Millennial Atmospheric Lifetime of Anthropogenic CO_2

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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. Although the models vary widely in their formulation and underlying assumptions, they are quite consistent in their prediction that release of fossil fuel CO_2 will impact climate for tens of millennia and longer into the future, subsiding on time scales typically associated with nuclear waste. Many slowly-responding components of the climate system, such as ice sheets, deep ocean temperature, permafrost, and methane hydrates, will be sensitive to the long tail of the CO_2 climate impact. Most of the CO_2 drawdown will take place on time scales of centuries, as CO_2 invades the ocean, but it is too simplistic to call the invasion timescale the atmospheric lifetime of the CO_2, as is commonly done in popular and scientific discussion. We argue that a better shorthand for the lifetime of anthropogenic CO_2 would be "hundreds of years plus a significant fraction that changes climate forever".

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} (for current data see http://cdiac.esd.ornl.gov/trends/co2/contents.htm).

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 ocean. 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 several well-defined stages (Figure 1) [*Archer et al.*, 1998; *Broecker and Takahashi*, 1978; *Walker and Kasting*, 1992]. The first stage can be called the CO_2 peak. The CO_2 is released into the atmosphere, and it equilibrates with the ocean, all on a time scale of a few centuries. If the ocean were infinitely large, or the buffer chemistry of seawater infinitely strong, then the ocean could remove all of the fossil fuel CO_2 in its equilibration, and global warming would go away in a few centuries. With the size and chemistry of the ocean carbon reservoir as they are, however, the fraction of a CO_2 release that is left behind in the atmosphere after equilibration is not negligible at all.

After atmosphere / ocean equilibration comes what we will call the neutralization stage. The pH of the ocean is perturbed by the invasion of the acidic CO_2 [*Caldeira and Wickett*, 2005]. The acidity is neutralized by excess dissolution of $CaCO_3$ rocks, from the land surface or from the sea floor. The excess of $CaCO_3$ dissolution globally, on land and in the ocean, over the deposition of $CaCO_3$ in sediments of the deep sea, acts to replenish the carbonate ion content of the ocean. With replenishment of carbonate ion, the CO_2 storage capacity of the ocean increases, drawing CO_2 down a bit further. This stage takes several thousand years.

At the end of the neutralization stage, the atmosphere still contains more CO_2 than it held in the original natural steady-state (say, the year 1750). The rest of the CO_2 awaits reaction with the CaO component of igneous rocks, a process called the silicate weathering thermostat [*Berner and Kothavala*, 2001; *Berner et al.*, 1983; *Walker and Opdyke*]. This final piece of the CO_2 tail takes hundreds of millennia to subside.

The excess CO_2 concentration in the atmosphere of the deep future would not consist of the exact same CO_2 molecules emitted from fossil fuel combustion, because of the copious exchange of CO_2 among the atmosphere, the ocean, and the terrestrial biosphere and soils. However, the CO_2 remains elevated relative to the unperturbed concentration, because of the larger inventory of CO_2 in the atmosphere / ocean / land carbon cycle.

Model Intercomparison on the Fate of Fossil Fuel CO_2

The CO_2 Peak

Most of the CO_2 released to the atmosphere by combustion of fossil fuels or decreasing the size of the terrestrial biosphere will be removed from the atmosphere by dissolution in the ocean. The land takes up some excess carbon, but the potential for fossil fuel carbon uptake is limited by the relatively small size of the land carbon pool and by ongoing deforestation. Equilibration with the ocean is slow enough that fossil fuel emission into the atmosphere produces a temporary build-up of atmospheric CO_2. This CO_2 peak will come and go on time scales of centuries.

We present a summary of results from a variety of model simulations of the long-term evolution of fossil fuel CO_2 in the Earth system, through the CO_2 peak and into the deep future. To our knowledge this represents all of the appropriate published or soon-to-be published literature. Some of the models are based on full three-dimensional ocean

circulation [*Goodwin et al.*, ms], interacting with a two-dimensional sea floor [*Archer*, 2005], but most have been simplified, to span the long time scales involved [*Lenton and Britton*, 2006; *Ridgwell and Hargreaves*, submitted; *Tyrrell et al.*, submitted]. We illustrate our discussion with simulations of intermediate complexity model CLIMBER-2 which includes 2-dimensional ocean and sediment modules (Figure 2).

