average. The draft report assumed that P_2 is lognormal with 2σ limits of 1.0 and 3.0. *See* IPCC (1992).

We also considered the correlation between winter and summer Antarctic warming. Uncertainties regarding polar amplification in summer and winter must be correlated, because changes in ocean circulation and sea ice would affect both. The correlation must be less than 1, however, because it is unlikely that all the processes that affect summer and winter temperatures would affect them in the same proportions.[19]

Because the correlation must be greater than zero but less than one, the draft assumes that $\rho_{P1,P2}=0.5$.

Southern Hemisphere Circumpolar Ocean Warming. The draft expresses the equilibrium change in circumpolar ocean temperatures as P_3 times the average equilibrium surface warming of the Earth.

As mentioned above, climate modeling studies suggest that the winter warming of Antarctic air temperatures does not result from warmer ocean temperatures as much as from the decline in sea ice, which enables oceanic heat to escape and warm the cold Antarctic air. By contrast, during summer, the surface air and the surface water should warm by about the same amount (although the change in water temperatures at ice-shelf depths may be different). This reasoning suggests that the summer Antarctic air temperature increase would be a better indicator of Antarctic ocean warming than the average annual warming of Antarctic surface temperatures, which would imply a warming of 0.67 to 1.5 times the global warming.

Coupled ocean-atmosphere models suggest that ocean waters will warm by less than the global average warming, at least for the first century. As discussed below, Manabe et al. (1991) estimated that the polar ocean may warm by only about 25 percent as much as global temperatures after one hundred years. Fitting a simple differential equation to those results suggests that the long-run warming would be only about 1/2 the global warming.[20]

The draft report assumed that P_3 is lognormal with a median of 0.5. As discussed below, such an assumption yields results that are consistent with the Manabe et al. (1991) results. Moreover, if extrapolated backwards in time, this assumption implies that during the last ice age, the circumpolar ocean temperature would have been hovering at about the freezing point.[21] Somewhat arbitrarily, we assumed a fourfold uncertainty (*i.e.*, σ limits of 0.25 and 1.0) and a 0.75 correlation with summer equilibrium warming. Thus, in only about

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[19] Note that the radiative effect of seaice retreat is positive in the summer but zero during the polar night. On the other hand, convection of heat from ocean to air is much more enhanced during winter, when the air is much colder than the water, than during summer, when they are both at approximately the same temperature.

[20] More recently, Manabe & Stouffer (1993) report that after 500 years, the circumpolar ocean warms as much as the global average temperature; *i.e.*, $\Delta T_{cdw}=\Delta T$. Manabe himself suggests that the Antarctic ocean temperatures should warm as much as the global average, but with a 100 to 300 year lag. *See* **Expert Judgment**, *infra*.

[21] The current circumpolar ocean temperature is about 1.9˚C above the *in situ* freezing point. A more realistic approach might have been to assume that dT_{cdw}/dT is low, as long as there is permanent sea ice, but that it increases as the area of sea ice, ice shelves, and icebergs decline. Such an assumption would resolve the inconsistency between the positive polar amplification that climatologists have long expected for a CO_2 doubling equilibrium and the fact that such an amplification cannot be extrapolated backwards without freezing much of the southern ocean. Lacking an objective basis for describing how this marginal rate of polar amplification might increase, we retained the proportional assumption. *But see* Hoffert's suggested distributions under **Expert Judgment**, *Circumpolar Ocean Warming, infra*.

15 percent of the simulations would the circumpolar deep water (CDW) warm by more than the global average—even in equilibrium. For the most part this would happen along with scenarios in which summer Antarctic warming is also greater than the global average warming (and thus where precipitation increases are significant as well).

Greenland Temperatures. IPCC (1990) assumed that Greenland warms 1.5 times the global average. As Table 3-1 shows, coupled ocean-atmosphere models suggest that Greenland warming will be between one and two times the global average warming. As with Antarctica, GFDL suggests that the summer warming will be less than the winter warming, as does the equilibrium mixed-layer run by the Canadian Climate Center (CCC). Although the United Kingdom Meteorological Office (UKMO) mixed-layer run suggests that summer warming will be greater than winter warming, the summer warming is still less than global average equilibrium warming. The draft report assumed that annual temperatures in southern Greenland rise P_7 times the global average, with P_7 being lognormal with two σ limits of 1 and 2. Because existing models for the Greenland contribution to sea level rise only consider annual temperatures, we follow suit.

Adjustment Times for Polar Temperatures

Manabe et al. (1991) employed a coupled ocean-atmosphere model with a linear time trend in forcing. They estimated that average global temperatures eventually follow a linear trend, after an initial "startup" of a few decades; such a temporal pattern could be approximately described by the first-order differential equation:

$$\frac{dT}{dt} = a\,(T_{eq} - T),$$

where $\mathbf{T}_{eq}$ is the equilibrium temperature implied by atmospheric forcing at a given time, and $1/\mathbf{a}$ is the e-folding time. Because $\mathbf{T}_{eq}$ follows a linear time trend, the trajectory for transient temperatures would be approximately:

$$\frac{dT}{dt} = a\,(Bt - T),$$

where **B** represents the annual trend of equilibrium (also called "committed") warming (*i.e.*, climate sensitivity expressed as the sensitivity to a CO_2 doubling, divided by the number of years CO_2 takes to double). If b=aB,

$$\frac{dT}{dt} = a\,(Bt - T),$$

and the only solution through the origin is:

$$T = \frac{b}{a^2}\,e^{-at} + \frac{b}{a}\,(t - \frac{1}{a}).$$

The GFDL results seem to suggest that the adjustment time for Antarctic temperatures may be much longer than for average surface warming, as shown in Table 3-2. Solving for **a** and **B** suggests that the e-folding times for global surface temperature, Antarctic air, and circumpolar water are nine, twenty-nine, and fifty years, respectively. Even so, the long-term warming trend for water temperatures is only about half that of air temperatures.

The simple linear first-order differential equation is only a rough summary of the dynamics.[22] A possible alternative approach for summarizing the dynamics would be to use higher order differential equations, and estimate the coefficients by fitting a nonlinear regression of their solutions through the annual (or at least decadal) time series. At least for surface air temperatures, a second-order equation seems likely to more accurately describe the dynamics: The first-order equation assumes that the difference between the equilibrium and the actual value declines exponentially; second-order equations, by contrast, can capture a response that declines as the sum of two declining exponentials. Given the evidence that the mixed layer adjusts in a matter of decades while the deep ocean takes centuries, such a functional form would seem applicable. On the other hand, the simplified version may be preferable for purposes of a Monte Carlo analysis, since each parameter clearly represents a particular issue.

A further problem remains with the simple differential equation: We are already using a one-dimensional upwelling-diffusion model to capture the dynamics of the global surface temperature adjustments. Different values of π, **k**, and **w** lead to different adjustment times and "shapes" of the adjustment function. Therefore, to use the lag functions derived from GFDL results for Antarctic air and water temperatures would leave us with the risk that for some combinations the temporal pattern of adjustment for the polar temperatures would be inconsistent with that of the

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[22] Consider transient surface air temperatures: the fit we obtain implies an equilibrium warming (for $2XCO_2$) of only 2.6, while the $2XCO_2$ equilibrium run by Manabe et al. with a mixed-layer ocean suggests 4.2. If we fit the simple differential equation using the equilibrium values, we obtain much longer e-folding times of 38 and 300 years for average and Antarctic air temperatures, respectively.

global temperatures.

To prevent such an inconsistency, we assume:

$$\frac{dT_{polar}}{dt} = \frac{P_1\,\Delta T_{global} - \Delta T_{polar}}{P_5}.$$

That is, polar temperatures tend toward an equilibrium that is functionally dependent on the calculated *transient* global temperature.

Based on the results from GFDL, the draft assumed that the median value of the e-folding time for Antarctic water at ice-shelf depths (P_4) is 40 years; we employed arbitrary 2σ limits of 20 and 80 years in a lognormal distribution.

For Antarctic surface air summer and winter temperatures (P_5 and P_6), the draft assumed that the lag is less certain. Unlike deep ocean temperatures, Antarctic air temperatures have been estimated by mixed-layer transient models, which do not show as much of a lag. Even though there is a consensus that mixed-layer ocean models are inferior, the draft assumed that they cannot be totally discounted. Therefore, the σ limit on the low end is one year, which implies that 16 percent of the time, the lag will be negligible. On the high end, we assumed a σ limit of 20 years, derived from the GFDL results. The correlation (of the logarithms) between P_4 and each of these parameters was assumed to be 0.5.

For Arctic temperatures, by contrast, the GFDL results suggest that the lag is not appreciably different from the lag for global temperatures. Therefore, the draft assumed that the one-dimensional model's estimate of the lag between forcing and global temperatures completely captures that lag for Greenland temperatures. This assumption is consistent with IPCC (1990).

