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EDITED AND REVIEWED BY
Hayley Jane Fowler,
Newcastle University, United Kingdom

*CORRESPONDENCE
H. Damon Matthews
damon.matthews@concordia.ca

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How much additional global warming should we expect from past CO_2 emissions?

H. Damon Matthews*

Department of Geography, Planning and Environment, Concordia University, Montreal, QC, Canada

KEYWORDS

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A Viewpoint on the Frontiers in Science Lead Article
The Zero Emissions Commitment and climate stabilization

Key points

- The committed or unrealized future warming of our climate due to past carbon dioxide (CO_2) emissions has been defined in many different ways, and has also been widely misunderstood both within and outside of the scientific community.
- The Zero Emissions Commitment (ZEC) is a clean estimate of unrealized future warming, but its application to understand the requirements of climate stabilization is complicated by how quickly we are able to reduce CO_2 emissions, as well as the climate response to changes in non-CO_2 emissions.
- The climate response to CO_2 emissions is well-represented by the combination of the Transient Climate Response to cumulative CO_2 emissions (TCRE) and ZEC.

Introduction

The amount of future climate warming that is anticipated to be caused by already emitted carbon dioxide (CO_2) is a quantity that has been defined in many different ways, and it is also one of the most widely misunderstood concepts in climate science. Terms such as “committed warming,” “warming in the pipeline,” or “unrealized warming” have frequently been used to invoke the idea that CO_2 already in the atmosphere will cause decades to centuries of continued warming, regardless of how quickly the world is able to decrease emissions. However, ongoing climate warming is predominantly caused by the CO_2 emissions that we continue to produce, not those that were emitted in the past. This understanding is clearly laid out by Palazzo Corner et al. (1), who describe the latest scientific knowledge of the “Zero Emissions Commitment” (ZEC) or the amount of continued global temperature change that we should expect in the absence of any future CO_2 emissions. The balance of current evidence suggests that ZEC is likely close to zero (albeit with large uncertainty in either direction), suggesting that if we were able to achieve zero CO_2 emissions, the most likely climate outcome would be stable global temperatures (1).

Climate commitment confusion

The misunderstanding that emerged surrounding the idea of committed climate warming is in part due to the history of how climate models have been developed. For most of the history of global climate model development, atmospheric CO_2 concentrations were a prescribed quantity, with no inclusion of the global carbon cycle dynamics that absorb more than half of the annual CO_2 emissions produced by fossil fuel combustion and land-use change. This was still the case at the time of the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report in 2007, which, for the first time, reported a series of model experiments in which atmospheric composition of CO_2 and other greenhouse gases was held fixed at year-2000 levels, and the models were run forward in time to quantify the amount of additional warming that would occur (2). This set of experiments showed continued climate warming as the slow-responding components of the climate system adjusted over time to a constant atmospheric composition. The resulting warming (of about 0.5°C over 100 years) was labeled the "constant composition commitment" (2).

This was an important finding and represented a novel quantification of the physical climate inertia that results in delayed warming in response to a change in forcing. However, this finding was widely reported and discussed—both within and outside of the scientific literature—as an unavoidable amount of future climate warming that would manifest regardless of how quickly we were able to decrease emissions (3). This often led to the assertion that, even if we were to stop emitting CO_2, warming would continue for decades to centuries. But this is not what the IPCC report showed: the constant composition commitment was in response to constant atmospheric concentrations, which is not the same as zero future emissions (4).

With the development of Earth system models that included carbon cycle dynamics, it became possible to simulate the climate response to zero emissions, rather than only the climate response to prescribed constant concentrations. These new models showed clearly that if CO_2 emissions were eliminated abruptly, atmospheric CO_2 concentrations would fall over time and global temperatures would probably remain approximately constant (4–8). The resulting zero emissions commitment was therefore shown to be close to zero, much smaller than the constant composition commitment (4). While the constant composition commitment was only an estimate of the effect of physical climate inertia, ZEC also includes the effect of carbon cycle inertia that acts to decrease atmospheric CO_2 over time and counteract the warming influence of physical climate inertia (3). ZEC is therefore the correct metric of climate commitment to use to estimate how much future warming we should anticipate from past CO_2 emissions.

