Contributions of past and present human generations to committed warming caused by carbon dioxide

Pierre Friedlingstein*[†] and Susan Solomon[‡]

*Institut Pierre Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement, Commissariat à l'Energie Atomique-Saclay, L'Orme des Merisiers, 91191 Gif sur Yvette, France; and [‡]National Oceanic and Atmospheric Administration, Boulder, CO 80305

We developed a highly simplified approach to estimate the contributions of the past and present human generations to the increase of atmospheric CO_2 and associated global average temperature increases. For each human generation of adopted 25-year length, we use simplified emission test cases to estimate the committed warming passed to successive children, grandchildren, and later generations. We estimate that the last and the current generation contributed approximately two thirds of the present-day CO_2-induced warming. Because of the long time scale required for removal of CO_2 from the atmosphere as well as the time delays characteristic of physical responses of the climate system, global mean temperatures are expected to increase by several tenths of a degree for at least the next 20 years even if CO_2 emissions were immediately cut to zero; that is, there is a commitment to additional CO_2-induced warming even in the absence of emissions. If the rate of increase of CO_2 emissions were to continue up to 2025 and then were cut to zero, a temperature increase of $\approx 1.3°C$ compared to preindustrial conditions would still occur in 2100, whereas a constant-CO_2-emissions scenario after 2025 would more than double the 2100 warming. These calculations illustrate the manner in which each generation inherits substantial climate change caused by CO_2 emissions that occurred previously, particularly those of their parents, and shows that current CO_2 emissions will contribute significantly to the climate change of future generations.

climate | greenhouse | radiative forcing

Changes in greenhouse gases and aerosols can alter Earth's energy budget, representing a radiative forcing that in turn leads to climate-system responses. Some of these responses can be rapid, as evidenced by changes in surface temperature and water vapor within months after major volcanic eruptions (1, 2). In contrast, the mixed layer of the ocean displays a response time scale of the order of decades, whereas the deep ocean and the great polar ice sheets change over centuries or even millennia. The thermal inertia of ocean and ice is thus among the key factors that cause lags between increases in concentrations of greenhouse gases and observed atmospheric temperature changes. Such lags have been variously referred to as unrealized warming, residual warming, or committed warming (3–7); here we use the term "committed warming." Regardless of the nomenclature used, these and other studies have highlighted the fact that simple physical considerations linked to time scales for heat transport within the Earth system imply that radiative forcing leads not only to warming at a given time but also to additional future warming even if the concentrations are stabilized. Commitments to warming are also accompanied by commitments to future sea-level rise over time scales of many centuries or even millennia (6–8), but in this article we confine our attention to committed warming only.

Previous studies have shown that a range of forcing agents is contributing to modern climate change (e.g., see refs. 9–11). It is well known that the time scale of commitment depends not only on the climate-system response time but also on the atmospheric lifetime of the radiative forcing agent in question (gas or aerosol) (e.g., see ref. 12). Relatively short-lived species such as aerosols, tropospheric ozone, and methane are associated with shorter commitments than longer-lived substances such as carbon dioxide or perfluorocarbons (13, 14). We do not attempt to examine the range of forcing agents that are believed to be contributing to climate change in this article, nor do we examine how feedbacks influence the climate changes caused by forcing.

The purpose of this article is to probe in a qualitative fashion the nature and scope of the warming commitments associated with increases in the dominant greenhouse gas, carbon dioxide, by using a highly simplified approach. We will show how multiple time scales that characterize the removal of this gas from the atmosphere affect the warming commitments associated with its emission. Because the time scale of these warming commitments may extend over decades to centuries, the commitments can be passed from one generation to another and are the focus of this study.