Changes in Antarctic Sea Ice

The draft report used the same functional form for seaice changes as we use for the change in **w** in the variable-**w** case (*i.e.*, sea ice declines as temperatures rise). We define the parameter P_{10} to describe how sea ice changes:

$$\text{seaice} = \text{seaice}_0\ P_{10}^{\Delta T}$$

The draft assumed that P_{10} has a lognormal distribution with the same median and 2σ limits as θ in the variable-**w** case. These estimates were justified primarily by the Parkinson & Bindschadler (1982) study.

TABLE 3-2
LINEAR FIRST-ORDER DIFFERENTIAL EQUATIONS FIT TO GFDL TRANSIENT ESTIMATE OF GLOBAL AND POLAR TEMPERATURES

Change in Temperatures

Year	Global Surface	75˚S Air	500 m-deep Circumpolar	South Greenland
15	0.3[a]	0.1	—	—
25	0.7	0.2	—	—
35	1.1	0.3	—	—
45	1.4	0.5[a]	—	—
50	1.5	0.5	—	2.0
55	1.6	0.5	—	—
65	2.0	0.4	—	—
70	2.3[b]	—	—	3.15–3.8[b]
75	2.5	1.0	0.75[a]	—
85	2.9	1.5	—	—
90	3.1	1.5	1.0[a]	4.6
95	3.3[a]	2.0[a,b]	—	—
Fitting equation to (**a**) years				
a	0.1147	0.0356	0.0202	—
B	0.0382	0.0221	0.0206	—
e-fold	8.7	28.1	49.5	—
ΔT_{2X}	2.66	1.54	1.44	—
Fixing B based on equilibrium run and fitting to year **b**				
a	0.02646	0.005	—	0.022–0.031
B	0.0603	0.115	—	0.0912
e-fold	38.7	200	—	31–44
ΔT_{2X}	4.2	8.0	—	6.1

[a] Years employed in solving for **a** and **B** in the equation $dT/dt = a\,(Bt - T)$. In each case, we used the first year that could be estimated from the graph along with the last year of the time series. To avoid arbitrariness of picking particular years, subsequent drafts might try nonlinear regression of the solution $Y = b/a^2\, e^{-aX} + b/a\,(X - 1/a)$, especially if more years are available for ocean temperatures. Moreover, with a regression it would be possible to test whether higher order differential equations yield significantly better fits.

[b] Greenland calculations are based on GFDL graphs, which indicate that by year 70 Greenland temperatures rise 0.5 to 0.6 times the equilibrium warming expected from a CO_2 doubling.

TABLE 3-3
CUMULATIVE PROBABILITY DISTRIBUTION
OF GLOBAL WARMING BASED ON
ASSUMPTIONS FROM THE
DRAFT REPORT (˚C)

Cumulative Probability (%)	2030	2100	2200
1	0.35	0.85	1.05
5	0.51	1.2	1.9
10	0.6	1.5	2.24
20	0.75	2.0	3.1
30	0.88	2.3	3.6
40	0.97	2.7	4.2
50	1.1	3.1	4.8
60	1.2	3.5	5.6
70	1.3	3.9	6.3
80	1.5	4.6	7.5
90	1.75	5.6	9.3
95	1.95	6.5	10.9
97.5	2.1	7.3	12.6
99	2.4	8.3	14.7
99.5	2.5	9.1	16.4
Mean	1.1	3.3	5.4
σ	0.45	1.6	2.9

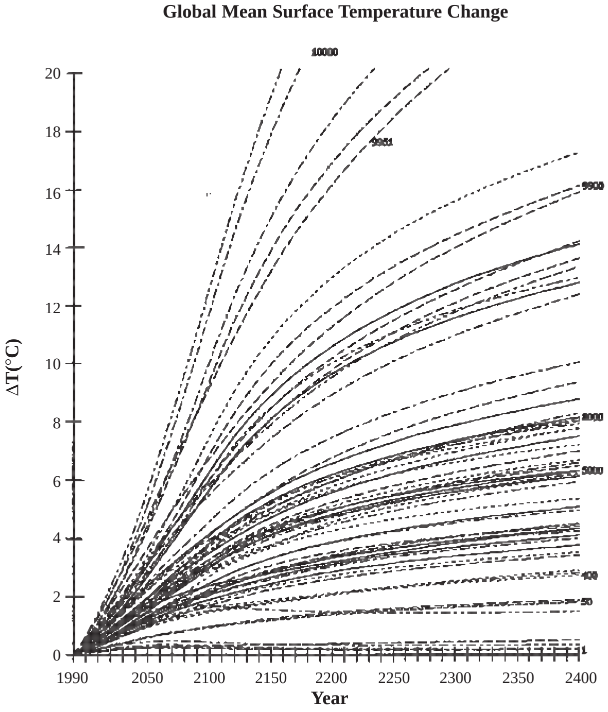

Figure 3-7. Selected Scenarios of Global Warming: Draft Report. See Figure 2-5 and accompanying text for explanation.

The draft also assumed that P_{10} and θ are perfectly correlated, implying that P_{10}=θ.

Results for Initial Draft Assumptions: Temperature and Thermal Expansion

Table 3-3 illustrates the probability distribution of global warming for selected years given the initial draft assumptions for concentrations (see Chapter 2) and the climate variables described above. As the table shows, our median estimate for the year 2100 was 3.1˚C, 10 percent higher than IPCC's 2.8˚C best estimate for the IS92a scenario. Our 90 percent confidence interval was also somewhat higher than the IPCC range: IPCC's low estimate for the IS92a scenario of 1.8˚C is 20 percent greater than our 5%-low estimate of 1.5˚C, while IPCC's high IS92 estimate of 4.2˚C is 35 percent less than our 5%-high estimate of 6.5˚C. The draft report's estimates for the year 2100 are somewhat higher than the IPCC projections principally because our lower values of π allow for a more rapid adjustment of surface temperatures.

Figure 3-7 illustrates temperature estimates for selected simulations through the year 2400.[23] Although temperatures increase throughout the simulation period for most runs, a few runs show a peak around the year 2075; that result stems from the declining emission rates assumed in IPCC scenario IS92c. Figure 3-8 shows the corresponding probability densities for 2100 and 2200.

The importance of the lower values of π is further affirmed when one compares our thermal expansion estimates (Figure 3-9 and Table 3-4) with those of IPCC (1990). For the year 2100, our median draft estimate of 30 cm was about 25 percent less than IPCC's "best estimate," even though our estimated temperature was about the same (the IPCC 1990 report had slightly higher temperatures than the 1992 report). Similarly, our 60 percent confidence interval (20 to 44 cm) was about 25 percent lower than the range spanned by the IPCC low-to-high range of 26 to 58 cm. Only 5 percent of our simulations exceed the IPCC high estimate, while

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[23] See Figure 2-5 and accompanying text for a discussion of the selection criteria for this and other spaghetti diagrams.

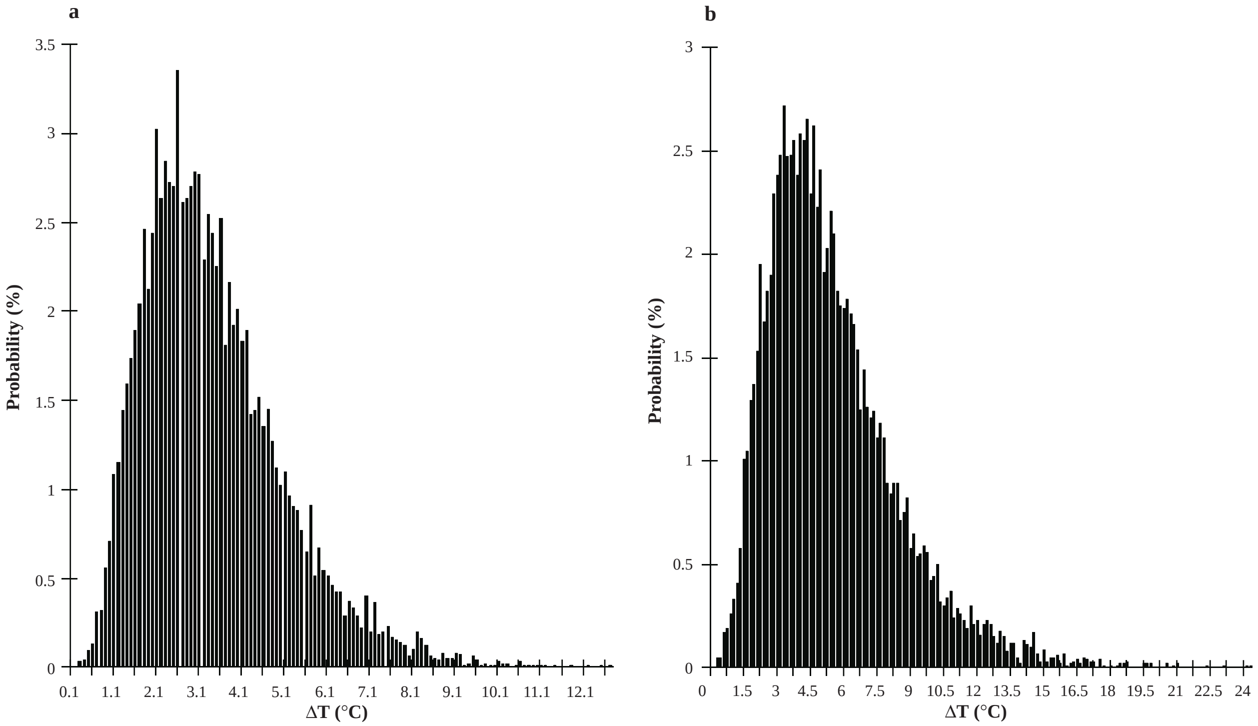

Figure 3-8. **Probability Density for Surface Warming: Draft Report.** Estimated probability density of surface temperature warming between 1990 and (a) 2100 and (b) 2200.

