Climatic Change (2008) 90:283–297
DOI 10.1007/s10584-008-9413-1

The millennial atmospheric lifetime of anthropogenic CO_2

David Archer · Victor Brovkin

Received: 19 December 2006 / Published online: 4 June 2008

Abstract The notion is pervasive in the climate science community and in the public at large that the climate impacts of fossil fuel CO_2 release will only persist for a few centuries. This conclusion has no basis in theory or models of the atmosphere/ocean carbon cycle, which we review here. The largest fraction of the CO_2 recovery will take place on time scales of centuries, as CO_2 invades the ocean, but a significant fraction of the fossil fuel CO_2, ranging in published models in the literature from 20–60%, remains airborne for a thousand years or longer. Ultimate recovery takes place on time scales of hundreds of thousands of years, a geologic longevity typically associated in public perceptions with nuclear waste. The glacial/interglacial climate cycles demonstrate that ice sheets and sea level respond dramatically to millennial-timescale changes in climate forcing. There are also potential positive feedbacks in the carbon cycle, including methane hydrates in the ocean, and peat frozen in permafrost, that are most sensitive to the long tail of the fossil fuel CO_2 in the atmosphere.

1 Introduction

The ocean contains 50 times more dissolved oxidized carbon than the atmosphere does, and 70% of the surface of the earth is covered by ocean. For these reasons, the prevalent opinion among earth scientists in the early twentieth century was that the oceans would prevent industrial activity from increasing the pCO_2 of the atmosphere. This view prevailed until precise measurements of free-atmosphere pCO_2 values showed an increasing trend of (at that time) 0.8 ppm yr^{-1} (Keeling 1961).

D. Archer (✉)
Department of the Geophysical Sciences, University of Chicago, 5712 S Ellis, Chicago, IL, USA
e-mail: d-archer@uchicago.edu

V. Brovkin
Potsdam Institute for Climate Impact Research, P. O. Box 601203, Potsdam, Germany

Present address:
V. Brovkin
Max Planck Institute for Meteorology, Bundesstr. 55, 20146 Hamburg, Germany

At about the same time as the first accurate pCO_2 measurements, Revelle and Suess (1957) showed that the uptake of CO_2 into seawater is enhanced by carbonate buffer chemistry, but only one tenth as strongly as might be naively inferred from the relative concentrations of carbon in the air and in the water. Most of the carbon dissolved in seawater is in the form of bicarbonate, rather than in the form of carbonate ion, which reacts to buffer CO_2 invasion. In the model results presented below, we will see that the CO_2 uptake capacity of the ocean diminishes with increasing CO_2 release, because of the depletion of the carbonate ion content of the ocean.

To make matters worse, the rate of CO_2 uptake by the oceans is much slower than might be inferred from the large surface area of the oceans. Only a small area of the ocean communicates with the largest "pool" of water, the deep sea. Therefore the equilibration time between the atmosphere and the ocean is several centuries, much longer than one might naively expect by simply looking at a globe, or at a "blue planet" photograph from space.

Carbon cycle models respond to a release of new CO_2 into the atmosphere in a series of several well-defined stages lasting for many millennia (Fig. 1; Archer et al. 1998; Broecker and Takahashi 1978; Caldeira 1995; Caldeira and Rau 2000; Sundquist 1990; Sundquist 1991; Tans and Bakwin 1995; Walker and Kasting 1992). The CO_2 in the atmosphere through this time will not consist of the exact same CO_2 molecules emitted from fossil fuel combustion, because of the copious exchange of carbon with the ocean and the land surface. However, the CO_2 concentration in the air remains higher than it would have been, because of the larger inventory of CO_2 in the atmosphere/ocean/land carbon cycle.

We present a summary of long-term carbon cycle models from the recently published literature (Table 1). Some of the models are more detailed than others, and the models make different assumptions about the responses of the terrestrial biosphere, and the ocean circulation, to climate changes. We also show new results from the CLIMBER model (Fig. 2).