We use 25 years as the approximate time scale for a human generation, noting that this may be somewhat lower than the time scale sometimes used to refer to certain types of generations of infrastructure (e.g., power plants, factories, etc.) and technologies. Our goal is to explore physical responses rather than to discuss the plausibility of possible future emissions scenarios. It should be noted that changes in atmospheric concentrations of carbon dioxide are well established for the 20th century, whereas the connections of concentrations to emissions are subject to greater uncertainties relating to sources and the details of processes that remove carbon dioxide from the atmosphere (e.g., see ref. 15). To probe the warming commitments undertaken by several past generations as well as the present one, we examine highly simplified test cases per generation by using (i) zero emissions, (ii) constant emissions, and (iii) increasing emissions derived from observations. Because of the long lifetime of carbon dioxide and its slow removal rate compared to current input emissions, the concentration of CO_2 will continue to increase even for constant emissions. Similarly, CO_2 concentrations do not decrease rapidly even in the complete absence of emissions. We will first show the implications of these different emission cases on the future evolution of atmospheric CO_2. Then, we will show that these cases illustrate how present and past changes in carbon dioxide concentrations affect the climate experienced by each generation, their children, their grandchildren, and later generations.

Description of the Approach

It is well known from atmospheric and ice-core data that the concentration of atmospheric carbon dioxide has changed during past ice ages through many hundreds of thousands of years. It has also increased dramatically in the industrial era at rates that are unprecedented compared to those of at least the previous half-million years (see Fig. 1). Today this carbon dioxide increase contributes ≈ 1.5 W/m^2 to warming of Earth's climate, which is $\approx 60\%$ of the estimated total forcing caused by all known radiative warming agents assessed by the Intergovernmental
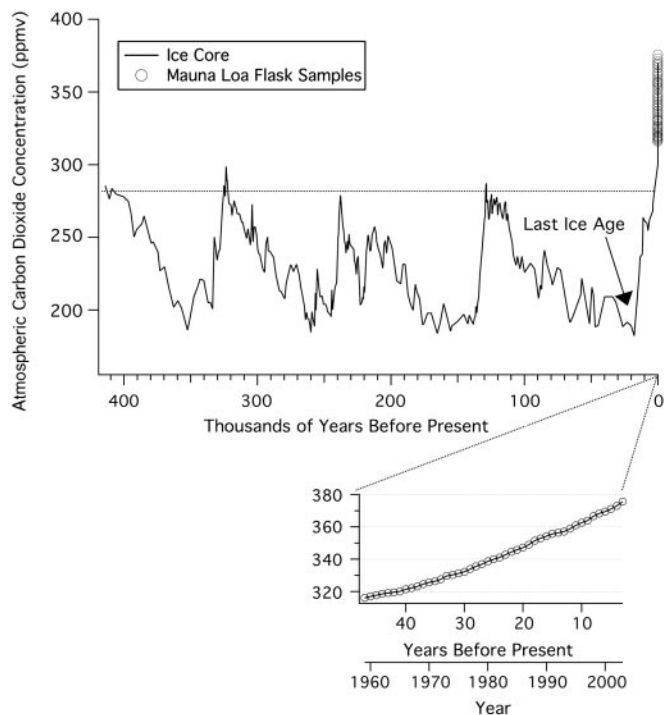

Fig. 1. Observed carbon dioxide concentrations versus time based on ice-core records spanning >400,000 years and flask air samples spanning almost 50 years. Note the different time scales in the figure and *Inset*.

Panel on Climate Change as of 2001 (12). Only carbon dioxide is considered in this article.

We divided the past 150 years into six 25-year-long generations as illustrated in Fig. 2. For each generation we examined the effects of the unrealistic cases of zero emissions (i.e., emissions are cut to zero at the end of that generation up to 2100) and constant emissions (for which emissions are set to their value at the end of that generation up to year 2100). A stepwise increment for each generation up to the year 2000 was also evaluated based on emission data from the Marland *et al.* (16) estimate for
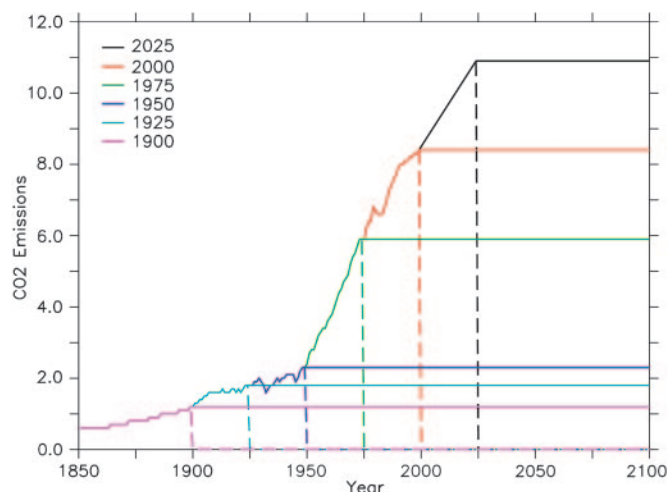