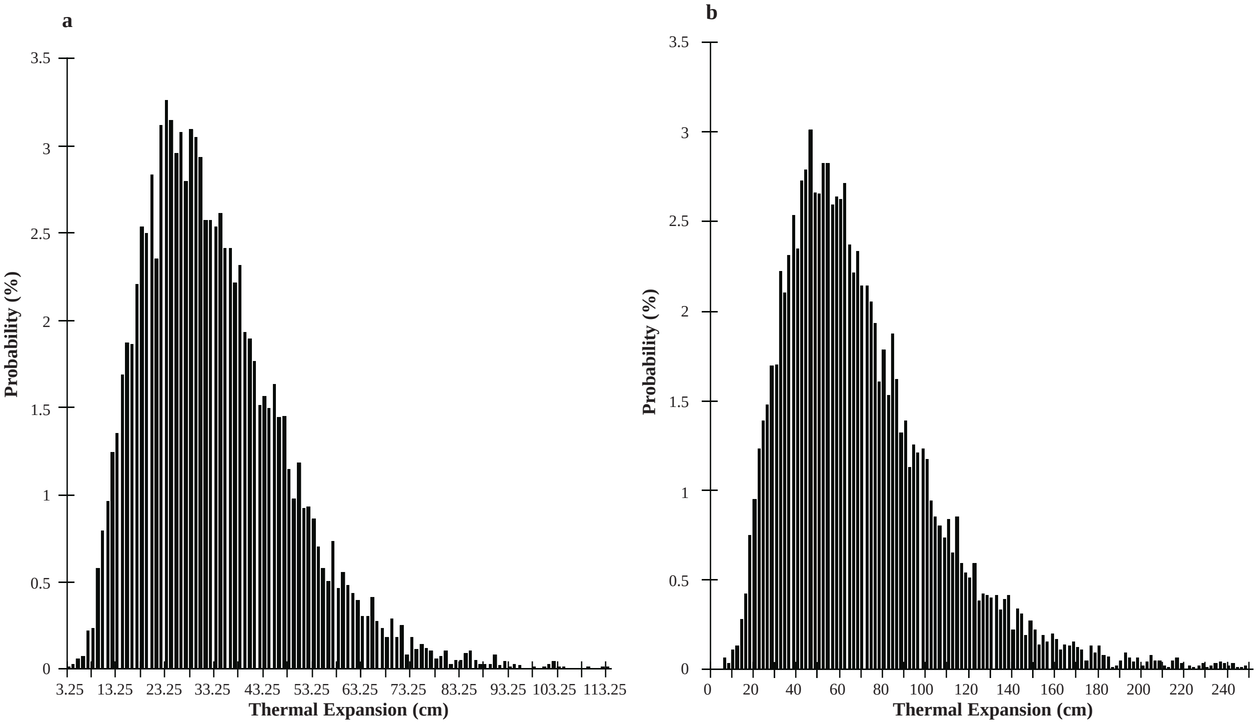

Figure 3-9. Probability Density for Thermal Expansion: Draft Report. Estimated probability density for sea level rise due to thermal expansion between 1990 and (a) 2100 and (b) 2200.

TABLE 3-4
CUMULATIVE PROBABILITY DISTRIBUTION OF THERMAL EXPANSION BASED ON ASSUMPTIONS FROM THE DRAFT REPORT (cm)

Cumulative Probability (%)	2030	2100	2200
1	2.8	8.7	16
5	4.0	13	23
10	4.8	16	30
20	5.8	20	39
30	6.8	23	46
40	7.5	27	53
50	8.4	34	61
60	9.3	38	71
70	10	44	79
80	11	52	93
90	13	60	115
95	15	78	137
97.5	—	—	161
99	18	113	193
99.5	—	—	215
Mean	8.8	32	68
σ	3.3	15	36

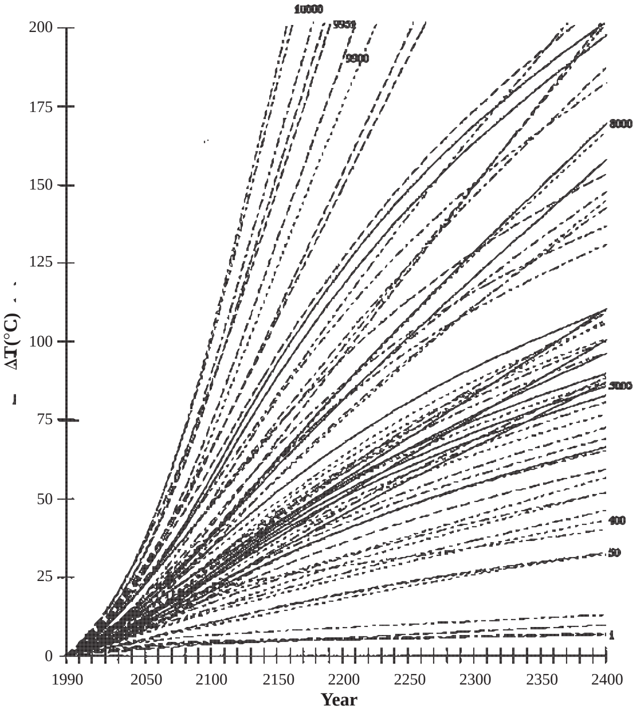

Figure 3-10. Thermal Expansion for Selected Simulations for the Period 1990–2400: Draft Report. See Figure 2-5 and accompanying text for additional explanation.

35 percent of them fell below the IPCC low estimate.

Figure 3-10 provides a spaghetti diagram of thermal expansion for the period 1990–2400. All scenarios show increasing expansion, including the few scenarios for which temperatures decline after 2075. The slight drop in temperatures would result in thermal contraction of the mixed layer; but because temperatures would still be about 1.5˚C warmer than today, the deep layers of the ocean would continue to warm and expand, more than offsetting contraction at the surface.

Figure 3-11 shows the warming of Greenland, Antarctic air temperatures, and circumpolar deep water for selected simulations. Please note that seven of the curves shown are from the upper 1 percent of all simulations. In spite of the occasional extreme simulation, for example, the 1%-high scenario resulted in a circumpolar ocean warming of about 6.5˚C during the next 200 years, less than half the 1%-high for global warming.

Expert Judgment

Our final results are based on the subjective distributions provided by expert reviewers for the various parameters; Table 3-5 lists the eight expert reviewers who examined the draft report and provided distributions for the climate assumptions other than precipitation.

Even though this final report is based on reviewer-specified distributions, we have focused on the initial distributions of the draft report for two reasons. First, the reviewers were reacting to an initial draft; so those desiring to scrutinize the methods and results of this report can only do so by considering the initial specifications to which the reviewers were reacting. Second, the initial distributions retain a residual relevance. In several cases, a given reviewer would find that, for a given parameter, our specifications were adequate: that is, while the reviewer would not have selected precisely the same values that we specified, she did not believe that her specifications would have been sufficiently different for alternative specifications to be worthwhile.