Table 1 summarizes the magnitudes of the CO_2 peaks from the available 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.

The model results are sorted according to the amount of CO_2 released, into "Moderate" and "Large" CO_2 slugs. Moderate is 1000-2000 gigatons of carbon (Gton C), while Large is 4000-5000 Gton C. For comparison, the IPCC business-as-usual scenario *(SRES A2?)* winds up releasing about 1600 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 5000 Gton C. Frozen methane hydrate deposits in the ocean contain another 5000 Gton C (more about which below). Humankind has already released about 300 Gton C.

The maximum airborne fraction is sensitive to the time scale over which the CO_2 is released. If the release were instantaneous, then the moment after the release the airborne fraction would be 100%. If the CO_2 was released very slowly, then invasion into the ocean could keep up, and the maximum airborne fraction would be much lower. The models assume that CO_2 will be released following bell curve logistic functions, analogous to Hubbert's peaks. The details of the release trajectories differ among the models, contributing in some part to the overall range of model results. CO_2 release typically tails off around the year 2300 or so for a Large release.

In spite of all the differences between the models, the maximum airborne fractions are quite consistent (Table 1). The maximum airborne fractions of the runs range from 45% to 75%. For Moderate CO_2 slugs of 1000-2000 Gton C, the models predict 50-60% maximum airborne fraction. For Large slugs of 4000-5000 Gton C, the models predict 60-70%. The impact of the terrestrial biosphere is most evident on the centennial timescale of the CO_2 peak, either smoothing the peak of amplifying it.

Intermediate Atmosphere / Ocean Equilibrium

After the peak passes, a substantial fraction of the released CO_2 slug remains in the atmosphere. The fossil fuel CO_2 is well mixed between the ocean and the atmosphere, but chemical reactions with carbonate and igneous rocks on land have not yet progressed to the extent that dissolution of $CaCO_3$ on land is balanced by deposition of $CaCO_3$ in the ocean. These weathering reactions are slow enough that in many models on a time scale of centuries they can reasonably be neglected altogether. Table 2 summarizes the results of a variety of ocean / atmosphere carbon cycle models, applied to the equilibrium partitioning of CO_2 released to the atmosphere. If the world consisted only of atmosphere and ocean, the atmospheric CO_2 concentration would remain at this equilibrium forever.

The studies predict that 20-25% of a Moderate carbon release would reside in the atmosphere in atmosphere / ocean equilibrium. If 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%.

Long-term Buffering by Sediments and Weathering

Natural cycles of weathering and sedimentation of limestone ($CaCO_3$) and igneous rocks will act to further remove a slug of anthropogenic CO_2 from the atmosphere, on time scales of thousands to hundreds of thousands of years. Reaction with $CaCO_3$ in the ocean [*Archer et al.*, 1998; *Broecker and Takahashi*, 1978] and on land [*Lenton and Britton*, 2006; *Walker and Kasting*, 1992] act to restore the pH of the ocean on time scales of millennia. Restoring the pH also replenishes the buffering ability of seawater to store CO_2, drawing CO_2 down below the atmosphere / ocean equilibrium value.

Reaction with the CaO component in igneous rocks results in the extraction of CO_2 from the atmosphere and deposition in sedimentary $CaCO_3$. This process is known as the silicate weathering thermostat (refs) and is responsible for the final drawdown of the fossil fuel CO_2.

Rather than attempt to deconvolve the different types of weathering processes into somewhat abstract "equilibrium" values, we tabulate the forecasts from the various carbon cycles models as a function of time. The airborne fraction at 1,000 years might be higher than the atmospheric / ocean equilibrium, if the invasion of CO_2 has not proceed 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.