The model results are sorted according to the amount of CO_2 released, into "Moderate" and "Large" CO_2 slugs. Moderate is 1,000–2,000 gigatons of carbon (Gton C), while Large is 4,000–5,000 Gton C. For comparison, the IPCC business-as-usual scenario (*SRES A1B*)

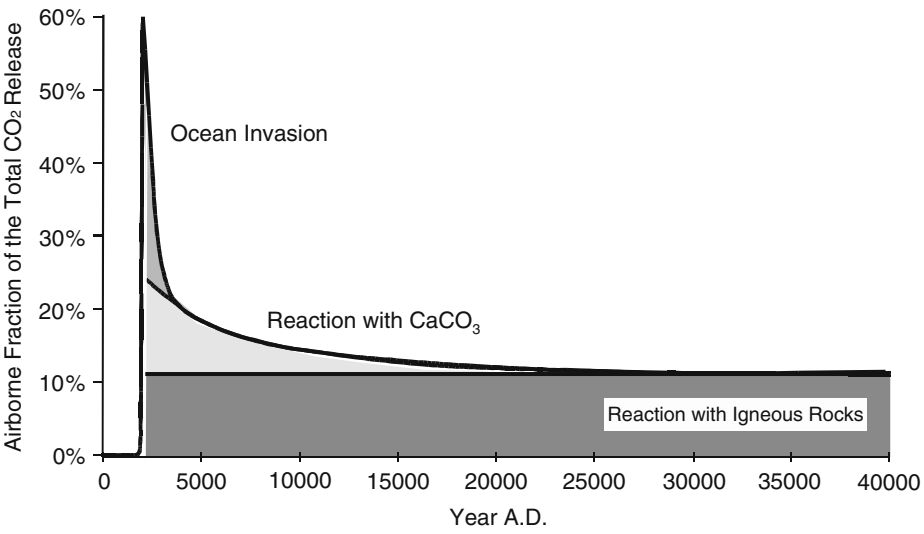

Fig. 1 Schematic breakdown of the atmospheric lifetime of fossil fuel CO_2 into various long-term natural sinks. Model results from Archer (2005)

Table 1 Model characteristics

	Changing ocean circulation	Carbon uptake by terrestrial biosphere	Sediments	Weathering feedback	Dimension
CLIMBER	Yes	Disabled	Yes	Yes	2D atmosphere/ocean, zonal mean seafloor
(Archer 2005)	No	No	Yes	No	3D ocean, 2D seafloor
(Lenton and Britton 2006)	No	Yes	Yes	Yes	Box ocean, box seafloor
(Ridgwell and Hargreaves 2007)	Yes	Yes	Yes	Yes	3D ocean, 2D seafloor
(Tyrrell et al. 2007)	No	No	Yes	No	Box ocean, box seafloor
(Goodwin et al. 2007)	No	No	No	No	3D ocean
(Eby et al., in preparation)	Yes	Yes	Yes	Yes	3D ocean, 2D seafloor

winds up releasing about 1,600 Gton C to the atmosphere by the year 2100. Business-as-usual to 2100 is generally considered to be a large carbon release, rather than moderate, but it is actually moderate relative to the available coal deposits, which total about 5,000 Gton C (Rogner 1997). Frozen methane hydrate deposits in the ocean may contain another

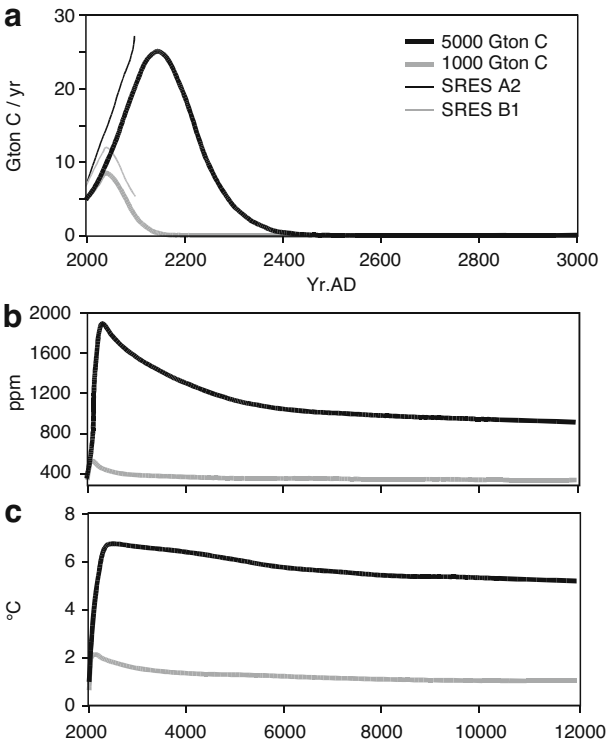

Fig. 2 A response of CLIMBER-2 model (Brovkin et al. 2002; Brovkin et al. 2007; Ganopolski et al. 1998) to Moderate (1,000 Gton C) and Large (5,000 Gton C) fossil fuel slugs. The equilibrium climate sensitivity of the model is 2.6°C. Temperatures were smoothed with a 250 filter to eliminate a spurious fluctuation of Antarctic sea ice caused by the low model resolution. The land carbon cycle was neglected in these simulations while deep sea sediments were explicitly simulated using a sediment diagenesis model (Archer 1991). **a** Emissions scenarios and reference IPCC SRES scenarios (B1 and A2). **b** Simulated atmospheric CO_2 (ppmv). **c** Simulated changes in global annual mean air surface temperature (°C)