All but one of the reviewers were participants in the IPCC (1990) Science Assessment. Our reasons for selecting these reviewers were that we wanted (a) repre-

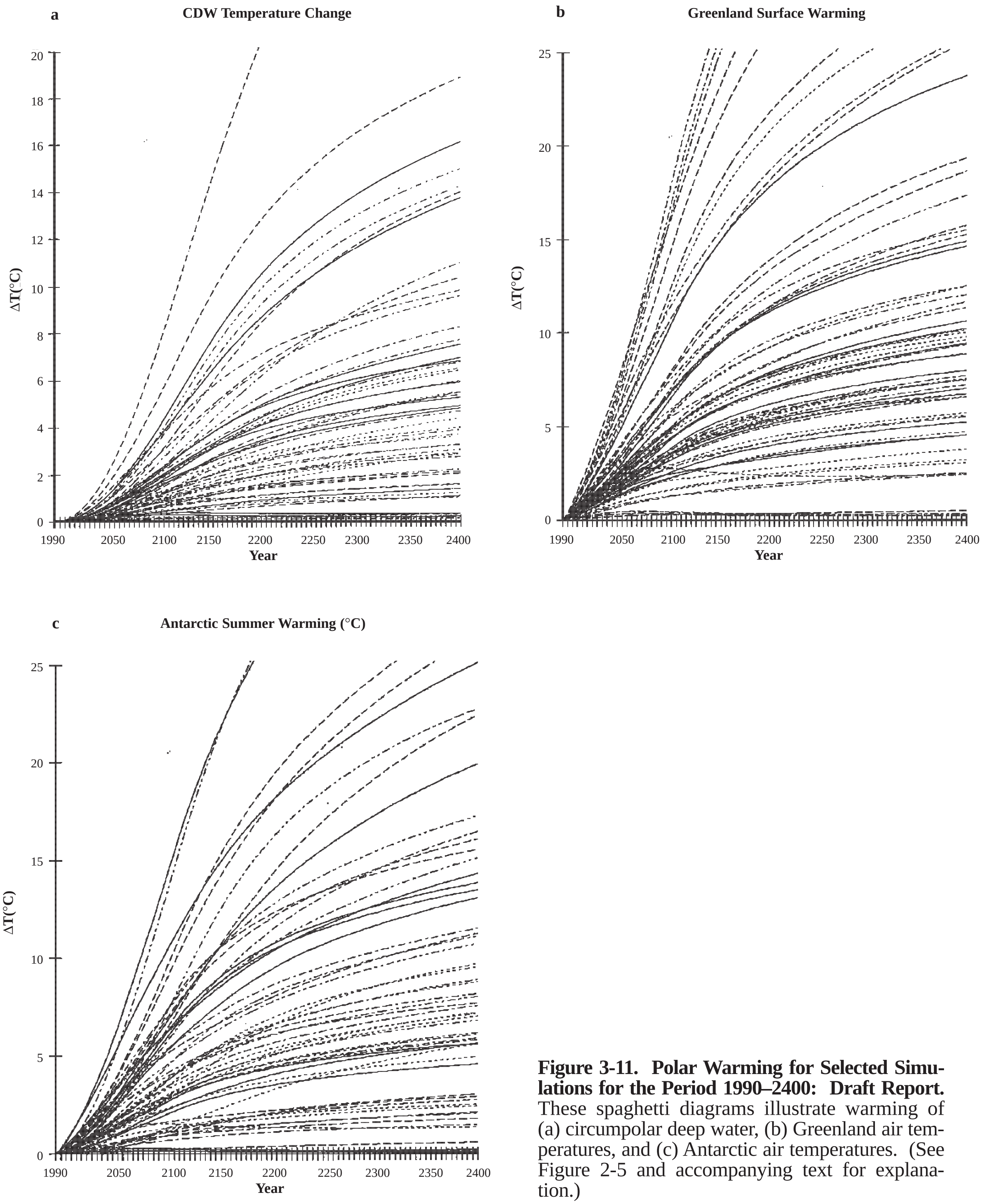

Figure 3-11. Polar Warming for Selected Simulations for the Period 1990–2400: Draft Report. These spaghetti diagrams illustrate warming of (a) circumpolar deep water, (b) Greenland air temperatures, and (c) Antarctic air temperatures. (See Figure 2-5 and accompanying text for explanation.)

TABLE 3-5
EXPERT REVIEWERS OF CHAPTER 3 (excluding precipitation)

Robert Balling	Arizona State University	Tempe, AZ
Francis Bretherton	University of Wisconsin	Madison, WI
Martin Hoffert	New York University	New York, NY
Michael MacCracken	Lawrence Livermore National Laboratories	Livermore, CA
Syukuro Manabe	NOAA/Princeton Geophysical Fluid Dynamics Laboratory	Princeton, NJ
David Rind	NASA/Goddard Institute for Space Studies	New York, NY
Stephen Schneider	National Center for Atmospheric Research	Boulder, CO
Sarah Raper	Climate Research Unit, University of East Anglia	Norwich, UK
Tom Wigley	University Center for Atmospheric Research	Boulder, CO

sentatives from the major general circulation models and (b) those with experience using one-dimensional models to project transient climate change. All of the major modeling groups were invited to participate, as were all of the authors of the IPCC chapter on time-dependent climate change. Almost all of the U.S. scientists contacted agreed to participate. We were less successful in securing the reviews of foreign modeling experts, with two notable exceptions: Tom Wigley and Sarah Raper from the University of East Anglia[24] provided a set of probability distributions based on a probability analysis that they had performed but not published. John Church from CSIRO in Australia offered to provide simulations from his model of thermal expansion, an offer that our time and budget constraints unfortunately prevented us from implementing.

There is an important difference between the ways that scientific assessments (*e.g.*, NAS 1979; IPCC 1990) and Delphic probability analyses choose models and parameter values. Scientific "assessments" usually are more than passive assessments; they often attempt to forge a consensus. As a result, in addition to providing a guide to policymakers, they have a feedback on the evolution of science. In a Delphic probability analysis, by contrast, we take the science as we find it. If the experts disagree, we make no effort to broker a compromise or pick the theory that is most likely to be correct—we simply try to ensure that the simulations reflect the fact that there is a difference of opinion. Thus, while the need to forge a consensus tends to discourage assessment panels from including those with dissenting views, such inclusion is essential in a Delphic analysis, lest the results artificially "compress the tails of the distribution" (*i.e.*, lest we mislead the reader regarding how certain the future really is).

For purposes of this chapter, the most important group of dissenting scientists are those who believe that the "mainstream" drastically overestimates the likely warming resulting from greenhouse gases. Since the original NAS (1979) assessment was published, Sherwood Idso of the U.S. Department of Agriculture in Tempe, Arizona has published dozens of publications disputing the estimate that a doubling of CO_2 would warm the Earth 1.5 to 4.5˚C. The second NAS (1982) assessment devoted about 10 percent of the main body of its report to taking issue with the findings of Idso and other dissenters.[25]

Nevertheless, there is a group of rational scientists that rejects the consensus view that the Earth will warm 1.5 to 4.5˚C from a CO_2 doubling and who (1) have an internally consistent theory for rejecting the consensus view, (2) are continually analyzing empirical data on the question, and (3) have a theory that will be

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[24] Tom Wigley subsequently relocated to the University Corporation for Atmospheric Research in Boulder, Colorado.

[25] Our own studies of climate impacts (*e.g.*, Barth & Titus 1984; Titus 1986; Titus 1991; Titus et al. 1991; Titus 1992) have generally attributed little information content to the dissenters; but our recommendations for coastal policies have always assumed that there is a substantial chance that the rise in sea level will be negligible.

impossible to completely prove or disprove for at least a decade. Two dozen of them met in 1990 and developed a proposed research agenda (Balling et al. 1990). Therefore, we asked Robert Balling of Arizona State University to review the draft report and provide comments reflecting the viewpoints of this important group of "greenhouse skeptics."

What is the most reasonable way of combining the different distributions suggested by the reviewers? It depends on where one draws the boundaries of "expertise." If we had been able to incorporate the judgments of fifty or sixty reviewers of this chapter, we might have defined "expert" on a parameter-specific basis. Thus, for example, the estimate for π might have been based primarily on the judgments of one-dimensional modelers such as Martin Hoffert and Wigley & Raper, while the estimates for ΔT_{2XCO2} would be based on the opinions of three-dimensional modelers such as David Rind and Syukuro Manabe. With only eight reviewers, however, such a procedure would leave us with only one or two opinions for most of the parameters.

At the other extreme, we might have secured the opinions of each reviewer for every parameter in the entire study; but such an approach would go too far in the other direction. Therefore, we divided the reviews by chapter and weighted the assessments of each reviewer equally; for example, there are 1250 simulations drawing from the distributions preferred by each of the eight reviewers listed in Table 3-4. When the reviews came in, it became apparent that some of the glaciologists reviewing Chapters 4 and 5 had expertise regarding polar precipitation changes, while several of the climate reviewers chose not to comment on precipitation. Therefore, precipitation is considered separately later in this chapter.

We now describe the probability distributions requested by the expert reviewers. Table 3-6 summarizes the most important assumptions.