Implications

Avoiding Dangerous Climate Change

The peak airborne fraction results in Table 1 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; *Hansen et al.*, 2006; *Hansen*, 2006; *Schellnhuber et al.*, 2006]. This would be decidedly warmer than the Earth has been in millions of years, and warm enough to eventually raise sea level by tens of meters (next section).

Assuming an equilibrium climate sensitivity of 3° C (and a 90% of the equilibrium warming during the CO2 peak), it would take an atmospheric pCO_2 of 470 ppm to keep the global warming below the 2° C danger limit. This would require 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 total emission of about 700 Gton C

(of which 300 Gton C is already 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. A 40% warming lag will also exist in the year 2100. Limiting our concern to the year 2100 and before, neglecting what comes after, results in a near-doubling of the calculated allowable emissions, to about 1050 Gton C. This calculation seems rather callous, almost sneaky, given the inevitability of warming once the CO_2 is released.

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, in the past and forecast for the future. During glacial time 18,000 years ago, sea level was 120 meters lower than today, and the Earth was 5-6° C colder. There was no ice in the northern hemisphere 3 million years ago, and the sea was 20 meters higher. During the Eocene optimum warm climate, there were no ice sheets, and sea level was 70 meters higher than today. The slope of covariation has been 10-20 meters per degree C.

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}. For a 2000 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, 1000 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. These results are tabulated in Table 4. If the past is the key to the future, 3° C of warming could raise sea level by 50 meters or more, eventually. 1,000 years might be pushing it but 10,000 years is certainly enough.

The forecast for the coming century is for only 0.5-1 meters, in spite of a temperature change of 3° C [*Houghton and Ding*, 2001]. The contrast with the data from the past is that it takes longer than a century to melt a major ice sheet, according to the ice sheet models used to generate the sea level rise forecast. 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. At any rate, if we consider that warming from CO_2 release persists for hundreds of millennia, we have plenty of time to change sea level. The correlation with the past seems to indicate that we could ultimately raise sea level by 50 meters.

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 half a million 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.

Long-term Positive Feedbacks in the Carbon Cycle

Permafrosts in the Arctic have large thermal inertia, and will be most profoundly impacted on long time scales. The ice complex, a subsurface sealed ice layer in Siberia, has been melting since the end of the last ice age, promoting intense erosion, called thermokarst, along the Siberian coast, releasing methane to the Arctic ocean [*Romanovskii et al.*, 2004]. Anthropogenic warming, amplified in high latitudes by the ice / albedo feedback, and especially warming of the Arctic ocean above the freezing point, will accelerate melting of permafrost soils. Permafrost protects peat and soil organic matter from chemical processing. Fossil mammoths, still edible after all these years, are examples of this phenomenon [*Herz*, 1904]. Peat deposits are a substantial reservoir of carbon, 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 a strong positive feedback to anthropogenic warming [*Walter et al.*, 2006].

Thousands of years will also be enough time to warm the deep ocean, with myriad geochemical and geophysical consequences [*Archer et al.*, 2004]. 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 kilometers water depth [*Archer*, in press]. The amount of methane is staggering; a release of just 10% of the methane to the atmosphere within a few years would be the radiative equivalent of a ten-fold increase in CO_2 concentration.

The impact of an increase in temperature would be to decrease the stability of hydrates at the base of the stability zone in the sediments, where the geothermal temperature gradient has already warmed the hydrate to the brink of melting. Methane bubbles produced from melting hydrate has the potential to remain in place, or it may migrate through the cold trap of the stability zone and escape to the ocean [*Flemings et al.*, 2003 Hornbach, 2004 #2692]. The most efficient way to transport hydrate methane to the atmosphere is by floating hydrate, which could be released from the sediment column in a landslide [*Brewer et al.*, 2002]. The amount of methane that could be released in a single landslide is small, however, and no one has proposed a mechanism by which a substantial fraction of the hydrate reservoir could be released to the atmosphere all at once [*Archer*, in press]. On time scales of centuries and millennia, however, the release of carbon from the hydrate reservoir could be substantial. Hydrate methane that is oxidized to CO_2 in the ocean will equilibrate with the atmosphere, contributing to and amplifying the long tail of the human-released CO_2 impact on climate [*Archer and Buffett*, 2005].

