PACIFIC CLIMATE IMPACTS CONSORTIUM

PCIC SCIENCE BRIEF: TWO QUESTIONS ABOUT THE RESPONSE OF THE EARTH'S CLIMATE TO CARBON EMISSIONS

Two recently published articles serve to answer two questions about the response of the Earth's climate to carbon emissions. The first paper, by Goodwin et al. (2014) in *Nature Geoscience*, investigates the question of why transient surface warming on the timescale of decades to centuries, due to cumulative carbon emissions, is nearly-linear. They find that this is the result of the competing effects of the ocean absorbing both heat and carbon. While the former initially reduces climate sensitivity by drawing down heat, it then increases climate sensitivity as this heat absorption reduces. This is offset by the latter, as the ocean removes carbon dioxide from the air. The authors also find, in line with previous research, that increasing emissions lead to increased surface warming and that this warming will last many centuries.

The second article, by Ricke and Caldeira (2014) in *Environmental Research Letters*, uses model output to analyze the response of the Earth's climate to pulses of carbon dioxide in order to answer the question of how long it takes for maximum warming to occur due to a given emission. They find that the median time between such an emission and the maximum warming due to that emission is 10.1 years. Their results lead the authors to state, "[o]ur results indicate that benefit from avoided CO_2 emissions will be manifested within the lifetimes of people who acted to avoid [those emissions]."

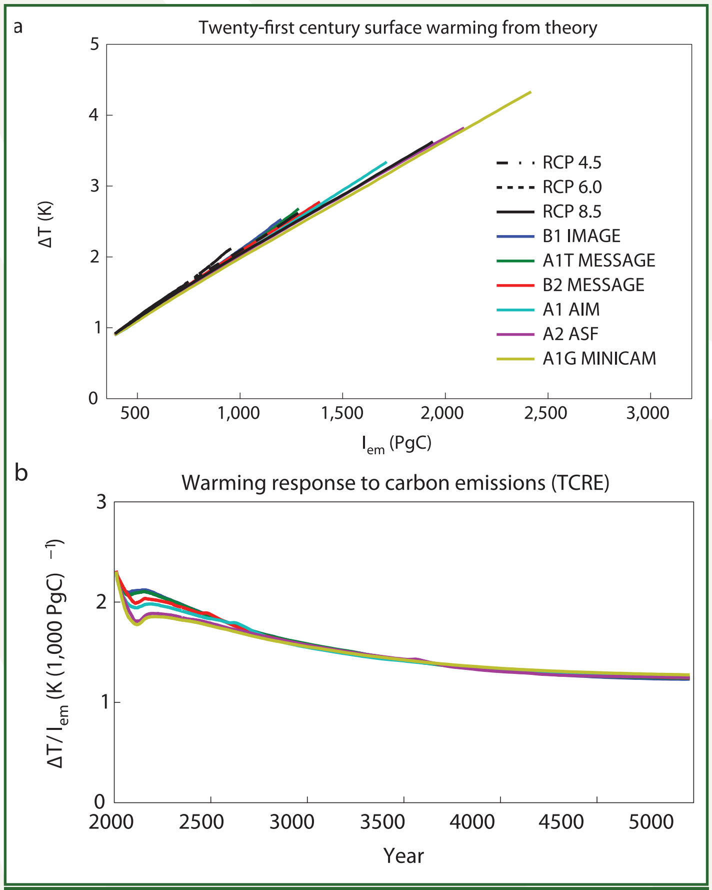

Figure 1: Warming from Carbon Emissions, modified from Goodwin et al. (2014).
Warming from carbon emissions from theory of Goodwin et al.: a) surface warming over the twenty-first century, versus cumulative emissions (denoted I_{em}) and b) surface warming response to cumulative emissions versus time.