5,000 Gton C (more about which below). Humankind has already released about 300 Gton C from fossil fuels and deforestation (Canadell et al. 2007).

2 An informal model intercomparison on the fate of fossil fuel CO_2

2.1 The CO_2 peak

The first stage can be called the CO_2 peak, after the CO_2 is released to the atmosphere but before it equilibrates with the ocean. The land surface may take up some excess carbon by virtue of the longer growing season in a warmer world, or it could release carbon as the soil respiration rate increases. In either case the potential for fossil fuel carbon uptake by the land surface is limited by the relatively small size of the terrestrial carbon pool and by ongoing deforestation (Table 2).

A typical ocean surface mixed layer is 100 m deep, and it will equilibrate with the atmosphere (that is, take up as much CO_2 as it will) in about a year. But most of the volume of the ocean is beneath the surface layer, and to get there, fossil fuel CO_2 has to wait for the overturning circulation of the ocean, which takes centuries or a millennium.

Of the 9 Gton C/year carbon release from fossil fuels and deforestation from the year 2000 to 2006, 5 Gton C/year is taken up naturally, half by the ocean and half into the terrestrial biosphere (Canadell et al. 2007). One might conclude from these numbers that the uptake time for CO_2 must be only a few years, but this would be a misconception. The rate of natural CO_2 uptake in any given year is not determined by the CO_2 emissions in that particular year, but rather by the excess of CO_2 in the atmosphere that has accumulated over the past century. The lifetime of the CO_2 can be gauged by the amount of time that the CO_2 has been waiting, which is longer than just a few years. The models find that CO_2 peak will come and fade on a time scale of a few centuries to millennia.

Table 3 summarizes the magnitudes of the CO_2 peaks from the model atmosphere/ocean equilibrium simulations. The CO_2 inventories are expressed as percentages of the total amount of CO_2 released throughout the model simulation, which we will call the maximum airborne fraction.

Because this is a review of published model results and not a formal model intercomparison, there are many reasons to expect the model results to differ from each other. For example, the maximum airborne fraction is sensitive to the time scale over which the CO_2 is released. If the release were instantaneous, say, then the moment after the release

Table 2 Sizes and response times of various carbon reservoirs in the carbon cycle

	Inventory, Gton C	Response time
Atmosphere	700	
Ocean	38,000	Exchanges with atmosphere in centuries
Land biosphere	500	Responds to climate in decades
Unfrozen soil	15,000	Decades
Permafrost soil	400	Melts and peat degrades over centuries
Ocean methane hydrates	1,000–10,000	Millennia or longer
Oil	200	Will be depleted in decades
Natural gas	200	Decades
Coal	5,000	A few centuries at current rates

Table 3 Maximum airborne fraction of CO_2 slugs

	1,000–2,000 Gton	4,000–5,000 Gton
CLIMBER, this paper	52%	67%
(Archer 2005)	58%	60%
(Lenton and Britton 2006)	50–63%	67–75%
(Ridgwell and Hargreaves 2007)		50%
(Tyrrell et al. 2007)		70%
(Eby et al., in preparation)	45%	75%

the airborne fraction would be 100%. If the CO_2 was released very slowly on the other hand, then invasion into the ocean could keep up, and the maximum airborne fraction would be much lower. The models typically assume that CO_2 will be released following bell curve logistic functions, analogous to following the Hubbert's peak trajectory characteristic of oil extraction (Deffeyes 2001). The details of the release trajectories differ among the models, however, contributing in some part to the overall range of model results. The rate of CO_2 release in the models typically tails off around the year 2300 for the Large release scenarios.

In spite of all the differences between the models, the maximum airborne fractions are quite consistent (Table 3). The maximum airborne fractions of the runs range from 45% to 75%. For Moderate CO_2 slugs of 1,000–2,000 Gton C, the models predict 50–60% maximum airborne fraction. For Large slugs of 4,000–5,000 Gton C, the models predict 50–75%.