Climate Sensitivity

With the exception of Robert Balling, all of the reviewers accepted the 1.5 to 4.5˚C range as the equilibrium surface warming from a CO_2 doubling; most reviewers accepted our initial characterization of this range as σ limits. Wigley & Raper suggested treating this range as a 90 percent confidence interval (*i.e.*, 1.5 and 4.5˚C are 1.65σ limits) due to the information that has accumulated since the original NAS (1979) report. Manabe agreed that 1.5 to 4.5˚C is a reasonable estimate of a 90 percent confidence range for how a randomly chosen general circulation model would respond to CO_2 doubling. However, because the future response of the actual atmosphere is less certain than the response of a climate model, Manabe suggested that we retain the assumption that 1.5 and 4.5˚C represent σ limits, not the 90-percent confidence interval. MacCracken agreed with Manabe's assessment, largely because the general circulation models do not currently include mode switching or ozone chemistry.[26]

Robert Balling concluded that, based on Idso & Balling (1991), ΔT_{2X} should be normally distributed with a mean of 0.35 and σ limits of 0 and 0.7. Balling was also concerned that the draft report suggested that there was no chance that the Earth would cool. Because a negative climate sensitivity is impossible given the scheme of a one-dimensional upwelling/diffusion model, we set negative values equal to zero. Neverthe-less, we incorporated the possibility of cooling by adding to all simulations a stochastic component, which we discuss below.

We also had to make a nonstandard interpretation of climate sensitivity to faithfully incorporate Balling's suggestions. One-dimensional models assume that the initial forcing from a CO_2 doubling is 4.4 W/m^2 regardless of climate sensitivity—enough to warm the Earth 1.2˚C in equilibrium—and that the remaining forcing results from climate feedbacks that increase linearly with temperature. As a result, to the extent that the deep oceans delay the warming from an increased forcing, they also delay the increased forcing associated with those feedbacks, further delaying the actual warming in high scenarios. For climate sensitivities less than 1.2˚C, however, the effect is the opposite: negative feedbacks increase with temperatures. Thus, the model would show an initial increase in radiative forcing followed by a decline in forcing over time. The Idso & Balling study, however, is based on the assumption that climate warming has at most a trivial delay.[27] To be consistent with this assumption, our Balling simulations adjust direct forcing downward and assume no long-term temperature-driven feedback; in the extreme case where climate sensitivity is zero, we simply assume no change in greenhouse forcing.

Baseline Stochastic Variability

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[26] However, MacCracken did suggest that we truncate the distribution at an upper limit of 9˚C, given the lack of evidence that the warming could be greater.

[27] In effect, Idso & Balling assume that the negative feedbacks occur rapidly (*e.g.*, the feedbacks are *forcing-dependent*).

TABLE 3-6
GLOBAL CLIMATE AND POLAR TEMPERATURE ASSUMPTIONS

	Balling	Bretherton/ Draft	Hoffert	MacCracken	Manabe	Rind	Schneider	Wigley^{c} & Raper
GLOBAL CLIMATE PARAMETERS								
ΔT_{2X}								
σ-low	$0.0^{n,t0}$	1.5	1.5	1.5	1.5	1.5	1.5	1.86^{c}
σ-high	0.7^{n}	4.5	4.5	4.5^{t9}	4.5	4.5	4.5	3.62^{c}
π								
2σ-low	0.2^{d}	0.2^{d}	$0.2, P_{Green}$	0.04	0.2	$P_{Green}, 0.0$	0.2	-0.04^{c}
2σ-high	1.0^{d}	1.0^{d}	$1.0, P_{Green}$	1.0^{t1}	0.2	$P_{Green}, 1.0$	1.0	0.58^{c}
$\mathbf{w}/\mathbf{w}_0$ given $\Delta T = 4^\circ C$ (in cases where **w** changes)								
2σ-low	0.27^{d}	0.27^{d}	0.27, 0.075	0.27	0.4	0.2	0.27, 0.2	N.A.
2σ-high	1.0^{d}	1.0^{d}	1.0, 0.445	1.0	0.4	1.8	1.0, 1.8	N.A.
PROBABILITY OF ALTERNATIVE SPECIFICATIONS OF CHANGES IN UPWELLING								
OM1	50^{d}	50^{d}	50	35	0	80	50	100
OM2	50^{d}	50^{d}	0	35	0	5	20	0
OM2.1	0	0	0	0	0	5	15	0
OM3	0	0	0	30	0	5	10	0
OM4	0	0	0	0	0	5	5	0
OM5	—	—	50	—	—	—	—	—
OM6	—	—	0	—	100	—	—	—
POLAR TEMPERATURE CHANGES								
P_{Ant}								
σ-low	0.67^{d}	0.67^{d}	2.38^{c}	0.5^{n}	0.67^{d}	1.63^{c}	0.5	0.62^{c}
σ-high	1.5^{d}	1.5^{d}	3.36^{c}	1.5^{n}	1.5^{d}	2.45^{c}	2.0	1.21^{c}
P_{cdw}								
σ-low	0.25^{d}	0.25^{d}	$1.0–2.0^{h}$	0.25^{d}	1.0	1.0	0.5	N.A.
σ-high	1.0^{d}	1.0^{d}	$1.0–4.0^{h}$	1.0^{d}	1.0	3.0	2.0	N.A.
τ_{cdw} (years)								
σ-low	20^{d}	20^{d}	57^{c}	20^{d}	100	80?	20?	N.A.
σ-high	80^{d}	80^{d}	131^{c}	80^{d}	300	90?	80?	N.A.
$P_{Greenland}$								
2σ-low	1.0^{d}	1.0^{d}	$1.0–2.0^{h}$	0.5	0.5	1.0	0.5	0.93^{c}
2σ-high	2.0^{d}	2.0^{d}	$1.0–4.0^{h}$	2.0	1.0	3.0	3.5	2.15^{c}

OM1: The original Wigley & Raper (1992) specification with fixed $\mathbf{w}=\mathbf{w}_0$ and specified distribution of π.
OM2: **w** declines geometrically: $\mathbf{w}=\mathbf{w}_0 (1-\theta)^{\Delta T}$; $\theta>0$.
OM2.1: **w** increases geometrically: $\mathbf{w}=\mathbf{w}_0 (1-\theta)^{\Delta T}$; $\theta<0$.
OM3: **w** declines suddenly by 80 percent when ΔT exceeds a threshold T_w. The threshold is between 1 and 4°C, with the higher values more likely; the cumulative probability distribution is: $F(T_w)=(T_w-1)^2/9$ for $1<T_w<4$.
OM4: **w** increases suddenly by 80 percent when ΔT exceeds the threshold T_w, whose distribution is the same as in OM3.
OM5 **w** and π are fixed for the first 1°C of warming, after which **w** declines linearly to 0.05 $\mathbf{w}_0$ by the time ΔT reaches a threshold T_w. π increases linearly from its initial value to the (transient) polar amplification parameter by the time T reaches T_w. T_w is uniformly distributed between 4 and 6°C.
OM6 π is fixed at 0.2, and **w** declines *linearly* with temperature: $\mathbf{w}=(1-0.15\Delta T)\,\mathbf{w}_0$ for $0<\Delta T<6$, and $\mathbf{w}=0.1$ for $\Delta T>6$.
$P_{Green} = P_{Greenland}$
c Reviewer's estimate was a "round number" but specified with respect to a different probability level than σ or 2σ used here.
d Did not disagree with the draft's suggested value, but did not explicitly endorse parameter value either.
— Reviewer did not consider OM5 and/or OM6; those options were proposed *sua sponte* by Hoffert and Manabe, respectively.
h Hoffert assumes that P=1 for $\Delta T<1$. For $1<\Delta T<T_w$, he assumes that P_{Green} and dT_{cdw}/dT (as opposed to P_{cdw}) rise linearly to a maximum value as shown. T_w is uniformly distributed between 4 and 6°C.
n Normal distribution.
r Rectangular (uniform) distribution with limits as specified.
tN Distribution truncated at a value of N.
? Rind and Schneider subsequently revised their estimates of τ to 20–100 and 20–200, respectively. Although these revisions have offsetting impacts on median T_{cdw} projections, they would broaden the range somewhat.

In response to Balling's comments, we also polled the various reviewers on the best way to characterize a baseline nongreenhouse forcing. IPCC (1990) points out that there has been a variation of about 0.3˚C on a century time scale, and that another 0.3˚C variation could result from anthropogenic aerosols.

Comments forwarded by the Dutch Delegation to the IPCC suggested that we use the autoregressive-moving average (ARMA) approach popularized by Box & Jenkins (1976). For example, the Dutch noted that Tol & Vos (1993) fit the following model:

$$\Delta T = -4.6 + 0.015\ CO_2(t - 20) + \varepsilon(t),$$

where

$$\varepsilon(t) - 1.07\ \varepsilon(t{-}1) + 0.18\ \varepsilon(t{-}2) = u(t) - 0.68\ u(t{-}1) - 0.67\ u(t{-}2),$$

u(t) is random noise with σ_u=0.11˚C, and (**t**) represents the average value of a particular variable during the year **t**.