The details of the response of the global average surface temperature to greenhouse gas emissions on timescales of decades to centuries are of great interest because this response is tied directly to the well being of ecosystems and human societies. While we now understand that most of the warming trend in surface temperatures since the mid-1900s has been due to human activities, primarily greenhouse gas emissions and land use changes, many important open questions remain. Among them are: (1) Why is it that surface temperatures have shown a near-linear response to emissions over the timescales of decades to centuries? And, (2) what is the amount of time between a given greenhouse gas emission and the maximum warming resulting from that emission? Both questions are important for our basic scientific understanding of Earth's climate system. In addition, the former is especially important for future climate projections. We would like to know why the response has been near-linear and what the response will be in the future. The latter question, while important for future climate projections, is also potentially relevant to ongoing discussions about addressing climate change, in both the economics and ethics literature. These discussions have often framed the issue as one of intergenerational equity. Considering the economic interests of present and future generations as regards the impacts of climate change involves attempting to quantify the weight of impacts to future generations in present day economic terms[1], which depends, in part, on the length of time between the present day and the future impacts. Intergenerational ethical concerns offer unique challenges, because the subjects of concern are, if far enough in the future, people who do not yet exist[2]. Knowing the length of time between an emission and its maximum warning would contribute to our understanding of how present or future generations would be affected by the present day's emissions.

In order to address the first question, Goodwin et al. (2014) first develop two equations to describe the response of the climate system to carbon dioxide emissions. In order to do this, they work from three separate relationships. The first is an energy conservation equation that relates changes in the Earth's surface air temperature to changes in the amount of radiation flowing into and out of the climate system from the top of the troposphere and the heat taken up by the Earth's oceans. The second is an empirical equation that relates the radiative balance at the top of the troposphere to the atmospheric concentration of carbon dioxide. The third equation uses conservation of mass and assumes a small perturbation of carbon in the atmosphere and ocean from preindustrial values, as well as constant concentrations of dissolved inorganic carbon in the ocean from soft tissue and calcium carbonate, in order to relate atmospheric carbon dioxide concentrations to emissions and the current concentrations of carbon in the ocean and atmosphere. The authors then combine these equations into two equations that they use to describe the climate system's response to carbon dioxide emissions. The equations are nearly identical, with the first dealing with the ocean and atmosphere only and the second also accounting for the carbon stored, emitted and drawn down by land.