2.2 CO_2 partition between the atmosphere and the ocean

After the peak passes, a substantial fraction of the released CO_2 slug remains in the atmosphere. Eventually, the excess CO_2 will be consumed by chemical reactions with $CaCO_3$ and igneous rocks, but this takes thousands of years. An intermediate stage, convenient for model intercomparison, is the airborne fraction of the CO_2 as it partitions between the atmosphere and the ocean, with no effects from sediments at all. Table 4 summarizes the results of a number of atmosphere/ocean carbon cycle models.

If the ocean were infinitely large, or the buffer chemistry of seawater infinitely strong, then the ocean could sop up all of the fossil fuel CO_2, and global warming would subside completely in a few centuries. With the size and chemistry of the ocean carbon reservoir as they are, however, a significant fraction of a CO_2 release remains in the atmosphere after

Table 4 Airborne fraction of a CO_2 slug after it has reached atmosphere/ocean equilibrium (no sediments)

	1,000–2,000 Gton	4,000–5,000 Gton
CLIMBER, this paper	22%	34%
(Archer 2005)	22%	33%
(Lenton and Britton 2006)	21–26%	34%
(Goodwin et al. 2007)	24–26%	40%
(Ridgwell and Hargreaves 2007)		34%
(Montenegro et al. 2007)		52%

the ocean has taken its fill. The studies predict that 20–25% of a Moderate carbon release would reside in the atmosphere in atmosphere/ocean equilibrium. When the release is Large, the buffering capacity of the ocean is depleted and the airborne fraction of the CO_2 slug rises to 30–40%. If the world consisted only of atmosphere and ocean, the airborne fractions of fossil fuel CO_2 in Table 4 would remain airborne forever.

2.3 Long-term buffering by sediments and weathering

After the invasion of fossil fuel CO_2 into the ocean, the acidity from the CO_2 provokes the dissolution of $CaCO_3$ from the sea floor (Archer et al. 1998; Broecker and Takahashi 1978). The warmer, wetter climate on land may also accelerate the rate of $CaCO_3$ dissolution (chemical weathering) on land (Lenton and Britton 2006; Walker and Kasting 1992). In the models, it takes thousands of years for this imbalance to restore the pH of the ocean to a natural value. Restoring the pH also replenishes the buffering ability of seawater to store more CO_2, so the airborne fraction of the fossil fuel CO_2 drops a bit further (Ridgwell and Hargreaves 2007).

At the end of the neutralization stage, the atmosphere still contains more CO_2 than it held before the fossil fuel era. The rest of the CO_2 awaits reaction with calcium oxide (CaO) component of igneous rocks. CO_2 is extracted from the atmosphere by these reactions and winds up on the sea floor in $CaCO_3$ deposits (Berner et al. 1983; Berner and Kothavala 2001; Walker et al. 1981). This final piece of the CO_2 tail takes hundreds of millennia to subside.

Rather than attempt to deconvolve the CO_2 drawdown into these two mechanisms, we tabulate the forecasts from the various carbon cycles models as a function of time in Table 5. The airborne fraction at 1,000 years might be higher than the atmospheric/ocean equilibrium value in Table 3, if the invasion of CO_2 has not proceeded to completion by this time, or it could be lower, if significant dissolution of $CaCO_3$ has taken place. For Moderate CO_2 slugs, the models predict that 15–30% of the CO_2 we release to the atmosphere in the coming decades will still reside in the atmosphere 1,000 years from now, dropping to 11–14% after 10,000 years. For a Large release, the airborne fraction increases, to 30–60% a 1,000 years, and 10–25% at 10,000 years.

Table 5 Airborne fraction of a CO_2 slug 1,000 and 10,000 years from now

	1,000 years	10,000 years
1,000–2,000 Gton Release		
CLIMBER, this paper	29%	14%
(Archer 2005)	24%	11%
(Lenton and Britton 2006)	17–19%	11%
(Eby et al., in preparation)	30%	17%
4,000–5,000 Gton C release		
CLIMBER, this paper	57%	26%
(Archer 2005)	33%	15%
(Lenton and Britton 2006)	14–16%	10–15%
(Ridgwell and Hargreaves 2007)	34%	12%
(Tyrrell et al. 2007)	42%	21%
(Eby et al., in preparation)	60%	30%

3 Implications

3.1 Avoiding dangerous climate change

The peak airborne fraction results in Table 3 translate directly into maximum allowable CO_2 emissions, if we are to avoid "dangerous climate change". A warming of 2°C has been proposed as a benchmark for a dangerous climate change (Caldeira and Wickett 2005; Schellnhuber et al. 2006), although a warming of only 1°C would certainly be preferable (Hansen et al. 2006; Hansen 2006). A warming of 2°C would be decidedly warmer than the Earth has been in millions of years. Previous interglacials in the ice core records never exceeded 1°C warmer than preanthropogenic, but even this amount of warming was sufficient to raise sea level by 4–5 m (more about this below).