There are two ways to fully implement this model: (1) use the ARMA model estimated by Tol & Vos or (2) fit a one-dimensional model to the historic data while simultaneously estimating an ARMA model of the residuals. We lacked the time to do the latter, which in any event might have required a different ARMA model for each value of π and ΔT_{2X}. We also decided not to use the Tol & Vos parameter estimates directly: Their model implies a decadal variation of 0.16˚C, which only increases to about 0.176˚C for time scales of a century and longer, which is too small.[28]

Therefore, we adopt a simpler approach: A first-order autoregressive model describing a random component that we add to the mixed-layer temperature calculated by the 1-D model at the end of each time period:

$$\text{noise}(t) = 0.9975\ \text{noise}(t - 1) + u(t),$$

where σ_u=0.011˚C and *u* is normally distributed. Although **noise**(**t**) is expressed in terms of temperature, for practical purposes we are assuming that there is a serially correlated atmospheric forcing that causes the 1-D model to miss the surface temperature in time period **t** by **noise**(**t**). Like other forcings, the noise is propagated downward during succeeding years. Figure 3-12 compares ocean model runs for IPCC (1992) emissions scenario A, with and without the noise forcing for a random series of *u* over the period 1765–2065.

The figure also illustrates the potential increase in uncertainty due to factors other than greenhouse gases and aerosol forcing. This uncertainty increases from the annual variation of 0.011˚C that we took from Tol & Vos, to 0.1˚C on a decadal time scale, 0.4˚C on a century time scale, 0.55˚C on a two-century time scale, and 0.62˚C on a four-century time scale.[29] This assumption seems reasonable: Although modeling by Wigley & Raper (1990) suggests natural variability of about 0.3˚C/century, increases or decreases on the order of 0.5˚C/century appear to occur about three times per millennia.[30]

Ocean Model

All eight reviewers agreed with the fundamental approach of using the Wigley & Raper one-dimensional model to project transient temperatures and thermal expansion.

Nevertheless, David Rind questioned our sole reliance on this model, on the grounds that 1-D models inherently provide a limited view of the spatial distribution of ocean temperature changes. For example, the GFDL and Church et al. (1991) models appear to result in more thermal expansion for a given warming than does the Wigley & Raper model. Our futile efforts in Figure 3-6 to pick combinations of π and θ that duplicate both transient temperature and thermal expansion from the GFDL model, he suggested, further highlight the inability of 1-D models to adequately summarize the insights available from 3-D models. Still, given the unfeasibility of running 3-D models in this exercise, he agreed that it was a good idea to fit 1-D models into 3-D results, but that we should do so for several models. We agreed with this suggestion and had planned to implement it; but unexpected budgetary limitations forced us to defer doing so until a subsequent analysis.

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[28] Their purpose in estimating the ARMA model was to remove short-term noise to get a better parameter estimate for the coefficients relating temperature to CO_2. By contrast, our objective here is solely to characterize the century-scale variation, as long as we do not severely overstate the short-term variation.

[29] By itself, the autoregressive equation we have used would simply increase as follows: $\sigma_{noise,t}=(0.0112+\sigma_{noise,t-1})^{1/2}$, which would imply values of 0.03, 0.1, and 0.13˚C. But the 1-D model's lag between forcing and temperature response further increases the effective serial correlation.

[30] *See e.g.*, IPCC (1990) at Fig. 7.1; and Schneider (1994) at 346.

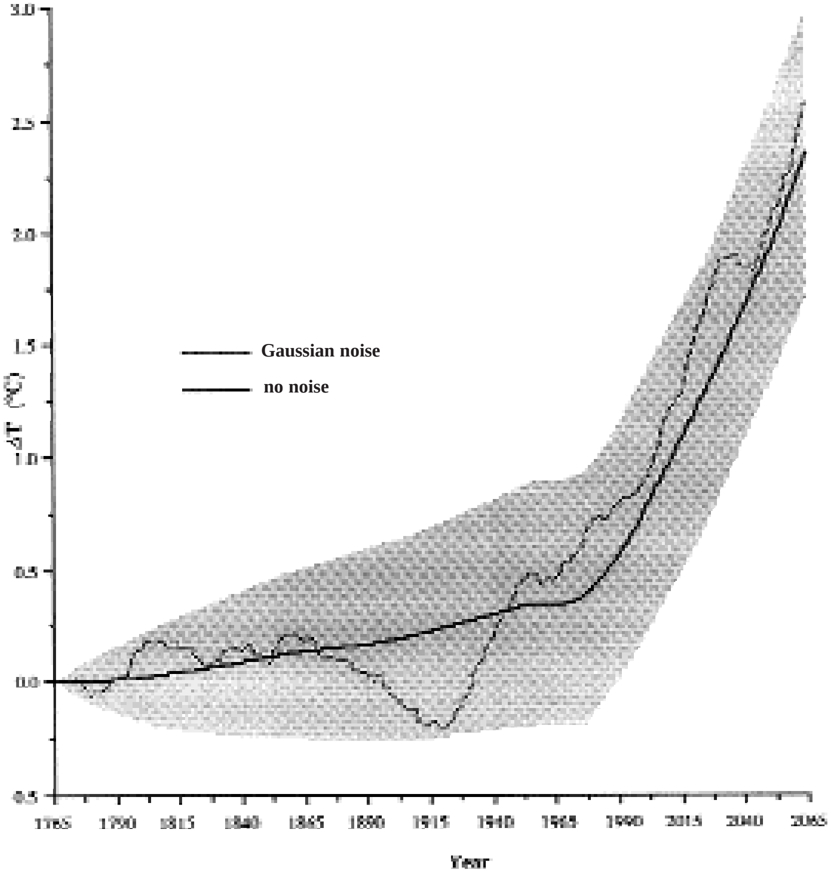

Figure 3-12. Surface Temperatures 1765–2065, With and Without an Illustrative Serially Correlated Nongreenhouse Forcing. The shaded area illustrates the σ limits of the nongreenhouse forcing; variation increases from 0.1˚C on a decadal time scale to 0.4˚C on a century time scale. All scenarios are based on IPCC (1992) emissions scenario A.

Robert Balling and Francis Bretherton concluded that they might have selected different parameter distributions had they undertaken the analysis, but that the initial values in the draft report were close enough to what they would have chosen. Thus, they decided that additional specification on their part would not be worthwhile. The other six reviewers had extensive comments on both the model specifications and the actual parameters employed.

Model Specifications. While the draft report switched between two alternative specifications, the expert reviewers suggested a total of seven different ocean models:

OM1 The original Wigley & Raper (1992) specification with fixed $\mathbf{w}=\mathbf{w}_0$.

OM2 Like the draft report's variable-**w** model, that is, **w** changes geometrically: $\mathbf{w}=\mathbf{w}_0\ \theta^{\Delta T}$. But unlike the draft report, where $\pi=0.2$, π is also drawn from a distribution.

OM2.1 The same as OM2, but θ is greater than 1.0 and thus upwelling increases.

OM3 **w** declines suddenly by 80 percent when ΔT exceeds a threshold T_w. The threshold is between 1 and 4˚C, with the higher values more likely; the cumulative probability distribution is: $F(T_w)=(T_w-1)^{2/9}$ for $1<T_w<4$.

OM4 **w** increases suddenly by 80 percent when ΔT exceeds the threshold T_w, whose distribution is the same as in OM3.

OM5 **w** and π are fixed for the first 1˚C of warming, after which **w** declines linearly to 0.05 $\mathbf{w}_0$ by the time ΔT reaches a threshold T_w. π increases linearly from its initial value to the (transient) polar amplification parameter by the time T reaches T_w. T_w is uniformly distributed between 4 and 6˚C.

OM6 Very similar to the draft report's variable-**w** model. π fixed at 0.2, and **w** declines *linearly* with temperature: $\mathbf{w}=(1-0.15\Delta T)\mathbf{w}_0$ for $0<\Delta T<6$, and $\mathbf{w}=0.1$ for $\Delta T>6$.

We discuss the specifications from each of the reviewers in turn.

Wigley & Raper recommended that we run their initial specification (OM1) for all of the simulations. While acknowledging the possibility that **w** would change over time, they did not believe that such an assumption would improve the projections. They suggested higher values of **k** (and hence $\mathbf{w}_0$): median of 1 cm^2/sec (3154 m^2/yr) with 90 percent (1.65σ) limits of 0.5 and 2.0 cm^2/sec (1576 and 6307 m^2/yr). For reasons discussed in Wigley & Raper (1991), they believe that low values of π are appropriate even with a fixed upwelling velocity. They recommend a shifted lognormal distribution, in which $\pi+0.4$ is lognormal with a median of 0.6 and 1.65σ limits of 0.4 and 0.9; the net effect of this assumption is that (a) the median is 0.2 and (b) 90 percent of the observations are between 0 and 0.5.