Fig. 2. Annual emissions for the zero-emissions (dashed line) and constant-emissions (solid lines) cases along with historical changes within each 25-year generation (gigatons of carbon per year) up to 2000. The 2000–2025 emissions case was obtained assuming linear increases of emission that are the same as those for the 1975–2000 period.

fossil-fuel CO_2 emissions and from Houghton and Hackler (17) for land-use-change CO_2 emissions.

For the current 2000–2025 generation, we also impose a simple test case assuming increases of emission that are the same as those for 1975–2000 (i.e., an additional 0.1 gigatons of carbon per year). Then in 2025 we again impose zero emissions as well as constant emissions for 2025–2100 for the present generation (Fig. 1). All calculations were performed for the 1850–2100 time period. Calculations including zero emissions were extended to 2200 to indicate the decay of CO_2 over longer time periods that would occur in the absence of emissions.

We first calculate the atmospheric CO_2 concentrations resulting from each of these emission time series by using a pulse-response approach. Atmospheric CO_2 is linked to removal by several different earth-system processes involving the biosphere and oceans. Some CO_2 is removed relatively rapidly, over a time scale of decades, whereas a portion ($\approx 15\%$) of the added CO_2 is expected to remain in the atmosphere even after a millennium, implying some long-ranging commitments over time scales of human history (18, 19). The atmospheric CO_2 change at time t for a CO_2 pulse at time $t0$ is given by the response function of Joos *et al.* (20, 21):

$$dCO_2(t) = dCO_2(t0)[b0 + b1(t - t0) + b2(t - t0)^2]/$$
$$[b0 + b3(t - t0) + b4(t - t0)^2 + b5(t - t0)^3],$$

[1]

where $dCO_2(t0) = emi(t0)/2.12$, with $emi(t0)$ being the CO_2 emission at time $t0$.

The actual change in CO_2 is therefore the integral of dCO_2 over past years. Uncertainties in this function are related to differences between different carbon-cycle models as well as dependencies on the absolute abundance of CO_2 (especially for larger perturbations relative to preindustrial conditions) and are on the order of $\pm 15\%$ for the limited range of CO_2 concentrations considered here (22, 23)

When forced with the fossil-fuel and land-use CO_2 emissions for the 1850–2000 period, these equations simulate an atmospheric CO_2 level that is consistent with ice-core data for the 1850–1950 period but slightly overestimate (up to 10 ppm) the CO_2 over the last few decades. We note that there is a large uncertainty in the sources of CO_2 from deforestation. Recent satellite-based estimates show tropical-deforestation emissions being a factor of 2 lower than the Houghton and coworkers (24, 25) estimate, which alone could explain the discrepancy in our simulated CO_2 calculations. Also, as mentioned above, there is uncertainty in the CO_2 pulse-response functions. Finally, such a response function makes the implicit assumption that the CO_2 sinks are only driven by atmospheric CO_2. This assumption may not be realistic for the land uptake, in which other processes such as climate change, nitrogen deposition, or changes in land management are also likely to play a role in the land carbon sink (e.g., see refs. 15 and 26).

The estimate of the corresponding climate change for a given CO_2 time series is made by using a temperature-change pulse function. The temperature change δT at time t caused by an atmospheric CO_2 change of δCO_2 at time $t0$ is assumed to be given by:

$$\delta T(t) = \frac{\alpha}{\tau} \delta CO_2(t_0) \exp(-t/\tau),$$ **[2]**

where α is the climate sensitivity and τ is the response time of the climate system to a CO_2 pulse. The actual temperature change is therefore the integral of δT over past years. These parameters are chosen to broadly match recent modeling studies (e.g., see ref. 7). The assumed climate sensitivity adopted here for a doubling of
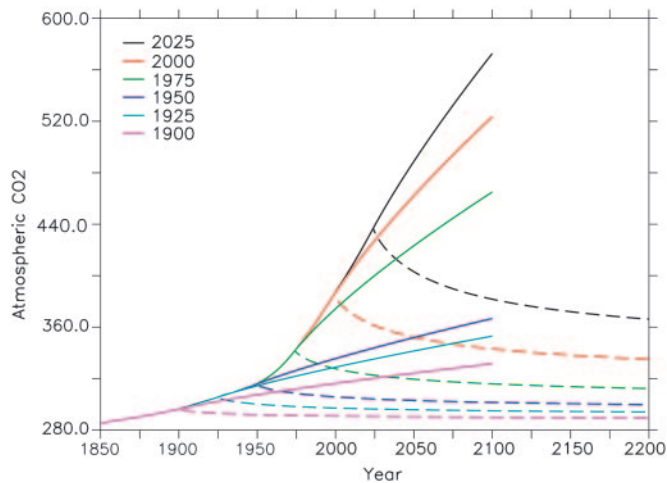
Fig. 3. Atmospheric CO_2-concentration commitments linked to each human generation since 1900. Solid lines represent the constant-emissions case, and dashed lines represent the zero-emissions case. The zero-emissions cases are extended to 2200.

Fig. 4. As described for Fig. 3 for CO_2-induced warming commitments linked to each human generation since 1900. Only CO_2 has been considered. The range between the dotted and dashed lines for each color illustrates the large range in realized temperatures caused by the effect of CO_2 emitted by each generation in the past along with the present (2000–2025) generation. Note, for example, the very large differences in estimated warming in 2100 depending on whether constant emissions are continued through the 21st century compared to zero emissions after 2025 (black lines).

atmospheric CO_2 compared to its preindustrial level is $\approx$3.5°C. A range of 1.5–4.5°C was estimated by the Intergovernmental Panel on Climate Change in *Climate Change 2001* (8), so here we are illustrating results for a value near the middle of the range.

Key Results

Atmospheric CO_2. We first estimate the relative contribution of each past generation to present-day (year 2000) and year-2100 CO_2 concentrations. Note that the upper end of CO_2 concentrations considered here is <600 ppm. Nonlinear impacts on radiative forcing are small for this range of CO_2 between current value and CO_2 doubling (less than 22% based upon the formula given in ref. 12), and are not explicitly considered here, but we note that nonlinear radiative transfer effects become significant for larger CO_2 abundances.

Fig. 3 shows the evolution of atmospheric CO_2 calculated for each generation, showing that even a zero-emissions strategy leads to limited near-term reductions in atmospheric CO_2; that is, Fig. 3 shows that there is prompt removal of a portion of the added CO_2, but only a portion. As an example, if emissions were set to zero in 2000, atmospheric CO_2 would be reduced by 20 ppm in the next 25 years and by 40 ppm by the end of the century. By 2100, the CO_2 concentration would be about the same as that in 1975. That is to say, it would take approximately a century to remove the bulk of the anthropogenic CO_2 injected in the atmosphere over the past 25 years. For the example shown above, extending this calculation beyond 2100 shows that the atmospheric CO_2 would only drop by another 20 ppm over the 22nd century and by another 10 ppm over the 2200–2500 period. The
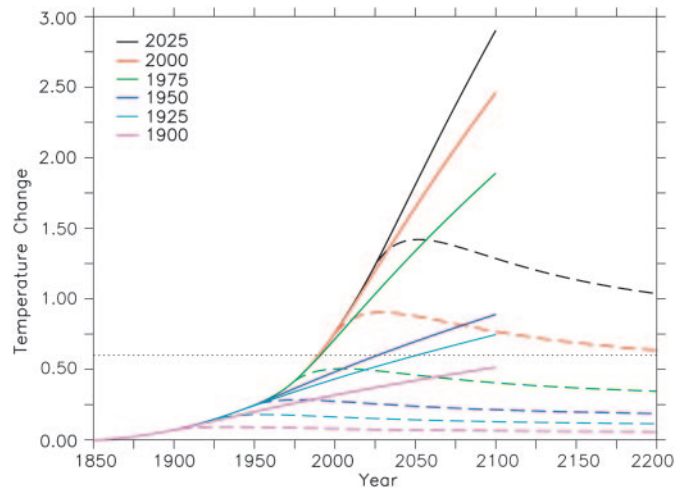
long time-scale retention of CO_2 in the atmosphere even after many centuries represents a commitment to future climate change that could include some very slow and uncertain aspects of the climate system, such as changes in the polar ice sheets that could affect sea level.