Assuming an equilibrium climate sensitivity of 3°C from doubling atmospheric CO_2, and 90% of the equilibrium warming at the time of the CO_2 peak from the Climber model, and also neglecting other anthropogenic greenhouse gases, it would take an atmospheric pCO_2 of about 490 ppm to keep the global warming below the 2°C danger limit. This corresponds to about 400 Gton C of anthropogenic carbon in the atmosphere. If we divide 400 Gton C by a maximum airborne fraction of 55%, we calculate a maximum allowable total emission of about 700 Gton C, of which 300 Gton C has already been released, if we are to avoid dangerous climate change at any time in the future.

This is a more restrictive estimate than we would get if we limited our scope to the year 2100 and earlier, because the Earth takes several centuries to warm. As CO_2 rises, the warming lags behind, largely because of the thermal inertia of the ocean. The warming we have experienced so far today is only about 60% of the equilibrium warming expected at today's atmospheric CO_2 value (Hansen et al. 2005). A 40% warming lag will also exist in the year 2100. Limiting our concern to what happens between now and the year 2100, neglecting what comes after, results in a substantial increase of the calculated allowable emissions, to about 1,050 Gton C. This calculation seems rather callous, given the inevitability of the eventual warming once the CO_2 is released, but it is the perhaps unintended consequence of limiting the scope of consideration to the year 2100.

3.2 Sea level

The longevity of the CO_2 perturbation to the atmosphere also has implications for the future of sea level. Figure 3 shows sea level changes correlated with changes in global average temperature, from the geologic past following Alley et al. (2005) and forecast for the future.

Looking into the past, during glacial time 18,000 years ago, sea level was 120 m lower than today, and the Earth was 5–6°C colder. Further back in time, during the last interglacial (Eemian) time, sea level was perhaps 4–5 m higher than it is today, when the Earth was perhaps 1°C warmer (Jansen et al. 2007). Prior to this, 3 million years ago, before our current interval of glacial/interglacial cycles, sea level was 20 m higher.

During the Eocene optimum warm climate about 40 million years ago, there were no ice sheets. Sea level on time scales of tens of millions of years is impacted by the configuration and changes in elevation of the continents, and perhaps also by release or uptake of water by the mantle. Following Alley et al. (2005), we base the sea level change estimate for the Eocene optimum on the present-day configuration of the continents, by taking the sea level rise expected if our ice sheets were to melt entirely, about 70 m.

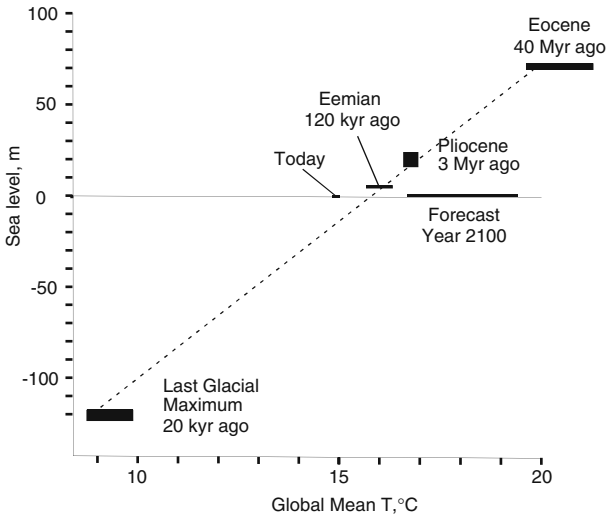

Fig. 3 The relationship between sea level and temperature on geologic time scales. Data from (Alley et al. 2005)

There is a clear and strong correlation between long-term global average temperature and sea level in the geologic record. Sea level has the potential to change much more than is forecast for the coming century, and it has done so in the past. The slope of covariation from the geologic record has been 10–20 m/°C. Of course, there is a world of complexity that is collapsed into this simple figure. The responses of individual ice sheets to rising global temperature will depend on their locations. The stability or instability of the West Antarctic ice sheet for example depends on the physics of its submarine grounding line (Oppenheimer 1998), as it might be affected by warmer water or higher sea level. Ice volume no doubt depends on the configuration of Earth's orbit, and (in deeper time) on the arrangement of the continents and oceans.