Syukuro Manabe also favors low values of π, but believes that downwelling is likely to decline. He recommends that we use a value for π of 0.2 and assume that **w** would decline as suggested by a graph published in Manabe & Stouffer (1993). We fit a linear regression equation of downwelling on transient temperature, which yielded a coefficient of 15 percent per degree (C), down to the point where downwelling has declined by 90 percent. We refer to this set of assumptions as OM6.

Michael MacCracken was the first of several reviewers to note the possibility of a sudden decline in bottomwater formation, suggesting that the probability of such a switch would rise to about 30 percent for a 4˚C warming; he accepted David Rind's functional specification regarding the uncertainty of the threshold T_w, *i.e.*, OM3, discussed below. MacCracken assumed that the fixed-**w** specification OM1 and the variable-**w** specification OM2 should each be used 35 percent of the time. For all three models, π has a median of 0.2 and 2σ limits of 0.04 and 1, with the distribution truncated at 1. For OM2, MacCracken retained the initial assumptions of the draft report that θ has a median of 0.85 (*i.e.*, **w** declines 15%/˚C) and 2σ limits of 0.72^2 (*i.e.*, 0.852) and 1.

MacCracken also explicitly assumed a 0.5 correlation between π and θ, which implies that lower values of π are accompanied by a greater decline in downwelling. This assumption was motivated in part by comparing his own comments with those of David Rind. He observed that there appear to be two schools of thought on what will happen with deepwater formation.

Some scientists, such as MacCracken and Manabe, believe that decreased Antarctic sea ice or increased high latitude precipitation could cause a decline in deepwater formation. The water that does sink will warm much less than the global average because (a) downwelling in the Southern Hemisphere continues to be caused largely by seaice formation, and (b) the North Atlantic Deep Water cannot sink if it warms too much (compared with the temperature of the thermocline). This view implies that π is low and that upwelling is sensitive to temperature.

Others view the downwelling as driven by a conveyor that is influenced by the equatorial upwelling, which could conceivably *increase* due to the enhanced evaporation at higher temperatures. Thus, polar waters could continue to sink even at higher temperatures. This view implies a higher value of π but a lower decline—and possibly even an increase—in downwelling.

David Rind preferred to assume a fixed **w** (OM1) 80 percent of the time. He divided the remaining 20 percent of simulations equally between (a) OM2, with a gradual decrease in **w**, using a median and 2σ limits for θ as specified in the draft report; (b) OM2.1, with its gradual increase in **w**, using a median and 2σ limits equal to the reciprocal of those specified for OM2; (c) OM3, with its sudden 80 percent decrease in upwelling; and (d) OM4, with its sudden 80 percent increase in upwelling. Rind's justification for the 80 percent change in upwelling was that deepwater formation apparently was 80 percent less during the last ice age. For both OM3 and OM4, he suggested that the probability density of a sudden change in upwelling should increase linearly from zero, for a warming less than 1˚C, to a maximum which is reached at 4˚C—hence the quadratic cumulative distribution function.

Unlike the previous reviewers, Rind recommended relatively high values for π. In the Northern Hemisphere, π_{NH} is perfectly correlated with the polar amplification parameter and lognormally distributed with 2σ limits of 1 and 3; in the Southern Hemisphere, π_{SH} is uniformly distributed between 0 and 1. Because only 20 percent of the downwelling occurs in the Northern Hemisphere, the net effect is that the global π has a median value of about 0.75.

Stephen Schneider made structurally similar recommendations, although he allocated the probabilities differently: OM1—50%; OM2—25%; OM2.1—10%; OM3—10%; and OM4—5%. For all cases, he used the initial distribution that the draft report applied for OM1; for example, π had a lognormal distribution with 2σ limits of 0.2 and 1.

Martin Hoffert favored devoting 50 percent of the simulations to OM1, using the initial assumptions of the draft report for all of the ocean model parameters. Based on Hoffert (1990), he allocated the remaining 50 percent to OM5. This model assumes that π and $\mathbf{w}$ are fixed for $\Delta T<1^\circ C$. For $1<\Delta T<T_w$, $\mathbf{w}$ declines linearly; for $\Delta T>T_w$, w remains fixed at 7.5 percent of its initial value $\mathbf{w}_0$.[31] Although Hoffert (1990) suggested that $T_w=4^\circ C$, for purposes of this study Hoffert suggests that T_w is uniformly distributed between 4 and 6°C.

Hoffert also assumes a gradual increase in the value of π. For $\Delta T<1^\circ C$, $\pi=1.0$. For $\Delta T>T_w$, Hoffert sets π equal to the transient polar amplification; *i.e.*, sinking water warms by the same amount as circumpolar ocean water. For $1<\Delta T<T_w$, π rises linearly between 1 and the polar amplification associated with a global warming of T_w. Thus, sinking water temperatures warm by the same amount as global temperatures for a warming less than 1°C; but as ΔT approaches T_w, the rise in sinking water temperatures gradually approaches the warming of the polar ocean water. Because of the drastic declines in **w**, however, the practical importance of π declines as ΔT rises from 1 to T_w.

Greenland Temperature

Most of the reviewers thought that Greenland is likely to warm more than the global average,[32] but most wanted some change to our initial assumption that P_7—the Greenland amplification parameter—has 2σ limits of 1 and 2. Wigley & Raper suggested that this range be viewed as 1.65σ (90 percent) limits. At the high end, Martin Hoffert suggested that Hoffert & Covey (1992) implies 2σ limits of 2 and 4 times the average global warming; Stephen Schneider suggested 2σ limits of 0.5 and 3.5. Noting that summer warming could be less than the annual average warming and that high altitude warming could be less than warming at sea level, Mike MacCracken suggested 2σ limits of 0.5 and 2.

At the low end of the spectrum, Syukuro Manabe suggested σ limits of 0.5 to 1, noting that the reduced North Atlantic deepwater formation projected by the GFDL model would reduce the warming from the Gulf Stream. In the cases where **w** declines drastically (OM3), David Rind made the similar assumption that $P_7=0.5$. Otherwise, he suggested that 2σ limits of 1 to 3 are more appropriate. Nevertheless, in cases where **w** changes gradually, he assumes a 0.5 correlation between θ and P_7, implying that low polar amplification accompanies reductions in deepwater formation. Rind points out that, according to IPCC (1990), Green-land was about 4°C warmer during the Eemian interglacial when global temperatures were 1 to 2°C warmer (Velichko et al. 1982). Moreover, during the Pliocene (3.3 to 4.3 million years ago), Greenland summers were 10°C warmer than today, while the mid-latitude Northern Hemisphere summers were only 3 to 4°C warmer (Budyko & Izrael 1987). Finally, during the Holocene climatic optimum, Greenland summer was about 3°C warmer than today, while the mid-latitude regions were only about 1°C warmer than today (Budyko & Izrael 1987).

Although David Rind was the only reviewer to explicitly suggest a correlation between P_7 (Greenland amplification) and θ (the change in downwelling), the combined impact of the reviewer assumptions also bears out such a correlation. Manabe and MacCracken see substantial declines in **w** and relatively low polar amplification. Wigley & Raper's simulations and 80 percent of Rind's simulations have no change in **w** and relatively large polar amplification. Schneider shows a slightly greater tendency for a decline in **w** than Rind, as well as a slightly lower polar amplification. Only Hoffert falls outside of this pattern, expecting a sharp decline in sea ice, which would contribute both to a high polar amplification and a large drop in downwelling.

All of the reviewers agreed with our assumption

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[31] Hoffert justified this assumption, like most of his comments, on the paleoclimatic record. Specifically, based on the Cretaceous period, he estimates that the ratio $(T_b-T_p)/(T_m-T_p)$ did not rise above 10/18, where $\mathbf{T_b}$ is the bottomwater temperature, $\mathbf{T_p}$ is the polar ocean temperature, and $\mathbf{T_m}$ is the mixed-layer temperature. Solving the 1-D model for its equilibrium depth-temperature profile, Hoffert finds that the ratio of 10/18 is consistent with a 92.5 percent decline in upwelling.

[32] *But cf.* Karl et al. (1995, in press) at Figure 2 (Greenland has cooled—perhaps due to sulfate aerosol forcing—as global temperatures warmed over last half century).

that Greenland warming would not lag significantly behind global warming. Martin Hoffert, however, assumes that polar amplification would initially be less than P_7. To be consistent with Hoffert (1990), he suggested that the amplification factor is 1.0 for the first degree of warming. He treats P_7 not as an equilibrium amplification factor, but rather as what the amplification factor would be once $\Delta T > T_w$. He then assumes that as ΔT increases from 1.0 to T_w, the polar amplification factor increases linearly from 1.0 to P_7. For example, if $T_w=5$ and $P_7=3$, then $\Delta T=1$, 2, and 3˚C imply amplification factors of 1, 1.5, and 2, resulting in $\Delta T_{Greenland}=1$, 3, and 6˚C, respectively. Thus, Hoffert's assumptions imply a Greenland warming similar to the projections of Manabe for the first degree, Wigley & Raper for the second degree, and Rind for the third degree. After that point, Hoffert's assumptions imply much greater warming for Greenland than any of the other reviewers.