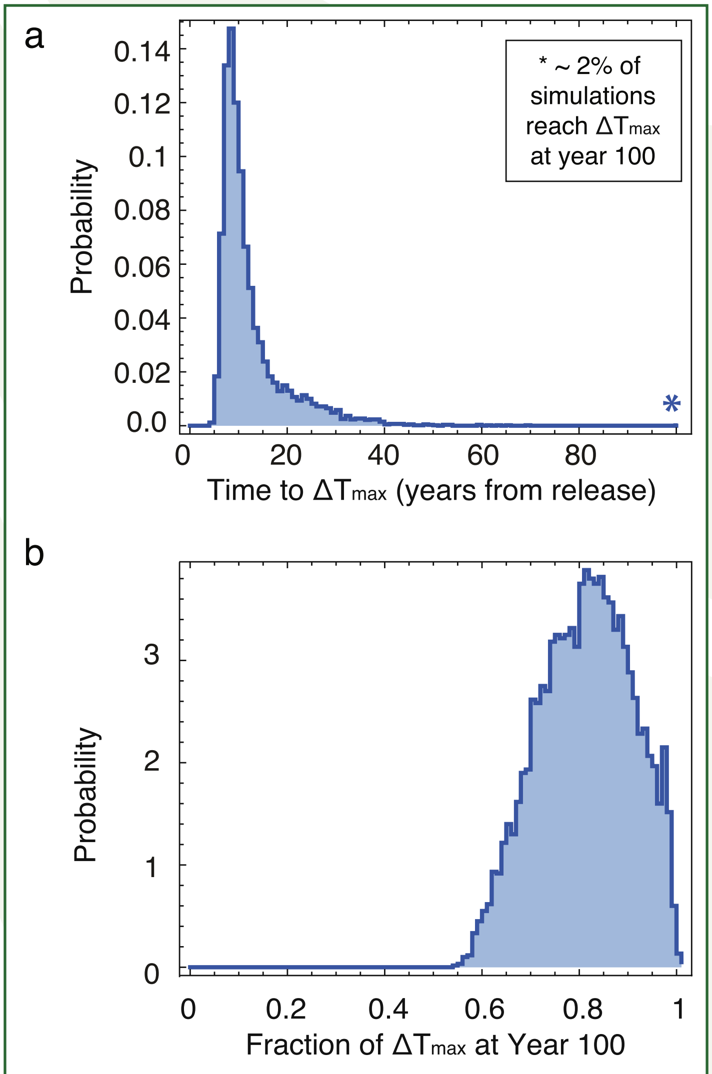

Figure 2: Temperature Response to a Carbon Dioxide Emission, from Ricke and Caldeira (2014).
Probability distributions from the theory of Ricke and Caldeira for: a) the time between a carbon dioxide emission and the maximum warming due to that emission, and b) the fraction of maximum warming remaining 100 years after an emission of carbon dioxide.

Using the equations they derive and the output from a type of simplified climate model[3] called an Earth System Model of Intermediate Complexity (EMIC) that is run using six different emissions scenarios[4], the authors derive estimates for the total amount of carbon that the ocean can accept from the atmosphere and the response of global

1. For an overview of the method of discounting used in translating the costs of future environmental impacts into present day value, see pp. 100-102 of Smith, S., 2011: Environmental Economics: A Very Short Introduction, Oxford University Press, New York, USA, 136 pp.
2. For an overview of some of the main arguments surrounding ethical obligations to future generations, see Chapter 2 of Brennan, A. and Y.S. Lo, 2010: Understanding Environmental Philosophy. Acumen Publishing Limited, Durham, UK, 234 pp. For an discussion of this problem in the context of the other issues that surround the addressing of climate change, see Gardiner, S.M., 2006: A Perfect Moral Storm: Climate Change, Intergenerational Ethics and the Problem of Moral Corruption. *Environmental Values*, **15**, 397–413, doi: 10.3197/096327106778226293.
3. The Grid ENabled Integrated Earth system model, or GENIE is an Earth system model of intermediate complexity. Such models are complex enough that they explicitly represent a number of essential climate processes, but are less complex than full global climate models that include a more comprehensive representation of Earth system processes that are important for long-term climate change. The GENIE model used in this research models the circulation of the ocean and atmosphere, contains simple representations of the effects of land ice, soils, vegetation and the chemistry of the ocean and atmosphere. For more on GENIE, see: Ridgwell, A. et al, 2007: Marine geochemical data assimilation in an efficient Earth System Model of global biogeochemical cycling. *Biogeosciences*, **4**, 87-104.

surface temperature to cumulative emissions. The EMIC is used both to determine the amount of carbon that the ocean can take up before reaching equilibrium with the atmosphere and for comparison, to determine whether the equations described also perform well in capturing the relevant physical processes needed to account for the response of surface air temperatures to cumulative carbon emissions.

After finding that their equations are consistent with model output, the authors use the physical processes represented by their equations to try to determine why the response of global surface temperatures to carbon emissions is nearly linear. Goodwin and colleagues find that it comes down to two competing effects, ocean heat uptake and ocean carbon uptake. Initially, ocean heat uptake reduces the sensitivity of surface temperatures to carbon emissions by drawing down heat from the atmosphere. This effect weakens as the ocean warms and absorbs less heat, which causes surface temperatures to become more sensitive to carbon emissions. The sensitivity of surface temperatures to carbon dioxide is also initially high because the ocean has not yet acted to drawn down the carbon, but as the ocean absorbs carbon, the sensitivity is reduced. The net effect is a near-linear response of surface temperatures to emissions over the twentieth century (Figure 1a), though the author's results show a slight decrease in sensitivity over time (Figure 1b).

The authors also use their equations to estimate the Transient Climate Response to cumulative carbon Emissions[5] (TCRE). Their estimate is approximately 1.5 °C ± 0.7 °C for every billion tonnes of carbon emitted in the ocean-atmosphere only case and 1.1 °C ± 0.5 °C for every billion tonnes of carbon emitted when land is included. These figures are consistent with the range of results from EMICs and models participating in the fifth phase of the Coupled Model Intercomparison Project[6] (CMIP5). The second figure is lower because the land surface draws down more carbon.

