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Drivers of peak warming in a consumption-maximizing world

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Peak human-induced warming is primarily determined by cumulative CO_2 emissions up to the time they are reduced to zero[1–3]. In an idealized economically optimal scenario[4,5], warming continues until the social cost of carbon, which increases with both temperature and consumption because of greater willingness to pay for climate change avoidance in a prosperous world, exceeds the marginal cost of abatement at zero emissions, which is the cost of preventing, or recapturing, the last net tonne of CO_2 emissions. Here I show that, under these conditions, peak warming is primarily determined by two quantities that are directly affected by near-term policy: the cost of 'backstop' mitigation measures available as temperatures approach their peak (those whose cost per tonne abated does not increase as emissions fall to zero); and the average carbon intensity of growth (the ratio between average emissions and the average rate of economic growth) between now and the time of peak warming. Backstop costs are particularly important at low peak warming levels. This highlights the importance of maintaining economic growth in a carbon-constrained world and reducing the cost of backstop measures, such as large-scale CO_2 removal, in any ambitious consumption-maximizing strategy to limit peak warming.

Under a traditional consumption-maximizing approach to climate policy, the benefits minus the costs of climate mitigation are maximized by reducing CO_2 emissions until the marginal abatement cost (MAC) of avoiding one more tonne of emissions is equal to the social cost of carbon (SCC), or the marginal harm done by emitting that tonne[6]. Although criticized as a policy-prescription tool[7], benefit–cost analysis remains useful 'to highlight the critical issues' in climate policy[8]. Many integrated assessment studies focus on identifying an 'optimal' (benefit–cost-maximizing) abatement path as a function of time[4–6], although integrated assessment can also be used to identify cost-effective paths[9] to a given temperature goal, and current international climate goals, consistent with the millennial-timescale impacts of cumulative CO_2 emissions[1,2], refer to peak warming, irrespective of timescale. A purist might question timescale-independent and response-independent[10] goals, but this opens normative issues that we do not address here. Instead, we focus on a diagnostic question: under an optimal benefit–cost-maximizing abatement strategy, what determines peak warming? In the spirit of ref. 5, we use a minimal-complexity form to clarify key assumptions and their implications.

Many integrated assessment models adopt, explicitly or implicitly, the following function for the real monetary cost per year of global climate impacts:

$$S_t = W_t D_0 T_t^{\gamma} \qquad (1)$$

where W_t represents total annual consumption and T_t is the increase in global average temperature relative to pre-industrial conditions at time t. D_0 is here defined as the damage done, as a fraction of global consumption, by 1 °C of warming and γ determines how impacts accelerate with rising temperatures. This expression applies only to less extreme levels of warming: we focus here on the range 0–3.5 °C. Other functional forms can be used to represent nonlinear climate change or impacts[11,12], but over this range and at the level of precision of aggregate impacts, most can be approximated by some combination of D_0 and γ. For simplicity, we focus on consumption, not welfare, so S_t scales with W_t: a rich world might be better able to cope with a 1% consumption loss than a poor world, but that 1% would still represents a larger loss in monetary terms. Computed in terms of welfare, impacts could still rise with global consumption[13], depending on what happens to regions or sectors most impacted.

Under conventional time discounting, the SCC is defined as

$$\mathrm{SCC}_t = \int_{t'=0}^{\infty} \delta S_{t+t'} \mathrm{e}^{-rt'} \mathrm{d}t' \qquad (2)$$

where $\delta S_{t+t'}$ is the marginal impact on S at time $t+t'$ resulting from the emission of one tonne of CO_2 at time t and r is the consumption discount rate. We assume that W is only marginally affected by climate change[14] over the period t to t'. In the long run, the cumulative impact of climate change on W through its impact on the consumption growth rate g might be very substantial[15], but our focus here is on drivers of the SCC at any given time, for which this impact can be approximated by adjusting the values of D_0 and γ.

