Atmospheric carbon dioxide removal: long-term consequences and commitment

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Abstract
Carbon capture from ambient air has been proposed as a mitigation strategy to counteract anthropogenic climate change. We use an Earth system model to investigate the response of the coupled climate–carbon system to an instantaneous removal of all anthropogenic CO2 from the atmosphere. In our extreme and idealized simulations, anthropogenic CO2 emissions are halted and all anthropogenic CO2 is removed from the atmosphere at year 2050 under the IPCC A2 CO2 emission scenario when the model-simulated atmospheric CO2 reaches 511 ppm and surface temperature reaches 1.8°C above the pre-industrial level. In our simulations a one-time removal of all anthropogenic CO2 in the atmosphere reduces surface air temperature by 0.4°C within a few years, but 1°C surface warming above pre-industrial levels lasts for several centuries. In other words, a one-time removal of 100% excess CO2 from the atmosphere offsets less than 50% of the warming experienced at the time of removal. To maintain atmospheric CO2 and temperature at low levels, not only does anthropogenic CO2 in the atmosphere need to be removed, but anthropogenic CO2 stored in the ocean and land needs to be removed as well when it outgasses to the atmosphere. In our simulation to maintain atmospheric CO2 concentrations at pre-industrial levels for centuries, an additional amount of CO2 equal to the original CO2 captured would need to be removed over the subsequent 80 years.

Keywords: climate change, climate geoengineering, atmospheric CO2 capture, carbon cycle

1. Introduction
Dramatic reductions in anthropogenic CO2 emissions have been called for to reduce the risk of dangerous climate change. It was estimated that to keep a twenty-first century peak warming below 2°C relative to pre-industrial levels, total anthropogenic CO2 emissions should be limited to about one trillion tons of carbon (Allen et al 2009, Meinshausen et al 2009). A number of studies have demonstrated that atmospheric temperature would not decrease appreciably for a long time even if anthropogenic CO2 emissions were to completely cease (e.g., Matthews and Caldeira 2008, Plattner et al 2008, Matthews et al 2009, Eby et al 2009, Solomon et al 2009). For example, using an Earth system model of intermediate complexity, it was found that if CO2 emissions were halted today, surface temperature would remain approximately constant for centuries (Matthews and Caldeira 2008). In another study, it was reported that if CO2 emissions were zeroed at the middle of this century when atmospheric CO2 reaches around 556 ppm in the Hadley Center climate/carbon cycle model, surface temperature would continue to increase slightly and remain 2°C higher than the pre-industrial level for at least a century (Lowe et al 2009).

It has been suggested that we might reach a state in which we would decide that we need to mitigate climate change by actively removing anthropogenic CO2 from the atmosphere and store it in reservoirs that are isolated from the atmosphere. One potential means to remove anthropogenic carbon dioxide is to directly capture CO2 from ambient air (Keith et al 2005, Keith 2009). Carbon dioxide can also be removed through other means such as land-use management and enhanced weathering (Royal Society 2009). The ultimate goal of these schemes is to diminish the amount of CO2 in the atmosphere from previous CO2 emissions, and thus mitigate global warming.
In this study, we investigate the response of global carbon cycle and temperature change to the removal of a large amount of atmospheric CO$_2$. We ask several questions: (1) What is the response of the coupled climate/carbon cycle system to a one-time removal of all anthropogenic CO$_2$ from the atmosphere? In other words, if we instantaneously remove all anthropogenic CO$_2$ from the atmosphere for only one time, how would atmospheric CO$_2$ and temperature change thereafter? (2) How much CO$_2$ would need to be removed from the atmosphere and at what rate to maintain pre-industrial CO$_2$ concentrations? We seek to answer these questions by conducting idealized atmospheric CO$_2$ removal simulations using an Earth system model with climate and carbon cycle components. Here we look at the response of the climate–carbon system to sudden and large reductions in atmospheric CO$_2$ concentrations. This is in contrast to previous studies that examined the climate response to sudden and large reductions in carbon emissions (e.g., Matthews and Caldeira 2008, Plattner et al. 2008, Eby et al. 2009, Matthews et al. 2009, Lowe et al. 2009, Solomon et al. 2009). This study has implications for the public and policy makers in that it provides quantitative information for the possible response of the climate–carbon system to the removal of large amounts of CO$_2$ from the atmosphere, and thus sheds light on the potential benefits and shortcoming from such technologies as a policy option. While our study does focus on the extreme case of complete removal of anthropogenic atmospheric CO$_2$, the general conclusions apply to all efforts to remove CO$_2$ from the atmosphere at any scale (e.g., planting trees, individual industrial facilities).

