CLIMATE CHANGE

The Closing Door of Climate Targets

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The linear relationship between cumulative carbon emissions and global climate warming implies that as mitigation is delayed, climate targets become unachievable.

Robust evidence from a range of climate–carbon cycle models shows that the maximum warming relative to pre-industrial times caused by the emissions of carbon dioxide is nearly proportional to the total amount of emitted anthropogenic carbon (*1*, *2*). This proportionality is a reasonable approximation for simulations covering many emissions scenarios for the time frame 1750 to 2500 (*1*). This linear relationship is remarkable given the different complexities of the models and the wide range of emission scenarios considered. It has direct implications for the possibility of achieving internationally agreed climate targets such as those mentioned in the Copenhagen Accord and the Cancun Agreements (*3*, *4*). Here I explain some of the implications of the linear relationship between peak warming and total cumulative carbon emissions.

The considerations presented here are based on the assumption of a generic set of carbon dioxide emissions scenarios that reasonably approximate what is presently observed and what needs to be done to limit warming below a specific global mean temperature increase. In these idealized and illustrative emissions scenarios (see Box 1), emissions follow an exponential increase with a constant rate until a given year, after which the emissions decrease exponentially at a constant rate. The scenarios delineate the boundaries for any discussion and decision process for global measures limiting anthropogenic climate change.

Results from a large number of Earth system model simulations suggest that peak warming, ΔT, and cumulative CO_2 emissions, C_∞, are nearly linearly related via the parameter β, which is the peak response to cumulative emissions (see Eq. 3 in Box 1). The value of β is estimated to be between 1.3° and 3.9°C per trillion metric tons of carbon (1 TtC = 10^{18} g carbon) (*1*). The uncertainty in β arises from the range of climate sensitivities and carbon cycle feedbacks in the models. More recent estimates of a closely related quantity, the transient climate response to cumulative emissions, take into account observational constraints and report 1.0° to 2.1°C $(TtC)^{-1}$ (*2*). However, this quantity is less useful here because warming can still continue when emissions stop. This warming is better captured by the peak response to cumulative emissions.

For a given β, the peak warming is determined by three quantities in these simple scenarios: the current rate of emission increase, the starting time of the Global Mitigation Scheme (GMS), and the rate of emission reduction realized by the GMS. The latter two depend on future choices and are therefore policy-relevant. As shown in the first figure, a delay in the start of the GMS results in a rapid increase in ΔT as a result of the continued exponential increase in emissions before the start of mitigation. Likewise, for a given starting date of mitigation, achieving a low climate target calls for very aggressive emission decreases. For example, under the present illustrative assumptions, keeping CO_2-induced global warming below 2°C would require emissions reductions of almost 3.2% per year from 2020 onward; this is more than doubled if GMS starts in 2032. Thus, every year counts; if mitigation actions are delayed, much larger emissions reductions are later required to maintain a selected target.

The simple emission pathway provides another important insight. If we assume that the most aggressive GMS is "zero emission" (that is, carbon will not be extracted actively from the atmosphere), the total amount of carbon emitted up to the start of GMS determines the lowest peak warming, or minimum climate target, ΔT_{min} (see Box 1, Eq. 4). An absolute limit then emerges in the climate system for the possibility of satisfying a climate target. Past cumulative emissions up to the time of sustained emissions reductions leave a legacy, or commitment, in the future, irrespective of any long-term mitigation efforts. As the starting time of GMS is delayed, the low climate targets are progressively lost. The door for these climate targets closes irreversibly (second figure, panel A).

Under the present illustrative assumptions, the 1.5°C target expires after 2028, and the 2°C target vanishes after 2044. These times would be later if a period of stabilized emissions preceded the GMS. The more likely situation, however, is that a specific climate target becomes unreachable much earlier, because there are upper limits on sustained emission reduction rates imposed by what the countries' economies can realize collectively given the present state of technology and infrastructure.

Economic models estimate that feasible maximum rates of emissions reduction may not exceed about 5% per year (*5*). Under this assumption, the 1.5°C target has become unachievable before 2012, the 2°C target will become unachievable after 2027, and the 2.5°C target will become unreachable after 2040.

These years are only illustrative of the finite time that climate targets remain available options in the presence of continued greenhouse gas emissions. Uncertainties in β, or in the rate of emission increase, do not change the overall findings (second figure, panel B). But it is clear that reducing uncertainties in the quantity β, which combines climate sensitivity and carbon cycle feedbacks (*2*), is most important for a more reliable estimate of which climate targets are still achievable.

As the emissions scenarios considered here illustrate, even well-intentioned and effective international efforts to limit climate change must face the hard physical reality of certain temperature targets that can no longer be achieved if too much carbon has already been emitted to the atmosphere. Both delay and insufficient mitigation efforts close the door on limiting global mean warming permanently. This constitutes more than a climate change commitment: It is the fast and irreversible shrinking, and eventual disappearance, of the mitigation options with every year of increasing greenhouse gas emissions.