Another complication is that ice sheets do not grow and decay simply and linearly with global average temperature. During Heinrich events, the Laurentide ice sheet surged into the ocean in response to no evident climate forcing at all. Once an ice sheet forms, its high albedo tends to stabilize it, perpetuating its own existence. However, this effect did not save the Eemian world from 4–5 m of sea level rise in a world only about 1°C warmer than preanthropogenic, nor is it evident at any other time in the past from Fig. 3. In spite of the potential complications, the figure shows a clear correlation between global temperature and sea level in the geologic past.

The forecast for the coming century is for only 0.2–0.5 m under business-as-usual (A1B scenario), in spite of a temperature change of 3°C (Solomon et al. 2007). The sea level response to global temperature is one hundred times smaller than the covariaton in the past. The contrast between the past and the forecast for the future is the implicit assumption in the forecast that it takes longer than a century to melt a major ice sheet.

There are reasons to believe that real ice sheets might be able to collapse more quickly than our models are able to account for, as they did during Meltwater Pulse 1A 19 kyr ago (Clark et al. 2004) or during the Heinrich events (Clark et al. 2004), neither of which are well simulated by models. Ice sheets are also demonstrating tricks today which models don't predict in advance, such as accelerating flow (Zwally et al. 2002) and seismic rumbling (Ekstrom et al. 2006) following the seasonal cycle in Greenland. Ice shelves such as the Larsen B on the Antarctic peninsula collapse catastrophically, and the ice streams that

flow into them accelerate (Bamber et al. 2007). Recognizing the insufficiency of current ice sheet models to simulate these phenomena, IPCC excluded what they call "dynamical changes in ice sheet flow" from their sea level rise forecast.

Regardless of whether sea level rise in the coming century could be higher than predicted, if we consider that warming from CO_2 release persists for hundreds of millennia, we have plenty of time to change sea level. Using a model of the coupled atmosphere/ocean/ice sheet system, Archer and Ganapolski (2005) showed that the climate forcing from the long tail of a large CO_2 release is comparable to the climate forcing from orbital variations, capable of overwhelming the natural evolution of ice ages for 500,000 years into the future. We would not argue for the benefits of a glaciation, but rather draw the conclusion that natural cooling is unlikely to offset the warming tendency of global warming, into the immense future.

The temperature of the Earth in the distant future can be estimated from the CO_2 concentrations, using an estimate of the climate sensitivity, ΔT_{2x}. These results are tabulated in Table 6. For a 2,000 Gton C release, assuming ΔT_{2x} of 3°C, and an airborne fraction of 25%, we find that the Earth would remain about 3°C warmer than natural, 1,000 years into the future. For a release of 5,000 Gton C, we get 3°C for 10,000 years, assuming a 20% airborne fraction at that time. Ice sheets might be able to survive a warming event 1,000 years long, but 10,000 years is long enough for even a sluggish ice sheet model to respond to a global warming. If the past is the key to the future, 3°C of warming could raise sea level by 50 m or more, eventually.

McGranahan et al. (2007) find that sea level rise of only 10 m would displace 10% of the world's population. Fifty meters of sea level rise resulting from say 5,000 Gton of carbon works out to about 10 cm^2 of area lost per kilogram of carbon. A gallon of gasoline burned floods about 50 cm^2. The average American household emits enough CO_2 to ultimately flood several hundred meters, its own living area, every year.

3.3 Long-term positive feedbacks in the carbon cycle

Thousands of years will also be enough time to bring about deep changes to the carbon cycle. Feedbacks in the carbon cycle had major impact on the evolution of the glacial/interglacial climate cycles, by ways and means that are not very well understood, amplifying the forcing from orbital variations and changing ice sheets (Torn and Harte 2006). One piece of the ice-age carbon cycle puzzle must be the solubility dependence of CO_2 on temperature (Martin et al. 2005). On long time scales into the future, we should worry that similar positive feedbacks will manifest themselves (Scheffer et al. 2006).