Drivers of unavoidable future warming

While ZEC tells us how much future warming we should expect from the CO_2 emissions already in the atmosphere, it does not tell us how much future warming is unavoidable. Climate inertia on its own (including both physical climate and carbon cycle inertia) does not seem to be a major factor in causing unavoidable future warming, but there are other important inertial factors that do. It is, of course, not possible to stop emitting CO_2 overnight, which reflects strong inertia within human technological and sociopolitical systems.

The concept of "committed emissions" is therefore key to understanding how much future CO_2-induced warming might be unavoidable, by virtue of unavoidable future emissions (9). Various studies have now estimated the committed future emissions resulting from existing fossil fuel infrastructure and have found that, in the absence of early retirement of key infrastructure, the world has already committed itself to enough future emissions to cause global temperatures to reach or even exceed the most ambitious climate targets of the Paris Agreement (10–13). Other inertial factors associated with political systems, corporations, and individual behavioral change are also key contributors to the overall societal inertia that has led to a slow mitigation progress and associated unavoidable future emissions (14).

Another key factor is the role of non-CO_2 greenhouse gases and aerosols, whose contribution to future warming is not captured by the CO_2-only ZEC. Several studies have quantified the ZEC associated with combinations of forcing agents, and while the long-term temperature level remains largely driven by CO_2, aerosols and short-lived greenhouse gases have a large influence on the peak temperature that will be reached after emissions are eliminated (10, 15–17). In particular, the aerosol warming commitment (warming that would occur if the current masking effect of anthropogenic aerosols was abruptly removed) has been flagged as a key threat to the achievement of global temperature targets (18, 19).

A final consideration is that ZEC quantifies the ongoing climate changes resulting from an abrupt elimination of emissions, and this may not be directly transferable to the climate response to a realistic decarbonization scenario. In a scenario where CO_2 emissions decrease to zero over a period of several decades, a portion of current committed CO_2-induced warming (as quantified by ZEC) would manifest during this decarbonization period. ZEC is therefore not a precise estimate of the ongoing warming after net zero CO_2 emissions are achieved in such a scenario. In the case that ZEC is exactly zero, this distinction between an abrupt versus gradual elimination of emissions would be immaterial. However, individual models display a large range of ZEC values (from positive to negative) (20), and the climate response to a decarbonization scenario in a particular model (e.g., 21) would therefore be influenced by that model's positive or negative ZEC value.

Characterizing the climate response to CO_2 emissions

Despite these complications, ZEC is a key metric that helps to quantify the climate response to CO_2 emissions and understand the requirements of climate stabilization. The overall climate response to CO_2 emissions is well characterized by ZEC, in combination with the transient climate response to cumulative CO_2 emissions (TCRE). Where TCRE measures the instantaneous temperature change resulting from a given quantity of cumulative CO_2 emissions (22, 23), ZEC represents the additional long-term change resulting from those same emissions (20, 24).

The overall climate response to CO_2 emissions can therefore be well-represented by different combinations of these two metrics, depending on how CO_2 emissions are changing (see Figure 1). During the period that CO_2 emissions are increasing, the global temperature change is equal to TCRE multiplied by the cumulative emissions to date (E_T). After CO_2 emissions reach net zero, the long-term temperature change is equal to the sum of TCRE * (E_T) and ZEC. Temperature change during the intervening period (characterized by declining CO_2 emissions) is equal to the sum of TCRE * (E_T) and the portion of ZEC that manifests during the transition between peak and net zero CO_2 emissions.