2. Method

2.1. Model

We use a coupled climate–carbon cycle model, University of Victoria Earth System Climate model (UVic ESCM), version 2.8. The model includes a general ocean circulation module with 19 vertical layers, coupled to a vertically integrated atmosphere module that simulates temperature and the hydrological cycle based on the energy and moisture balance (Weaver et al. 2001). The atmosphere and ocean climate module is coupled to a global carbon cycle module to allow for the interactions between CO$_2$ emissions, CO$_2$ concentrations, and climate change. The terrestrial carbon cycle is simulated by the Hadley Center Met Office land surface scheme ‘MOSES’ (Cox et al. 1999) coupled to the dynamic vegetation module ‘TRIFFID’ (Cox 2001), which simulates the response of both the vegetation and soil carbon to atmospheric CO$_2$ and climate. The ocean carbon cycle module is represented by both an inorganic carbon component that simulates CO$_2$ uptake by the solubility pump and a nutrient-phytoplankton-zooplankton-detritus marine ecosystem component that simulates carbon uptake by the biological pump (Schmittner et al. 2008). The spatial resolution of the coupled climate–carbon cycle model is 1.8° by latitude and 3.6° by longitude.

2.2. Simulations

The UVic model was first integrated under a fixed pre-industrial atmospheric CO$_2$ concentration of 278 ppm for 5000 years to allow approach to a quasi-equilibrium state for both climate and the carbon cycle. This near-equilibrium state was assumed to be the modeled pre-industrial state for the nominal year 1800. Then the model was integrated under prescribed historical CO$_2$ concentrations between year 1800 and 2008. From year 2009 to 2049, the model was forced with prescribed CO$_2$ emissions following the IPCC A2 emission scenario (Nakicenovic et al. 2000). Starting from year 2050 CO$_2$ emissions were halted and two idealized and extreme CO$_2$ removal simulations were performed. In one simulation atmospheric CO$_2$ was instantaneously set to its pre-industrial level of 278 ppm at the beginning of year 2050 by removing all anthropogenic CO$_2$ from the atmosphere, and then atmospheric CO$_2$ was allowed to evolve freely in response to exchange with both the land biosphere and ocean. In another simulation atmospheric CO$_2$ was instantaneously set to 278 ppm at year 2050 and then held at that level thereafter. For both simulations CO$_2$ removed from the atmosphere is assumed to be taken out of the atmosphere–ocean–land surface system, and both simulations were integrated until year 2500. In this study non-CO$_2$ forcings, including forcings due to other greenhouse gases and aerosols, were not included.

3. Results

3.1. One-time CO$_2$ removal

In our simulations by the end of year 2049 an amount equal to 54% of the cumulative anthropogenic CO$_2$ emissions is absorbed by the ocean and terrestrial biosphere with the remaining 46% stays in the atmosphere (table 1). At year 2050 an extreme one-time removal of all anthropogenic CO$_2$ from the atmosphere instantaneously restores atmospheric CO$_2$ to its pre-industrial level of 278 ppm. Following the instantaneous restoration, atmospheric CO$_2$ concentrations initially increase and then decrease somewhat (figure 1). Release of CO$_2$ from both the land biosphere and ocean causes an overshoot in atmospheric CO$_2$ with a peak concentration of 362 ppm reached 30 years after CO$_2$ removal. Then atmospheric CO$_2$ is diminished as a result of ocean absorption (table 1, figure 1), gradually approaching a level of 341 ppm by year 2500. That is, a size of 27% carbon that is initially removed from the atmosphere returns to the atmosphere. Based on the logarithmic dependence of radiative forcing on atmospheric CO$_2$ concentrations we estimate that a complete one-time removal of anthropogenic CO$_2$ from the atmosphere eliminates about two-thirds of the radiative forcing on the centennial timescales (table 1).