A vast inventory of methane exists frozen into hydrates or clathrates buried in sediments of the ocean margin, ranging in depth from 0.5–3 km water depth (Kvenvolden 1988). The amount of methane is staggering, with estimates ranging from 1,000 to 10,000 Gton C (Archer 2007; Milkov 2004). A release of just 500 Gton C in the form of methane to the atmosphere within a few years would be the radiative equivalent of a ten-fold increase in CO_2 concentration.

Table 6 Long-term temperature implications of fossil fuel CO_2 release, summary of results of all models

	1,000 years	10,000 years
2,000 Gton C release	>3°C	>1.5°C
5,000 Gton C release	>5°C	>3°C

Fortunately, no one has thought of a mechanism by which a substantial fraction of the hydrate reservoir could be released to the atmosphere all at once (Harvey and Huang 1995). Most of the hydrates in the ocean are submerged in over 500 m of water and a few hundred meters of sediment, where it should be insulated from climate warming for several thousand years. When hydrate melts it produces methane bubbles, which might migrate through the sediment column to the ocean, and perhaps some fraction could reach the atmosphere, but this is easier to imagine as a slow, chronic release of methane, analogous to wetland emission, rather than a sudden release of a catastrophic amount of methane. Submarine landslides might allow hydrate to float to the ocean surface, to melt and release its methane to the atmosphere (Brewer et al. 2002). The amount of methane that could be released in a single landslide is small, however, compared to the atmospheric inventory of methane (Archer 2007).

On geologic time scales, however, it is difficult to imagine a return to the hothouse climates of the distant past without provoking the eventual release of some of the carbon in present-day hydrates. Hydrate methane that is oxidized to CO_2 in the ocean will equilibrate with the atmosphere after a few centuries, accumulating alongside the fossil fuel CO_2. The fate of the hydrates in a warming world is not well constrained, but Archer and Buffett (2005) found that in the worst case, the hydrate reservoir could release as much carbon as we do by burning fossil fuels, thereby amplifying the long tail of the human-released CO_2 impact on climate.

Permafrost soils in the Arctic have large thermal inertia, and will be most profoundly impacted on long time scales. The frozen condition protects a substantial reservoir of peat deposits, estimated to be 350–450 Gton C (Stockstad 2004). With a thaw will come accelerated decomposition of this organic matter, increasing the flux of CO_2 and CH_4 (Liblik et al. 1997; Rivkina et al. 2004; Rivkina et al. 2000), potentially leading to another positive feedback to anthropogenic warming (Walter et al. 2006).

3.4 Geoengineering climate

It would be technologically possible to lower the temperature of the Earth by deliberate injection of aerosols into the stratosphere where they would scatter some fraction of sunlight back to space. The idea is not new but received renewed interest following the recent advocacy paper by Crutzen (2006). The impacts of stratospheric haze on climate are well known, based on the measurable and predictable climate response to volcanic eruptions, in particular Mount Pinatubo (Soden et al. 2002).

Climate engineering might be practical for a few centuries, but not for hundreds of thousands of years. The lifetime of aerosols in the stratosphere is only a few years, so that engineering the climate by this means would require an ongoing effort. Other strategies, such as mirrors at the Legrange point between the Earth and the sun, would require similar ongoing maintenance. If the artificial cooling stopped at some point in the future, due to some recession or breakdown of society, the accumulated CO_2 emissions in the atmosphere would generate a massive warming within a few years (Brovkin et al., submitted). The only geoengineering strategy that would really solve the problem on the long term would be to remove CO_2 from the atmosphere.

4 Discussion

4.1 A widespread misconception

The notion that global warming will last only a few centuries is widespread in the popular and even in the scientific literature on global warming. This misconception

may have its roots in an oversimplification of the carbon cycle. The atmosphere today contains about 200 Gton C in excess of the natural 1,750 value. The ocean takes up 2 Gton C per year, while the land surface, including deforestation, is currently in near balance. If the ocean were going to take up all of the CO_2 following a simple first-order kinetics rate law, the CO_2 drawdown would follow a decaying exponential trajectory, and the e-folding time for the uptake would be determined by dividing 200 Gton C by 2 Gton C/year, to yield about 100 years. The fallacy of this reasoning is that the real carbon uptake follows a sum of exponentials, rather than a single exponential decay. After the fastest exponential decay is finished, there is still CO_2 left in the atmosphere awaiting slower uptake mechanisms.