The carbon cycle interacted with ice ages in the past, by ways and means that are not very well understood, such that CO_2 changed to amplify the forcing from orbital variations and changing ice sheets (ref). One piece of the ice-age carbon cycle puzzle must be the solubility dependence of CO_2 on temperature. On long time scales into the

future, we should worry that similar positive feedbacks will manifest themselves [*Scheffer et al.*, 2006; *Torn and Harte*, 2006].

Discussion

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. It can be found on the United States EPA web site (http://www.epa.gov/nonco2/econ-inv/table.html), and in popular books on climate change [*Goodstein*, 2004; *Kolbert*, 2006; *Lovelock*, 2006]. Lovelock in particular advocates a climate engineering approach, putting smoke in the stratosphere or mirrors in space to deflect incoming solar radiation. This strategy might be practical for a few centuries, but not for hundreds of thousands of years.

The root of the misconception appears to be an entry of 5-200 years for the atmospheric lifetime of CO_2 compared with other gases given in Table 1 of the Technical Summary of the 2001 IPCC Scientific Assessment. The entry for CO_2 is accompanied by the caveat "No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes", but there is no indication that CO_2 can remain in the atmosphere for longer than the stated range. An article in the Economist in September, 2007(6??), interpreted this entry, reasonably enough but incorrectly, as “up to 200 years”.

The confusion may have arisen from oversimplification. It is true that most of the CO_2 does go away by dissolution in the ocean, on a time scale of centuries. If the full complexity of the carbon cycle must be boiled down into a single number for public discussion, it makes practical sense to approximate an "atmospheric lifetime" for the climate perturbation as the air/seawater equilibration timescale of a few centuries. The real CO_2 drawdown can be approximated by a sum of exponentials, but the atmosphere / ocean equilibration time scale of centuries is the piece of the equation that affects us the most. In such a situation, it is easy to forget about the longer impacts.

The commonly presumed short lifetime for CO_2 might also have its roots in a linearization of the carbon cycle. The atmosphere today contains about 200 Gton C in excess of the natural 1750 value. The ocean takes up 2 Gton C per year. If the ocean were going to take up all of the CO_2, according to simple linear first-order rate kinetics, the e-folding timescale for CO_2 drawdown could be derived by dividing 200 Gton C by 2 Gton C / year, to yield an e-folding lifetime of 100 years. The fallacy of this reasoning is that the real carbon uptake is expected to be comprised of a sum of exponentials, rather than a single exponential.

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. 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.

Analogous Issues

Persistence is an issue for other pollutants as well. Nuclear power creates hazardous radioactive waste products which must be stored, safely isolated from reaching groundwaters. Most of the radioactive products of nuclear fission are is 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). By analogy to the implicit treatment of the CO_2 lifetime in the atmosphere, one could argue that the lifetime of nuclear waste is only a few days or years, because for most of the material that is true. This 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 an issue. 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].

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 CO2 emissions will stay in the atmosphere for millennia, and a part of fossil fuel CO2 will remain in atmosphere forever. Many slowly-responding components of the climate system, such as ice sheets and methane hydrates, will be affected, and significant sea level rise is inevitable.

Although none of us will be alive 100,000 years from now to regret our energy decisions today, the long time-scale of the projected climate perturbation does lend some gravity to the energy policy debate. The longevity of nuclear waste is well known to the public, and seems to be important in the consideration of nuclear energy. For CO_2, the approximate lifetime "hundreds of years, with 25% lasting forever", translated to the gasoline pump, pulls out several gallons, out of every tank of gasoline. 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 the age of human civilization so far.

Figure Captions

Figure 1. Schematic division of the atmospheric pCO_2 consequences of fossil fuel CO_2 release to the atmosphere.

