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PERSPECTIVE

The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission

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Abstract

In a recent letter, Ricke and Caldeira (2014 *Environ. Res. Lett.* **9** 124002) estimated that the timing between an emission and the maximum temperature response is a decade on average. In their analysis, they took into account uncertainties about the carbon cycle, the rate of ocean heat uptake and the climate sensitivity but did not consider one important uncertainty: the size of the emission. Using simulations with an Earth System Model we show that the time lag between a carbon dioxide (CO_2) emission pulse and the maximum warming increases for larger pulses. Our results suggest that as CO_2 accumulates in the atmosphere, the full warming effect of an emission may not be felt for several decades, if not centuries. Most of the warming, however, will emerge relatively quickly, implying that CO_2 emission cuts will not only benefit subsequent generations but also the generation implementing those cuts.

In a recent letter, Ricke and Caldeira [1] estimated that the time lag between a carbon dioxide (CO_2) emission and the maximum warming response is a decade on average. This is an important finding as it indicates that the full climate damages expected to occur in response to a CO_2 emission will already be felt by the generation responsible for those emissions. Conversely, the relatively short response timescale implies that CO_2 emission cuts implemented today have the potential to influence the rate of warming in the short term. Thus, their finding corroborates the notion that the rate of warming over the next decades is not inevitable, but will be determined by future CO_2 emissions [2].

A range of previous studies has explored the warming commitment of past CO_2 emissions [3–9]. A robust finding of these studies is that the CO_2-induced warming persists for many centuries. The novel aspect of the letter by Ricke and Caldeira [1] (henceforth referred to as R&C) is its focus on the time lag between a CO_2 emission and the resulting maximum warming response.

In their study, R&C used simple representations of the carbon cycle and the physical climate system. The carbon cycle was simulated by impulse response functions derived from the response of a range of Earth System Models to a 100 GtC emission pulse [10]. The physical climate system was represented by one-dimensional diffusion or two-box models fitted to Coupled Model Intercomparison Project phase 5 (CMIP5) simulations with an abrupt quadrupling of atmospheric CO_2. Combinations of these models made it possible to sample 6000 realizations of the coupled climate-carbon cycle system.

For a 100 GtC pulse of CO_2 released into the atmosphere with a background CO_2 concentration of 389 ppm, R&C found the median time between an emission and maximum warming to be 10.1 years, with a 90% probability range of 6.6–30.7 years.

A pulse emission of CO_2 results in an abrupt increase in atmospheric CO_2 concentrations, followed by a slow decline as CO_2 is taken up by the ocean and terrestrial biosphere. The radiative forcing associated with the CO_2 increase causes warming, but the warming is delayed due to the long timescales of ocean heat uptake. Initially, the ocean takes up a large amount of heat, but this heat uptake decreases over time, allowing the atmosphere to warm. The timing of peak warming is determined by the balance between two opposing processes: the decline of radiative forcing of atmospheric CO_2 following the pulse emission (which has a cooling effect on the atmosphere), and the decrease of ocean heat uptake (which has a warming effect).
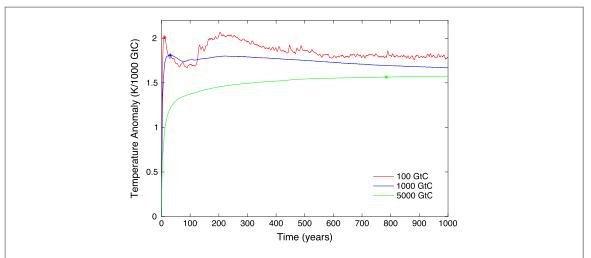
Figure 1. Global mean temperature response to CO_2 emission pulses ranging from 100 to 5000 GtC as simulated by the UVic ESCM. CO_2 pulses were released into an atmosphere in equilibrium with pre-industrial atmospheric CO_2 levels [10]. The temperature data was normalized to facilitate comparison across simulations. The star symbols indicate the first temperature peak for each simulation. The data from the 100 GtC pulse simulation was smoothed using a 5 year running average. The UVic ESCM pulse simulations were conducted as part of the CO_2-impulse response function model intercomparison project [10].

This balance is sensitive to a range of factors, which differ widely across Earth System Models: the sensitivity of the marine and terrestrial carbon sinks to changes in atmospheric CO_2 and climate, which determines the decline of atmospheric CO_2; the rate of mixing of heat into the deep ocean, which determines the decrease of ocean heat uptake; and the equilibrium climate sensitivity which also controls the response time-scale of the system. R&C take these uncertainties into account and show that uncertainty in the temperature response timescale can only be narrowed if uncertainty in all three contributing factors is reduced.

One important factor that can be expected to affect the timing of maximum warming, however, was not considered in the uncertainty analysis: the size of the CO_2 emission pulse. As the pulse size increases, the CO_2 decline from peak levels slows [4]. The decline in radiative forcing slows even more due to its logarithmic dependence on atmospheric CO_2. At the same time the decrease in ocean heat uptake is also reduced, delaying the warming further. The combination of these two processes has the potential to significantly delay the time of peak warming for larger CO_2 emission pulses.

Figure 1 shows the temperature response to pulse emissions ranging from 100 GtC (the pulse size used in the analysis of R&C) to 5000 GtC, as simulated with the University of Victoria Earth System Climate Model (UVic ESCM) [4, 11]. For a pulse emission of 100 GtC the temperature response has a double-peak structure: the first peak occurs in response to the abrupt increase in radiative forcing, amplified by climate feedbacks. The temperature decline from the first peak is caused by the relatively fast decrease in atmospheric CO_2 and thus radiative forcing, which exceeds the decrease in ocean heat uptake. The run-up to the second peak is caused by the decrease in ocean heat uptake now

exceeding the decrease in radiative forcing. The second peak is reached when these two processes balance. If the time-horizon of the analysis is limited to 100 years (as in R&C), the maximum warming occurs at year 11, in agreement with the median of R&C. For pulse emissions of 1000 GtC, the double-peak shape remains but is less pronounced and the maximum warming occurs 31 years after the emission. For very large pulses (5000 GtC), the first peak disappears due to the decline in ocean heat uptake overwhelming the radiative forcing decline. In this case, the maximum warming occurs 785 years after the emission.

The response time to larger pulses matters, as future cumulative CO_2 emissions are almost certain to exceed 100 GtC. These cumulative emissions will arise from successive small emission pulses, and the response time for the total emission will be the average response time for these individual pulses. From our finding that the response time increases with pulse size it follows that the response time of an individual CO_2 emission is longer the later it is released (i.e. the more CO_2 has already accumulated in the atmosphere).

Our results indicate that as CO_2 continues to accumulate in the atmosphere, the full warming effect of an emission may take several decades, if not centuries to emerge. A large fraction of the warming, however, will be realized relatively quickly (93% of the peak warming is realized 10 years after the emissions for the 1000 PgC pulse). This implies that the warming commitment from past CO_2 emissions is small, and that future warming will largely be determined by current and future CO_2 emissions. Each additional CO_2 emission will contribute to warming that will persist almost indefinitely. Thus, emission reductions implemented today will equally benefit current and future generations.

Acknowledgments

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