The treatment of the atmospheric lifetime of CO_2 was substantially revised in the most recent IPCC Scientific Assessment Report in 2007 (Solomon et al. 2007). Previous Assessment Reports recognized the long tail to the CO_2 peak in the detailed chapters, but listed an atmospheric lifetime of 50–200 years in the First Assessment Report in 1995, revised to 5–200 years in the Second and Third Assessment Reports. The caveat was given in the Third Assessment Report that "No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes", but the existence of the long tail was easily missed by most readers.

Confusion of net versus gross carbon fluxes can also lead to a conclusion of a short CO_2 lifetime. The lifetime of an individual CO_2 molecule released to the atmosphere may be only a few years, because of exchange fluxes with the ocean and with the terrestrial biota. Carbon dissolves in the ocean in one place, and different carbon evaporates to the atmosphere someplace else. Each year, about 100 Gton C is exchanged between the atmosphere and the ocean, while the net invasion of CO_2 from the atmosphere into the ocean is only about 2 Gton C per year (Denman et al. 2007). However, exchange of carbon has no impact on climate, only net uptake of carbon. The lifetime of climate impacts from CO_2 release will be much longer than the lifetime of the particular CO_2 molecules we release. The 5-year low end estimate of the lifetime of CO_2 from the 2001 IPCC must be an exchange lifetime, rather than an invasion lifetime.

4.2 Analogous issues

Persistence is a central consideration in many other environmental issues. The clearest analogy is to nuclear power and the waste products that it generates. Most of the radioactive products of nuclear fission are relatively short-lived. The highest activity nuclides in the Chernobyl reactor, for example, were xenon-133 (5 days), neptunium-239 (2.3 years), molybdenum-98 (66 days), and cerium-141 (32 days), in decreasing order of activity (Kirhner and Noack 1988). However, there is a component of nuclear material that has much longer lifetime, such as the isotopes plutonium 239 (24,000 year half-life), thorium 230 (80,000 years), and iodine 129 (15.7 million years). Ideally, these substances must be stored and isolated from reaching groundwaters until they decay, but the lifetimes are so immense that it is hard to believe or to prove that this can be done.

In the discussion of climate change, it seems easy to ignore the climate changes in the distant future, either explicitly using a discount rate in some economic model, or implicitly by recognizing that none of us will personally witness the climate impacts from fossil fuels a thousand years from now anyway. It seems to us that this position is less commonly taken in discussion of nuclear energy. If the lifetime of nuclear waste were only a century, instead of tens of millennia, that would probably make a substantial difference in many people's opinions of nuclear power.

The majority of the CO_2 we release, about 75%, will disappear into the oceans on a time scale of a few centuries, and so perhaps it is natural to neglect the long tail on the CO_2 lifetime. The same mistake applied to nuclear energy would lead us to the conclusion that nuclear waste is short-lived also. Nearly all of the radioisotopes released by Chernobyl, 97%, had a half-life of two weeks or less. To claim based on this that nuclear material only lasts two weeks would clearly be a gross, and deceptive, oversimplification.

DDT and other organochlorine pesticides are not very toxic to mammals when they are applied. Their specificity to insects such as malaria-spreading mosquitoes led to their praise as miraculous by Winston Churchill during World War II. In 1962 Rachel Carson published Silent Spring, in which she made the case that the persistence of DDT created unanticipated problems of bioaccumulation in birds and mammals. Current pesticides are designed to limit their lifetimes in the environment. Some, such as the organophosphates, substitute short-term toxicity for long-term persistence.

Freons are another example of a pollutant for which persistence is a central consideration. Engineered to be inert, the ultimate problem with freons arose because of their eventual transport to the stratosphere, where their breakdown product, chlorine radical, catalyses ozone destruction. Again, their replacements, hydrochlorofluorocarbons, substitute short-term toxicity (in the form of a breakdown product called trifluoroacetic acid), for dangers associated with persistence (Dekant 1996; Tsai 2005).

5 Conclusion

The model studies we reviewed here differ substantially from each other in parameterizations of oceanic and land carbon uptakes, the deep-sea sediment response, and emissions pathways. However, despite all these differences, the models agree that the substantial fraction of projected CO_2 emissions will stay in the atmosphere for millennia, and a part of fossil fuel CO_2 will remain in atmosphere for many thousands of years. Many slowly-responding components of the climate system, such as ice sheets and sea level, and ocean temperature and methane hydrates, will be most strongly affected by the longest-lasting component of the fossil fuel climate impact. Fossil fuels will be depleted on a time scale of centuries, decades perhaps for oil and natural gas, but the climate impacts will persist for longer than any of us can really imagine.

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