Figure 2. A response of CLIMBER-2 model [*Brovkin et al.*, 2002; *Brovkin et al.*, submitted; *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. Land carbon cycle was neglected in the simulations while deep sea sediments were explicitly simulated using carbonate diagenesis model by Archer [*Archer*, 1991]. (A) Emissions scenarios and reference IPCC SRES scenarios (B1 and A2). B) Simulated atmospheric CO2 (ppmv). C) Simulated changes in global annual mean air surface temperature (°C).).

Figure 3. The relationship between sea level and temperature on geologic time scales. Data from [*Alley et al.*, 2005].

Table 1. Maximum airborne fraction of CO_2 slugs

	1000-2000 Gton	4000-5000 Gton
This paper	52	67
Archer 2005	58%	60%
Lenton et al. 2006	50-63	67-75
Ridgwell et al. subm.		50
Tyrell et al. subm		70

Table 2. Atmosphere / ocean equilibrium CO_2 distribution

	1000-2000 Gton	4000-5000 Gton
This paper	22	34
Archer 2005	22	33
Lenton et al 2006	21-26	34
Goodwin et al. subm.	24-26	40
Ridgwell et al. subm		31

Table 3. Airborne fraction of CO_2 slug 1,000 and 10,000 years from now.

	1,000 years	10,000 years
1000-2000 Gton Release		
This paper	29%	14%
Archer 2005	24%	11%
Lenton et al. 2006	17-19%	11%
4000-5000 Gton C release		
This paper	57%	26%
Archer 2005	33%	15%
Lenton 2006	14-16%	10-15%
Ridgwell subm	34%	12%
Tyrrell subm.	42%	21%

Table 4. Long-term temperature implications of fossil fuel CO_2 release

	1,000 years	10,000 years
2000 Gton C release	>3° C	>1.5° C
5000 Gton C release	>5° C	>3° C