Antarctic Air Temperatures

The Antarctic contribution to sea level depends on changes in both air and water temperatures. As discussed in Chapter 6, the melting of Antarctic ice shelves is assumed to respond to both declines in sea ice and warmer water temperatures. Warmer air temperatures contribute both to declines in sea ice, discussed in the previous section of this chapter, and the countervailing impact of increased precipitation, discussed in Chapter 3B.

Most of the reviewers focused on the more important Antarctic water temperatures and let stand our initial draft assumptions for the equilibrium southern polar amplification and the speed at which the adjustment takes place. MacCracken suggested that declines in Antarctic sea ice could possibly allow summer air temperatures to cool; therefore, he suggested that we use a normal distribution with σ limits of 0.5 and 1.5 for the summer amplification parameter P_1, which implies a 2 percent chance that Antarctic summers will cool if global temperatures warm. Wigley & Raper also suggested a range of 0.5 to 1.5, albeit for a lognormal distribution and 90-percent limits. Schneider retained our initial assumptions for winter warming; he thought that summer warming was most likely to be equal to average global warming, but suggested 2σ limits of 0.5 and 2 times the global warming. Hoffert, by contrast, suggested 2σ limits of 2 and 4, consistent with his Northern Hemi-sphere assumptions. Rind assumed a median amplification of 2, with 2σ limits of 1.33 and 3.

Hoffert and Wigley & Raper were the only reviewers to change the simple first-order linear adjustment by which Antarctic temperatures respond to transient global temperatures. Hoffert adopted the specification that he employed for Greenland temperatures. Wigley & Raper assumed no additional lag.

Circumpolar Ocean Warming

The reviewers generally agreed with the draft report's assumption that circumpolar ocean temperatures will respond more slowly than Antarctic and Greenland air temperatures. Three of the reviewers suggested no change to our initial assumptions of an amplification (P_3) with σ limits of 0.25 and 1.0, along with an adjustment time (P_4) with 2σ limits of 20 and 80 years. Manabe suggested that the circumpolar ocean will eventually warm as much as the global average warming, but with an adjustment time of 100 to 300 years (σ limits). For the year 2100, this assumption yields about the same circumpolar warming as our initial median assumptions.

Three of the reviewers, however, suggested substantially higher sensitivities than reflected in the initial draft report. Schneider agreed with Manabe that the most likely long-term amplification would be 1 but retained our initial assumptions regarding the likely lag. He also suggested a relatively wide uncertainty range, involving 2σ limits of 0.5 and 2. While agreeing with the initial adjustment times from the draft report, he added that the adjustment would be (relatively) slower in cases where the warming is more rapid. Therefore, he suggested a 0.5 correlation between the adjustment time and both emissions and temperature sensitivity.

Rind and Hoffert both suggested that circumpolar ocean temperatures should warm more than the global average, in equilibrium. Rind suggested 2σ limits of 1 and 3, the same as his suggested range for air temperatures. He noted, however, that the North Atlantic deep water tends to stabilize both sea ice and circumpolar water temperatures, so that very little warming could occur until warmer North Atlantic water arrived. Based on Broecker & Takahashi's (1981) estimate that it takes 80 to 90 years for deep water to arrive from the North Atlantic, Rind specified an absolute lag of 80 to 90 years; *i.e.*, rather than assuming a linear adjustment in which some warming occurs immediately, he assumed that the global warming in a given year alters the circumpolar ocean temperatures 80 to 90 years later.

Hoffert also suggested that the impact of global warming on water temperatures could eventually be as great as the impact on air temperatures. As with polar air temperatures, however, he assumed that the amplification factor starts out at 1 and rises with temperatures up to a maximum value of P_3, as ΔT rises from 1 to T_w; P_3 has 2σ limits of 2 and 4. However, unlike air temperatures, where the amplification factor is the ratio $\Delta T_{polar}/\Delta T$, for water temperatures this amplification factor represents the derivative dT_{cdw}/dT. For example, for his median assumptions of P_3=3 and T_w=5, and using values of ΔT=1, 2, and 3˚C, his assumptions imply derivatives of 1, 1.5, and 2, and ΔT_{cdw}=1, 2.25, and 4˚C, respectively. For a warming of 5˚C, however, Hoffert's median assumptions imply equilibrium circumpolar ocean warming of 7˚C. Thus, Hoffert assumes that for each degree of global warming, the circumpolar ocean warms in equilibrium by less than the polar air temperatures, until $\Delta T=T_w$. At this point, Hoffert assumes that permanent sea ice would disappear, removing the primary process that prevents the circumpolar ocean from warming as much as polar air temperatures. Hoffert assumes that the circumpolar ocean warming lags behind global warming with a linear adjustment. He assumes a median e-folding time of 86 years, with 3σ limits of 25 and 300 years, which implies 2σ limits of approximately 40 and 200 years. Thus, Hoffert, Rind, and—to a lesser extent—Manabe expect greater equilibrium warming of the polar ocean than assumed in the draft report; but they also expect a slower adjustment.

Sea Ice

Only two of the reviewers recommended a change in our sea ice assumptions. Rind suggested that, for the most part, the Parkinson & Bindschadler (1982) study (*i.e.*, a 5˚C warming causes a 50 percent reduction) overestimated the response of sea ice, because it omitted the stabilizing influence of North Atlantic Deep Water. He therefore suggested that it would be more appropriate to assume that the decline is only one-half as great as assumed in the draft report. In the (10 percent) cases where deepwater formation declines, however, this stabilizing influence would be diminished, and thus the initial draft assumptions would be more appropriate.

Hoffert, by contrast, thought that the Parkinson & Bindschadler study *under*stated the decline in sea ice. Hoffert (1990), for example, suggested that a 4˚C global warming would eliminate all of the permanent sea ice. However, because the Antarctic models employed in Chapter 5 depend on annual seaice formation, not the total extent of sea ice, we used the Parkinson & Bindschadler sensitivities for the Hoffert simulations.

Implications of Reviewer Comments for Projecting Sea Level

The net effect of the comments from the reviewers of Chapter 3 is to substantially widen the uncertainty range compared with the initial report. At the low end of the spectrum, the incorporation of Robert Balling's comments ensures that approximately one-eighth of the simulations assume temperature sensitivities (ΔT_{2X}) well below the low end of the consensus range adopted by the NAS (1979), IPCC (1990), and others. The net effect is that the median and mean values of ΔT_{2X} are 2.4 and 2.7˚C (as opposed to 2.6 and 3.0˚C in the draft), with 25 percent of the simulations using values below 1.5˚C.

At the high end of the spectrum, the reviewer comments tend to slightly depress projections of future temperatures. Three of the eight reviewers—Balling, MacCracken, and Wigley & Raper—compressed the upper end of the distribution in some fashion, but the overall effect is relatively small, with 13 percent of the simulations having values of ΔT_{2X} that exceed 4.5˚C, and 5 percent exceeding 6˚C.

The reviewer comments for π and **w** have a greater impact at the high end of the range: The combined comments of Manabe, Hoffert, Rind, Schneider, and MacCracken imply that **w** declines by at least 80 percent for about one-fifth of the simulations in which warming eventually exceeds 5˚C (in addition to the more modest declines that occurred in about half the simulations in the draft report). Given the 0.5 to 0.75˚C cooling that Figure 3-4 shows for the more modest decline in upwelling, this greater decline reduces warming by about 1˚C by the year 2100. In addition, two reviewers suggested substantially higher values of π. For a small warming, the Rind and Hoffert comments imply that about 20 percent of the simulations have a value of π exceeding 0.6, with about 15 percent having a value greater than 1.0. As Figure 3-4 shows, this higher value could decrease warming by about 0.5˚C in the median temperature scenario.[33]

The slower warming, however, is offset by the increased thermal expansion implied by reduced upwelling. As Figure 3-4 shows, even a modest decline in **w** results in a one-third increase in the warming at a depth of 500 m; and the resulting expansion of the thermocline more than offsets the reduced expansion of the mixed layer that results from the smaller surface warming. Higher values of π enable the deep ocean to warm more; a value of π=1 results in 20 percent more expansion after 100 years than a value of 0.2. Thus, five of the

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[33] The 1%-high temperature estimate for the year 2050 from Schneider's assumptions is almost twice the estimate implied by Manabe's assumptions. The only material difference in their assumptions are the values for π and **w**: Schneider allows thermohaline circulation to increase in some scenarios, while Manabe has a substantial decrease. *See* Appendix 1 and Figure 3-13, *infra*.