The change in atmospheric CO$_2$ is governed by the change in carbon flux between the atmosphere, land, and ocean (table 1, figures 2 and 3). In response to a reduction in atmospheric CO$_2$, there is an efflux of CO$_2$ from both the terrestrial biosphere and ocean to the atmosphere (figures 2 and 3). The efflux of carbon from land is associated with different responses of net primary production (NPP) that acts as a sink of atmospheric CO$_2$ and soil respiration that acts as a source of atmospheric CO$_2$. In response to a reduction in atmospheric CO$_2$, both NPP and soil respiration decrease,
but the rate of NPP decreases is much greater than that of soil respiration. This is because changes in NPP are mainly determined by changes in atmospheric CO$_2$ through CO$_2$-fertilization effect, while changes in soil respiration are mainly controlled by temperature change, which lags the change in atmospheric CO$_2$. Because the decrease in NPP is much faster than the decrease in soil respiration, the land turns from a sink to a source of atmospheric CO$_2$ in response to a reduction in atmospheric CO$_2$ (figure 2). In response to atmospheric CO$_2$ removal the ocean also initially releases CO$_2$ to the atmosphere, and then the ocean starts to absorb atmospheric CO$_2$. By the end of year 2500, for the amount of total anthropogenic carbon stored in the land and ocean at the time of atmospheric CO$_2$ removal, 22% releases to the atmosphere and 52% and 26% remains in the ocean and land respectively (table 1). In our continued simulations without processes involving deep-ocean sediments, by year 4000, 18%, 60%, and 22% of the anthropogenic carbon originally stored in the land and ocean at the time atmospheric CO$_2$ removal stays in the atmosphere, ocean, and land biosphere, respectively.

Because of the large thermal inertial of the ocean temperature change lags changes in atmospheric CO$_2$ (figure 1). Before atmospheric CO$_2$ removal modeled surface air temperature is 1.8°C higher than the pre-industrial level. A one-time removal of all anthropogenic CO$_2$ from the atmosphere reduces surface air temperature by 0.4°C within one year and 0.8°C within five years. Then surface temperature declines slowly with a rate of about 0.02°C/century. By year 2500, atmospheric surface temperature is 1.0°C higher than its pre-industrial value; a one-time removal of CO$_2$ offsets less than 50% of the warming experienced at the time of removal.

### 3.2. Maintenance of atmospheric CO$_2$ at pre-industrial level

Continued CO$_2$ removal is needed to keep atmospheric CO$_2$ at its pre-industrial level. We simulated a one-time removal of all anthropogenic atmospheric CO$_2$ at the beginning of year 2050 together with a cessation of anthropogenic emissions, and continued removal of all CO$_2$ subsequently released from the land biosphere and ocean. In this case following a continuous removal program starting from year 2050, surface air temperature returns to its year-2000 value within 5 years, and within 70 years surface warming diminishes to only 0.1°C higher above the pre-industrial level (figure 1).

To keep atmospheric CO$_2$ at a pre-industrial level, not only does all anthropogenic CO$_2$ that is already in the atmosphere need to be removed, but anthropogenic CO$_2$ stored in the land and ocean needs to be removed as well when it outgasses to the atmosphere. In our simulations to maintain CO$_2$ concentrations...
at pre-industrial levels, an amount of additional carbon dioxide equal to the original CO\textsubscript{2} removal of 494 PgC (1 PgC = 1 GtC = 10^{15} g carbon) would need to be removed over the subsequent 80 years. By the end of year 2500 an amount equal to 94\% of the anthropogenic carbon stored in the ocean and land before the start of the removal program has released to the atmosphere that keeps a CO\textsubscript{2} concentration of 278 ppm, with 304 PgC from the land and 249 PgC from the ocean (table 1). To keep atmospheric CO\textsubscript{2} at its pre-industrial level, the remaining 6\% anthropogenic carbon originally stored in the ocean and land would be eventually released and needs to be removed over the next thousands of years.