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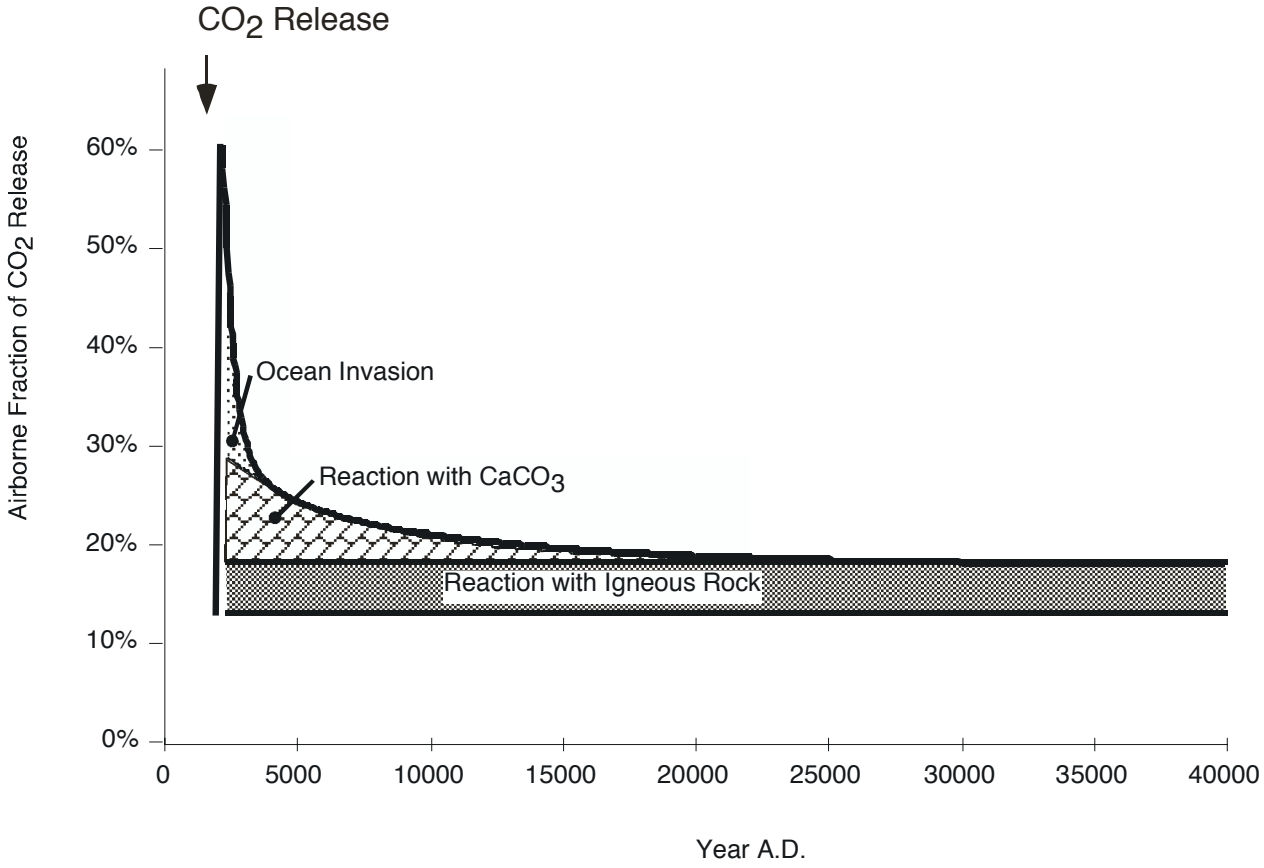
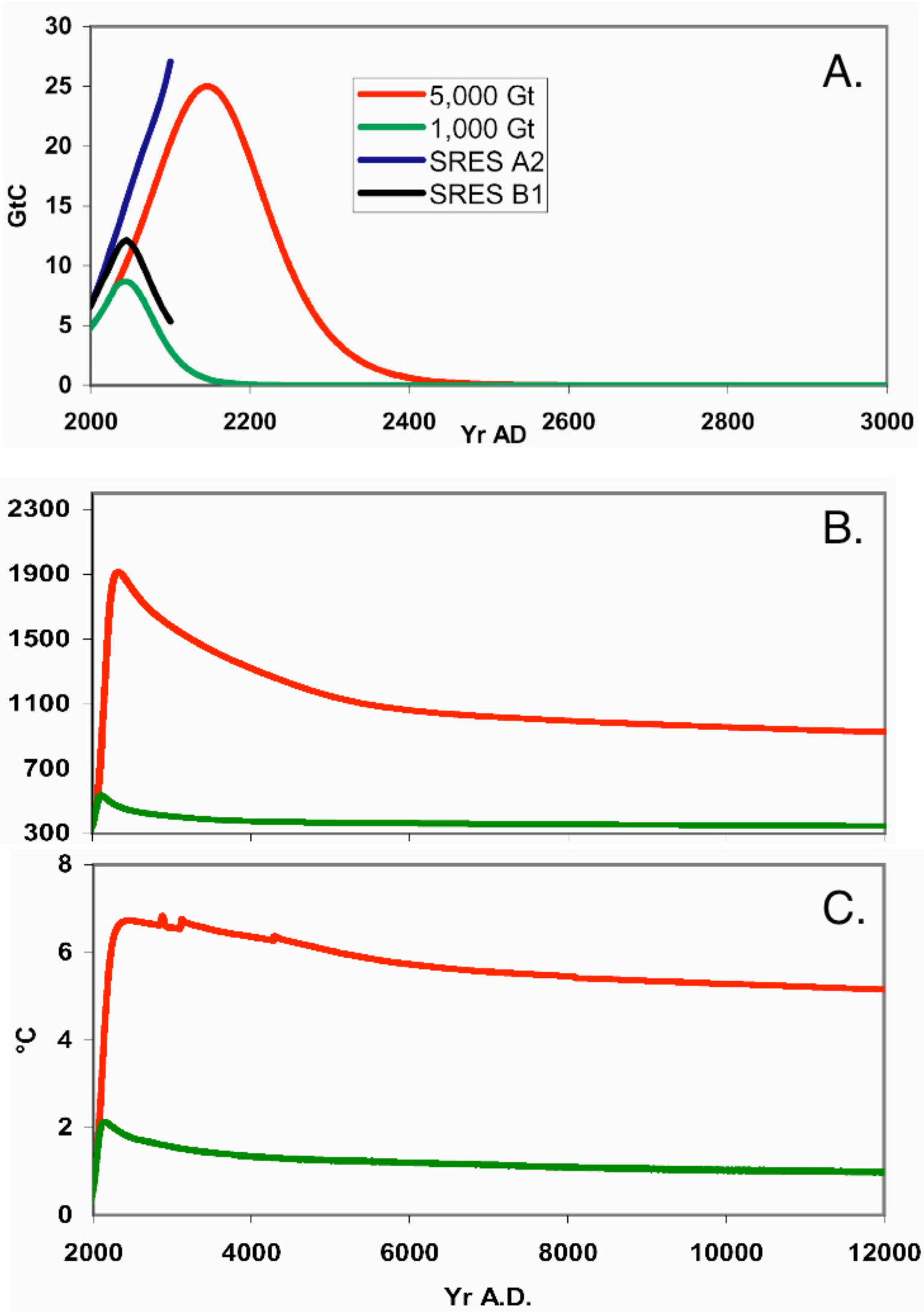