In order to address the second question, Ricke and Caldeira use results from two experiments. The first is a carbon-cycle model intercomparison project[7] that included models of varying complexity simulating the response of the climate system, including carbon cycles, to a pulse of carbon dioxide. The authors use this to characterize the response of the carbon cycle to a pulse emission of carbon dioxide. The second is an experiment in which the global climate models participating in CMIP5 simulate the response of the climate system to a sudden quadrupling in the concentration of atmospheric carbon dioxide. The authors use this to characterise the response of surface temperatures to such a quadrupling. They also use two simple models that account for the ocean's thermal inertia. The use of this range of model output also allows the authors to develop uncertainty estimates that sample from a wide range of model parameters. With the response of surface air temperatures to a sudden quadrupling of carbon dioxide, the response of the carbon system to a pulse of carbon dioxide and estimates of the thermal inertia of the ocean in hand, the authors develop a set of 6000 projections approximating the response of global surface temperatures to an individual emission of carbon dioxide.

Using these methods, Ricke and Caldeira find that the median time between a given emission and the maximum warming from that emission is approximately 10.1 years, with a likely value between 6.6 and 30.7 years (Figure 2a), with ranges and the median determined by the distribution of projections. Though the maximum warming effect will be felt over this relatively short period of time, the authors find that the effects of an emission remain for a long time, with the fraction of maximum warming remaining a century later having a median value of 0.82 and likely range between 0.67 and 0.92 (Figure 2b). This means that the warming from an emission can be approximated as a step function, with temperatures "stepping up" relatively quickly from an emission and remaining elevated over the timescale of a century or longer. The distribution of responses shown in Figure 2 reflects three sources of uncertainty: carbon cycle response, climate sensitivity and

4. These emissions scenarios were taken from those published by the Intergovernmental Panel on Climate Change in 2000 and are known as the Special Report on Emission Scenarios (SRES) scenarios. They were developed in order to provide input for evaluating the consequences of various trajectories of future greenhouse gas emissions. For more on the these emissions scenarios, see here: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=23.

5. The Transient Climate Response to cumulative carbon Emissions (TCRE) is defined in the glossary of IPCC Working Group I's contribution to the Fifth Assessment Report as: "the transient global average surface temperature change per unit cumulated carbon dioxide emissions, usually 1000 PgC." Put more loosely, this means the warming seen soon after the emission of a billion tonnes of carbon, in the form of carbon dioxide, into the atmosphere.
IPCC, 2013: Annex III: Glossary [Planton, S. (ed.)]. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

6. For more information on the Coupled Model Intercomparison Project, see here: http://cmip-pcmdi.llnl.gov/.

7. For more information on this carbon cycle model intercomparison project, see: Joos, F., et al., 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics*, **13**, 2793–825, doi:10.5194/acp-13-2793-2013.

thermal inertia. Ricke and Caldeira find that, even if uncertainty is reduced in any one of these factors, most of the overall uncertainty remains, which means that reducing uncertainty for climate projections at the century scale requires reducing uncertainty in all three areas. In addition, the authors also arrive at an estimate for TCRE of 2.2 °C (with a likely range of between 1.6 °C and 2.9 °C) for every billion kilograms of carbon emitted, which is also consistent with the range of values from the models participating in CMIP5.

Taken together, these findings may be of interest to those engaged in long-term planning, economics modelling, mitigation policy development and climate ethics. The conclusions support earlier research showing that the results of carbon emissions are long-lasting and suggest that the response of surface temperatures to carbon dioxide will remain near-linear over the course of this century. In addition, the authors' results suggest that reducing emissions today would allow current generations to avoid some of the warming that would have resulted had they continued to emit, the maximum warming from which would have been felt in their lifetimes.

Goodwin, P., R.G. Williams and A. Ridgwell, 2014: Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake. *Nature Geoscience*, **8**, 29–34, doi:10.1038/ngeo2304.

Ricke, K.L. and K. Caldeira, 2014: Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters*, **9**, 12, 124002, doi:10.1088/1748-9326/9/12/124002.

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