If the current (2000–2025) generation emits carbon dioxide at the same rate as the previous generation and cuts emissions abruptly to zero in 2025, the calculated atmospheric CO_2 in 2025 reaches 437 ppm and only drops to 382 (approximately the current level in 2005) by 2100. It is worth recalling that constant emissions will lead to a linear increase in atmospheric CO_2, not to stabilization. Atmospheric CO_2 stabilization can be reached only with an emission scenario that eventually drops to zero.

These simple calculations highlight the time lag between reduction of emissions and reduction of atmospheric CO_2 concentrations.

If a zero-emissions scenario had been adopted after each of the six successive past generations, the atmospheric CO_2 levels reached in 2000 would be $\approx$287, 291, 297, 306, 328, and 383 ppm, respectively (Table 1), which indicates the contribution each generation has made to the present-day CO_2 increase. The 1975–2000 generation alone increased atmospheric CO_2 by $\approx$45 ppm, more than half of the total increase over the industrial era.

Similarly, we calculated the carbon dioxide burden that would have been incurred because of each past generation if a constant-

Table 1. Commitment of atmospheric CO_2 and global warming by 2000 and 2100 for each generation under the zero- and constant-emissions cases

	1850–1875	1875–1900	1900–1925	1925–1950	1950–1975	1975–2000	2000–2025
Zero emissions, ppm (°C)							
CO_2 (δT) by 2000	287 (0.03)	291 (0.07)	297 (0.16)	306 (0.27)	328 (0.5)	383 (0.75)	387 (0.76)
CO_2 (δT) by 2100	287 (0.02)	290 (0.06)	295 (0.13)	302 (0.21)	316 (0.4)	343 (0.77)	382 (1.29)
CO_2 (δT) by 2500	287 (0.02)	289 (0.05)	293 (0.1)	298 (0.15)	308 (0.28)	326 (0.51)	351 (0.82)
Constant emissions, ppm (°C)							
CO_2 (δT) by 2000	307 (0.22)	316 (0.32)	329 (0.43)	336 (0.48)	374 (0.71)	387 (0.76)	387 (0.76)
CO_2 (δT) by 2100	317 (0.35)	332 (0.51)	353 (0.75)	367 (0.89)	465 (1.89)	524 (2.46)	573 (2.9)

Also shown is the long-term commitment (up to 2500) for the zero-emissions case.

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emissions strategy had been adopted. The rate of increase in CO_2 emission was largest for the 1950–1975 generation (before the first oil crisis). Keeping emissions constant at the 1975 level would lead to an atmospheric CO_2 level of 465 ppm by 2100, or $\approx$100 ppm more than what would be reached if emissions had been capped at the 1950 level (Table 1). Capping the emissions at the year 2000 level would add 60 ppm in the atmosphere, whereas doing the same by 2025 would add another $\approx$50 ppm. We also note that the difference in estimated CO_2 by 2100 if the current and future 21st-century generations were to adopt a zero-emissions versus a constant-emissions strategy is almost 200 ppm (573 versus 382 ppm). Thus, Fig. 3 and these examples show how current and near-future actions on CO_2 emissions are expected to have a very large impact on atmospheric CO_2. In the next section we show how these actions will affect the climate experienced by the next several generations.

Estimated Temperature Changes. Fig. 4 shows estimated temperature changes due to the calculated carbon dioxide time series presented in Fig. 3. In terms of contributions to current warming caused by carbon dioxide increases, Fig. 4 illustrates that the past two generations (1950–1975 and 1975–2000) are believed to share much of the responsibility for the present-day CO_2-induced warming. Currently, globally averaged warming since 1850 is estimated to be 0.6 ± 0.2°C, reflecting contributions to warming and cooling from CO_2 and other radiative forcing agents not considered here (8). Thus, the currently observed warming is comparable to the values shown for 2000 in Fig. 4. The temperature change caused by the first 4 generations from 1980 to 1950 represents $\approx$0.27°C, or approximately one third of the total estimated CO_2-induced warming in 2000. The 1950–1975 generation added $\approx$0.23°C, and the 1975–2000 generation added another 0.25°C.