3.3. Cessation of emissions

If anthropogenic CO\textsubscript{2} emissions are halted at the middle of this century without any direct removal of atmospheric CO\textsubscript{2}, there is a slight trend of continued warming for about 100 years, and then surface temperature declines at a slow rate of about 0.02 °C/century (dashed lines in figure 1). By year 2500 surface air temperature is 1.9 °C higher than the pre-industrial level; about the same warming experienced in year 2049 before the halt of CO\textsubscript{2} emissions (dashed lines in figure 1). The significant lag of temperature response to reductions in CO\textsubscript{2} emissions is consistent with results from a number of recent studies showing that atmosphere surface temperature would not decline significantly (or even shows a slight increase) for several centuries even if CO\textsubscript{2} emissions were to cease completely (Matthews and Caldeira 2008, Plattner et al 2008, Eby et al 2009, Lowe et al 2009, Solomon et al 2009). To stabilize surface temperature at the current level near zero anthropogenic CO\textsubscript{2} emission are required in the future (Matthews et al 2009, Allen et al 2009, Meinshausen et al 2009).

4. Discussion and conclusions

Direct removal of large amounts of anthropogenic CO\textsubscript{2} from the atmosphere could bring atmospheric temperature to
lower levels in a short period, but the removal deployment needs to be continued to maintain atmospheric CO$_2$ and temperature at low levels. To maintain atmospheric CO$_2$ concentrations at pre-industrial levels for centuries, ultimately an amount of CO$_2$ approaching the total cumulative amount of anthropogenic CO$_2$ emissions would need to be removed from the atmosphere.

Here we simulated idealized and extreme scenarios of atmospheric CO$_2$ removal to illustrate feedbacks and responses of the coupled climate–carbon cycle system to reduced burden of atmospheric CO$_2$. We have made no attempt to consider the technological and economical feasibility of this extreme CO$_2$ removal scenario. There are no known relevant physical limits to CO$_2$ removal from the atmosphere, but industrialized CO$_2$ removal is thought to cost more than the capture and storage of an equivalent amount of carbon from power plants using conventional techniques (IPCC 2005). We do not present our scenarios as a plausible prediction of the future but rather use them to illustrate fundamental climate and carbon cycle responses that would come into play at any scale of deployment.

Our simulations show that in addition to the halt of CO$_2$ emission, a one-time removal of all anthropogenic CO$_2$ from the atmosphere at the middle of this century could reduce surface warming from a peak value of 1.8$^{\circ}$C to 1$^{\circ}$C within a few years, but the 1$^{\circ}$C warming above the pre-industrial level would persist for a few centuries. This temperature response is a result of both CO$_2$ outgassing from the ocean and land and thermal inertia of the ocean. This characteristic of temperature response, i.e., rapidly fast cooling followed by a much slower cooling, is consistent with a recent study that used an atmosphere–ocean general circulation model to investigate temperature response to an instantaneous return of pre-industrial forcing (Held et al 2010). Additional simulations show that if atmospheric CO$_2$ was restored to 350 ppm for one time, a surface warming of 1.2$^{\circ}$C would last for several centuries. To maintain atmospheric CO$_2$ and surface temperature at low levels, continued efforts are needed to remove not only anthropogenic CO$_2$ that is in the atmosphere, but anthropogenic CO$_2$ that had been previously taken up by the ocean and land, which would then release to the atmosphere in response to atmospheric CO$_2$ removal.