Net zero requirement for climate stabilization

The combination of ZEC and TCRE, as well as an estimate of the non-CO_2 effect on future temperature change, can be used

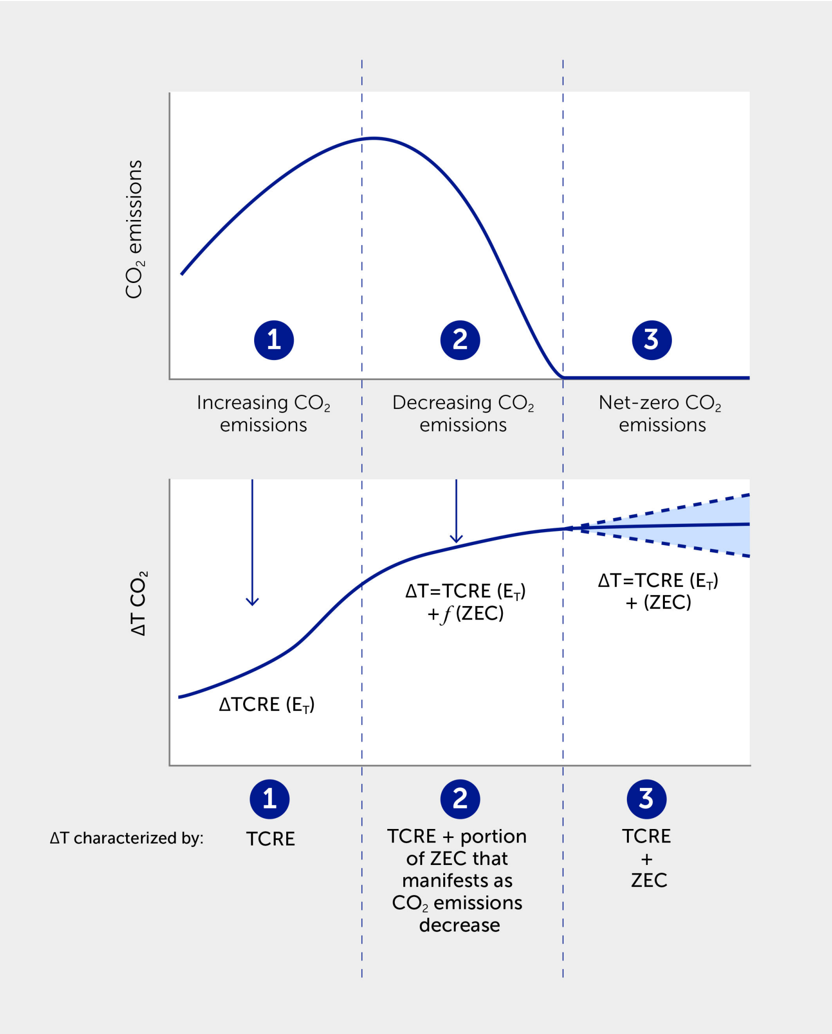

FIGURE 1
Climate response to carbon dioxide (CO_2) emissions. The temperature changes caused by CO_2 emissions are well characterized by the Transient Climate Response to cumulative CO_2 Emissions (TCRE) and the Zero Emissions Commitment (ZEC). When CO_2 emissions are increasing (period 1), temperature change (ΔT) is equal to TCRE * E_T, where E_T represents the cumulative CO_2 emissions to date. After CO_2 emissions reach net zero (period 3), temperature change is equal to the sum of TCRE * E_T and ZEC. In the intervening period, characterized by decreasing CO_2 emissions (period 2), temperature change is equal to TCRE * E_T plus the portion of ZEC that manifests during the transition to net zero CO_2 emissions.

effectively to estimate the remaining carbon budget—the total amount of future CO_2 emissions that is consistent with limiting global temperature to a particular target (23, 25, 26). Recent estimates of the remaining carbon budget have generally adopted a best estimate of zero for ZEC (25, 27), though have also shown that ZEC uncertainty is a key contributor to overall uncertainty on the remaining carbon budget (26). Palazzo Corner et al. (1) reaffirmed this best estimate, suggesting that while ZEC remains a highly uncertain quantity, the balance of current evidence suggests that we should not expect much, if any, additional global warming caused by past CO_2 emissions.

In its Summary for Policymakers, the latest IPCC Assessment Report stated that "limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions" (28). This assessment reflects the current understanding that climate stabilization will require the elimination of net anthropogenic CO_2 emissions, combined with ambitious mitigation of non-CO_2 emissions. ZEC is a key metric underlying the IPCC's conclusions, so continuing to improve and refine our estimate of ZEC will in turn improve our estimates of overall mitigation requirements to limit peak warming and stabilize global temperatures.

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Author contributions

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