Because of the time response of the carbon cycle shown above along with the response times of the climate system (particularly linked to the lags between oceanic and atmospheric temperature), if emissions were set to zero by 2000, temperature would still keep increasing by another several tenths of a degree Celsius for another $\approx$30 years (Fig. 4), although atmospheric CO_2 would display some decrease (Fig. 3). Thus, the comparison between Figs. 3 and 4, particularly the shapes of the curves after cessation of emissions in the two cases, illustrates the character and duration of the warming commitment. Different climate models suggest quantitative differences in the magnitude and duration of the existing warming commitment, believed to be linked largely to differences in representations of ocean/atmosphere interactions, but the general behavior shown in Fig. 4 is robust across models (e.g., see refs. 27 and 28).

Stated differently, Fig. 4 underscores the character of the warming commitment: today's observed climate change represents a portion rather than the total of what is expected to occur in the future even if emissions of CO_2 are reduced dramatically. Although the warming commitment implies that near-term actions do not have an immediate effect on CO_2-induced climate change, Fig. 4 shows that they do have an affect within a few decades (i.e., on the time scale of the next assumed generation). This change occurs because CO_2 removal is characterized by multiple time scales, i.e., a portion of the emitted CO_2 is removed on time scales of decades.

Thus, the difference between cutting emissions to zero in 2025 and continuing constant emissions is $\approx$0.5°C of added warming by approximately 2050. Because of additional removal of CO_2 on longer time scales, the difference reaches 1.6°C by 2100. That is, cutting the emissions of CO_2 to zero in 2025 leads to a total warming of 1.3°C by 2100, with a peak value of 1.4°C around 2050, whereas capping emissions at their 2025 level leads to a warming of $\approx$1.9°C by 2050 and 2.9°C by 2100. Thus, the actions of each generation influence the climate passed on to their children and later generations, but each inherits much of their own climate. Fig. 4 illustrates how this also applied for the last generation. Constant emissions after 2000 lead to a warming of 1.7°C higher than with zero emissions by 2100.

Summary

This article has probed some simple ways in which time scales influence how carbon dioxide emissions lead to future commitments to a warmer climate. There is an existing and substantial commitment to additional CO_2-induced climate change that is expected to dominate the global average temperature changes in the next several decades. Stated differently, the current human generation is already committed to greater CO_2-induced warming in decades to come than that observed today.

Warming commitments are linked to several factors. One is the commitment of the physical climate system to additional changes in response to the radiative forcing linked to increased concentrations of carbon dioxide. The physical constraints on how each generation passes climate change to the next (even if emissions had been constant or zero) are tied to the time responses of carbon dioxide as well as those of the climate system. In the absence of other changes (such as changes in shorter-lived radiative forcing agents, including human-made contributions to aerosols, methane, or tropospheric ozone, or natural forcings such as volcanic cooling), global mean temperatures are expected to increase by several tenths of a degree Celsius in coming decades as a result of this commitment.

Fig. 2 shows that estimated CO_2 emissions have increased with each passing generation during the 20th century. Although not explicitly probed here, it is evident that these increases in emissions are linked to a different type of commitment: that to energy sources and practices. We emphasize that the zero- and constant-emissions cases assumed here are not realistic and serve only to elucidate the physical-science aspects of the warming commitment.

The simple calculations shown here illustrate that each past generation has inherited substantial climate change caused by carbon dioxide increases that occurred previously. Although substantial quantitative uncertainties are associated with the highly simplified approach taken in this article, the results are qualitatively robust and linked to basic physical considerations. They serve to illustrate how each human generation to date has added to carbon dioxide concentrations, thereby passing increasing warming commitments on to its children, grandchildren, and later descendants. Thus, today's carbon dioxide emissions can be expected to contribute significantly to the climate to be experienced by future generations.

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