We have used a coupled climate–carbon cycle model to investigate the response of climate–carbon system to an extreme reduction in atmospheric CO$_2$. The magnitude and timescale associated with the response of atmospheric CO$_2$ and temperature depend on the strength of carbon cycle feedbacks, as well as climate sensitivity and the efficiency of heat uptake by the ocean. The model configuration we used has a climate sensitivity of 3.5$^{\circ}$C, which is in the middle range of 2.0 to 4.5$^{\circ}$C estimated by IPCC (2007). The simulated land and ocean carbon uptake and temperature change under different CO$_2$ emission and concentration scenarios by the UVic model are comparable to the results from a suite of atmosphere and ocean general circulation models as well as Earth system models of intermediate complexity (Friedlingstein et al 2006, Plattner et al 2008). Here we only considered the effect of CO$_2$ forcing. The inclusion of non-CO$_2$ greenhouse gases and aerosols could modify the response of the carbon cycle and temperature through their effects on radiative forcing. The exact effects would be strongly scenario dependent. Nevertheless, the essential characteristics of the carbon cycle and temperature response to large reductions in atmospheric CO$_2$ presented here are robust and are largely independent of future changes in non-CO$_2$ forcings.

The general behavior of the carbon cycle response to atmospheric CO$_2$ removal can be inferred from our mechanism understanding of the carbon cycle. On a timescale of several thousands of years, anthropogenic CO$_2$ largely equilibrates between the atmosphere and ocean with approximately 80% of anthropogenic CO$_2$ absorbed by the ocean (Archer et al 1997, Solomon et al 2009, Cao et al 2009). In other words, after a halt of anthropogenic CO$_2$ emission and/or an implementation of atmospheric CO$_2$ removal, the remaining anthropogenic CO$_2$ in the atmosphere–ocean–land system would be redistributed in such a way that about 20% the excess carbon would stay in the atmosphere on a timescale of several thousands of years. Processes involving chemical reactions of deep-ocean sediments and carbonate and silicate rocks that are not included in the simulations here will ultimately restore atmospheric CO$_2$ to pre-industrial levels on timescales of more than hundreds of thousands of years (Archer et al 2009).
In our simulations a one-time atmospheric CO₂ restoration to 278 and 350 ppm from 511 ppm results in a surface cooling of 0.80 and 0.54 °C respectively on century timescales, which roughly corresponds to a cooling of 0.16 °C for every 100 PgC CO₂ removal (in this case, a ‘negative’ CO₂ emission). This result is consistent with the simulated relationship between temperature increase and cumulative CO₂ emissions using the same model (Matthews and Caldeira 2008). The proportionality of global warming to cumulative CO₂ emissions has been found in several studies from both observational constraints and a variety of climate–carbon cycle simulations with a surface warming of 0.10−0.25 °C per 100 PgC CO₂ emission (Matthews and Caldeira 2008, Matthews et al. 2009; Allen et al. 2009). Our simulations show that the concept of proportional temperature change to cumulative CO₂ emissions can also be applied to CO₂ removal scenarios, which would help us to assess the effectiveness of CO₂ removal projects in mitigating global warming.

In this study we have shown that a one-time removal of 100% excess CO₂ from the atmosphere diminishes the amount of warming at the time of CO₂ removal by less than 50%. More generally, we would expect the percentage reduction in surface warming to be much less than the percentage one-time reduction in atmospheric CO₂ concentrations. In our simulations following a one-time removal of CO₂, as a result of ocean thermal inertia, temperatures decrease as atmospheric CO₂ concentrations increase. If effective heat capacity of the climate system is less and/or the CO₂-degassing timescale to atmospheric CO₂ removal is longer, it would be possible to have overshoots in which temperatures decrease with CO₂ removal and then increases as CO₂ re-accumulates in the atmosphere. However, this is not observed in our simulations.

If the goal is to maintain atmospheric CO₂ concentrations at some specified level, a one-time reduction of atmospheric CO₂ to that level would need to be followed by continued removal of CO₂ released from the land biosphere and ocean; thus such a program entails a long-term commitment to atmospheric CO₂ removal. Intentional reduction of atmospheric CO₂, either by direct capture of CO₂ from the atmosphere, or by land and/or ocean-based carbon sequestration schemes, may become an important climate mitigation tool. However, the amount of CO₂ that would need to be removed from the atmosphere could be much greater than the desired reduction in atmospheric CO₂ concentrations, and may exceed the total burden of excess atmospheric CO₂ at the time of initial CO₂ removal.

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