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Box 1. A set of simple analytic greenhouse gas emissions scenarios

For simplicity, we assume that past greenhouse gas emissions followed an exponential path which is a reasonable approximation for historical emissions (*6*). To extract some essential characteristics and consequences of increasing emissions followed by sustained mitigation, we construct a simple emission path that consists of two exponentials,

$$E(t) = \begin{cases} E_0 \cdot e^{r\cdot(t-t_0)} & t_0 < t \le t_1 \\ E_0 \cdot e^{r\cdot(t_1-t_0)} \cdot e^{-s\cdot(t-t_1)} & t > t_1 \end{cases} \qquad (1)$$

where $E(t)$ are the anthropogenic CO_2 emissions at time t, E_0 = 9.3 GtC year^{-1} is the emission at t_0, taken here as the year 2009 (*7*), and r is the rate of emission increase per year until time t_1. The exact path of emissions before t_0 is not important here, because its effect can be taken into account by the cumulative emissions until t_0, C_0. We select C_0 = 530 GtC (*6*). A Global Mitigation Scheme (GMS) starts at time t_1 with emissions reductions at the constant rate of s. We take r = 1.8 % per year, which is somewhat lower than a recent estimate of r (*6*) for the entire historical period, in order to be more consistent with the cumulative emission until 2009 as also estimated by (*6*). Similar peak-and-decline emissions trajectories represented by analytical functions were used recently (*8*), with a smooth transition path to sustained emissions reductions.

The scenario path for $t > t_1$ in Eq. 1 implies that negative emissions (active removal of carbon from the atmosphere) on a global scale will not be realized anytime in the future. This should be considered as a conservative, but likely realistic, assumption. The total cumulative emissions C_∞ follow from Eq. 1 and are given by

$$\begin{aligned} C_\infty &= C_0 + \int_{t_0}^{+\infty} E(t)dt \\ &= C_0 + E_0 \cdot (\tfrac{1}{r} + \tfrac{1}{s}) \cdot e^{r\cdot(t_1-t_0)} - \tfrac{1}{r} E_0 \end{aligned} \qquad (2)$$

This simple scenario can be used to illustrate some fundamental and policy-relevant consequences of the robust linear relationship between peak warming and cumulative emissions. I consider implicitly only long-lived greenhouse gases, which is appropriate unless temperatures peak in the next few decades.

Simulations with many Earth system models (*1*, *2*) show a near linear relationship between peak warming, ΔT, and cumulative CO_2 emissions, C_∞,

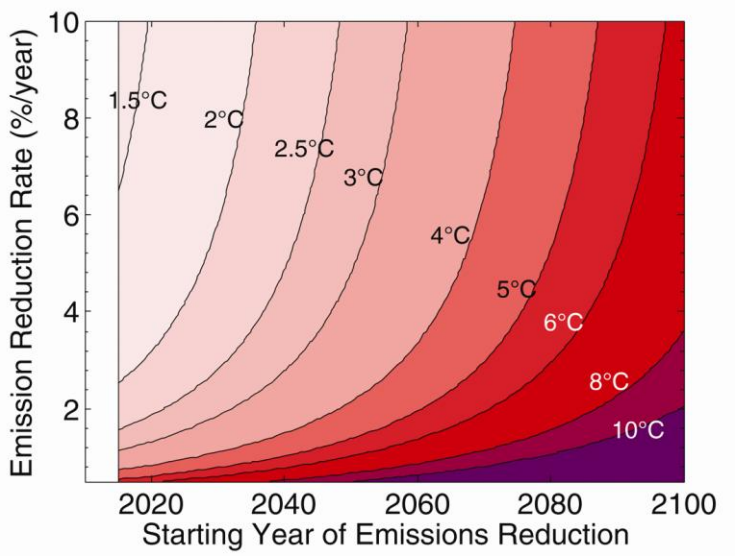
$$\Delta T = \beta \cdot C_\infty \qquad (3)$$

where β is the factor of proportionality between cumulative emissions and peak warming and is referred to as the peak response to cumulative emissions.

By taking in Eq. 2 the limit of $s = \infty$, and using Eq. 3, one obtains

$$\Delta T_{\min} = \beta \cdot (C_0 + \tfrac{1}{r} E_0 \cdot (e^{r\cdot(t_1-t_0)} - 1)) = \beta \cdot C_1 \quad (4)$$

which is the minimum peak warming resulting from the most aggressive GMS, that is, zero emissions from time t_1 onwards. Achievable climate targets are therefore determined by the cumulative emissions until time t_1, C_1.



Contours of peak warming. Contours of peak CO_2-induced warming (as given by Eq. 3 in Box 1) as a function of the starting date of the Global Mitigation Scheme and the implemented reduction rate of emissions. Parameters are C_0 = 530 GtC, E_0 = 9.3 GtC per year, β = 2°C $(TtC)^{-1}$, and r = 1.8% per year. The later the Global Mitigation Scheme starts, the higher the required emission reduction rate is for a given peak warming.

A closing door. (**A**) Contours of required emission reduction rate s (% per year), derived from Eq. 3, as a function of the starting date of the Global Mitigation Scheme and the desired climate target. The red line indicates the achievable minimum climate target as a function of the starting date as given by Eq. 4. Climate targets increase exponentially with later starting years of the Global Mitigation Scheme and become unachievable in the gray shaded area. Parameters are as in the first figure. (**B**) Achievable minimum climate target for three values of the peak response to cumulative emissions, β, and the rate of emission increase used in the first figure (solid curves, r = 1.8 % per year), and a lower emission rate roughly representative of the past 10 years, r = 1.5% per year (dashed curves). Higher values of β imply higher peak warming.