CO_2 Release
Airborne Fraction of CO_2 Release
60%
50%
40%
30%
20%
10%
0%
Ocean Invasion
Reaction with $CaCO_3$
Reaction with Igneous Rock
0
5000
10000
15000
20000
25000
30000
35000
40000
Year A.D.

Figure 1


A.
5,000 Gt
1,000 Gt
SRES A2
SRES B1
GtC
30
25
20
15
10
5
0
2000
2200
2400
Yr AD
2600
2800
3000
B.
ppm
2300
1900
1500
1100
700
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C.
°C
8
6
4
2
0
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4000
6000
8000
10000
12000
Yr A.D.

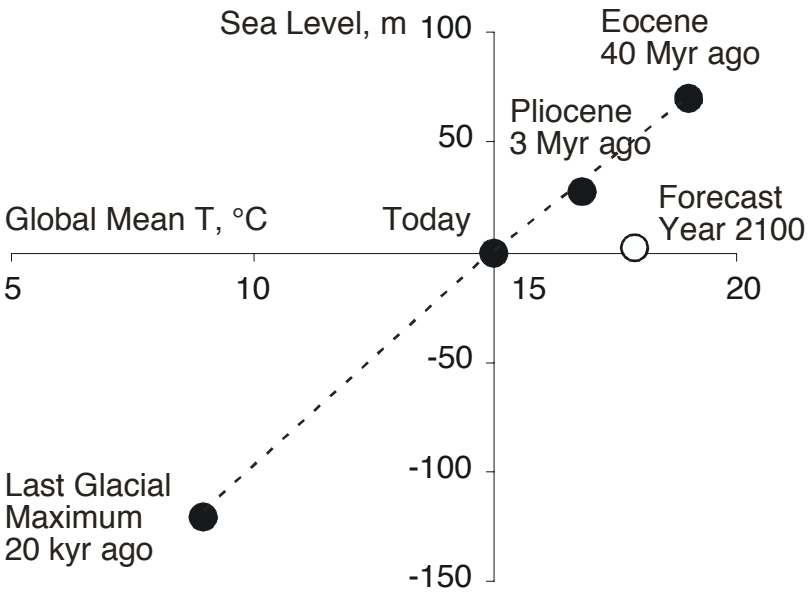
Sea Level, m
100
50
-50
-100
-150
Eocene
40 Myr ago
Pliocene
3 Myr ago
Forecast
Year 2100
Global Mean T, °C
Today
5
10
15
20
Last Glacial
Maximum
20 kyr ago

Figure 3