Finally, the observation that global temperatures increase in line with cumulative CO_2 emissions suggests a very simple expression for the temperature response to a pulse emission of an additional tonne of CO_2 at time t:

$$\delta T_{t+t'} = T_{\mathrm{TCRE}} \left(1 - \mathrm{e}^{-k_s t'}\right) \qquad (3)$$

where k_s^{-1} is the initial pulse-adjustment timescale (IPT) of the climate system[16,17], which is of the order of a decade or less, and T_{TCRE} is the transient climate response to cumulative carbon emissions, which is approximately constant (see Methods). Despite its simplicity, this expression is supported by pulse-injection and sustained emission experiments with more comprehensive models[18,19] for cumulative emissions up to 5,000 $GtCO_2$ (ref. 20). It applies to CO_2-induced warming: the simplest way to accommodate other agents is to assume that total anthropogenic warming remains, as now, approximately 10% greater than CO_2-induced warming[3,21] and adjust T_{TCRE} accordingly. This may be optimistic: other factors could add up to 0.5 °C to peak temperatures even under stringent mitigation scenarios[1], but it has also been argued that aggressive

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action could more than halve this non-CO_2 warming[22], returning it to about 10% of the total.

Despite its simplicity, this formulation allows us to make some observations about the mitigation problem. For example, suppose an approach to abatement yields a MAC that is inversely proportional to the carbon intensity of global consumption, so the fractional consumption loss due to each successive percentage emissions reduction is the same as the last, as less productive uses of fossil carbon are eliminated, or $\mathrm{MAC}_t = A_E W_t / E_t$, with A_E (the initial MAC times the carbon intensity of consumption) approximately constant. In the long run, for relatively low discount rates ($k_s \gg r-g$), this yields an approximate (see Methods) benefit–cost-maximizing rate of emission of

$$E_t \approx \frac{A_E\,(r-g)}{\gamma D_0 T_{\mathrm{TCRE}} T_t^{\gamma-1}} \quad (4)$$

Emissions eventually fall as temperatures rise, provided $\gamma > 1$, but never reach zero because the marginal benefits of emitting one more tonne of CO_2 always exceed the social cost.

The assumption that marginal abatement costs rise indefinitely as emissions fall is, however, unrealistic[23]. Eventually it becomes economic to deploy a 'backstop' package of mitigation measures for which the cost per tonne abated, A_B, does not depend on E, or the availability of emissions to mitigate[24]. We do not assume that A_B is constant over time, but we do require that it does not increase as fast as W_t. This would be the case if A_B is dominated by the cost of energy for CO_2 disposal, for example, but not if A_B represents the cost of a global ban on fossil carbon use. Both the opportunity and enforcement costs of such a ban would probably increase faster than W_t.

In this consumption-maximizing framework, there is a unique relationship (see Methods) between this final mitigation cost A_B, peak temperature $T_{\max}$, and the ratio between the (geometric) average rate of economic growth $\tilde{g}$ and average emissions $\bar{E}$ between now and the time at which temperatures peak (when emissions reach zero):

$$A_B = \gamma G T_{\max}^{\gamma-1} \exp\left(\frac{\tilde{g}}{\bar{E}} \frac{(T_{\max} - T_0)}{T_{\mathrm{TCRE}}}\right) \quad (5)$$

where γ, G (a constant defined in the Methods) and T_{TCRE} all depend on the physical response of the climate system and future adaptation and discounting decisions, but not on near-term mitigation policy. This relationship holds whether or not consumption growth g is affected by climate change and does not require g at the time of peak warming to be equal to $\tilde{g}$ in the meantime, but it does assume that consumption continues to grow, and the SCC with it. It also assumes that temperatures remain constant over the discounting timescale $(r-g)^{-1}$ after their peak, which excludes aggressive geoengineering scenarios.

Figure 1 shows how peak warming $T_{\max}$ varies as a function of A_B (the marginal cost of reducing net CO_2 emissions to zero) and $\tilde{g}$ (average rate of future economic growth), assuming backstop mitigation measures are available and deployed when the benefits outweigh the costs, an $\bar{E}$ of 75% of the 2014 rate (a mid-range value for $\bar{E}$ in the mitigation scenarios of ref. 23), a 'growth-corrected discount rate'[8,24] $r-g = 1.5\%$ per year at the time of peak warming, and other geophysical and economic parameters given in the Methods.

Figure 1 illustrates a number of points. First, growth matters, provided mitigation measures are available and deployed when socially cost-effective. In a consumption-maximizing framework, for any A_B, the faster we can grow the world economy while not allowing average emissions to rise, the faster the monetary value of the SCC rises and the sooner our descendants will find it cost-effective to reduce emissions to zero.

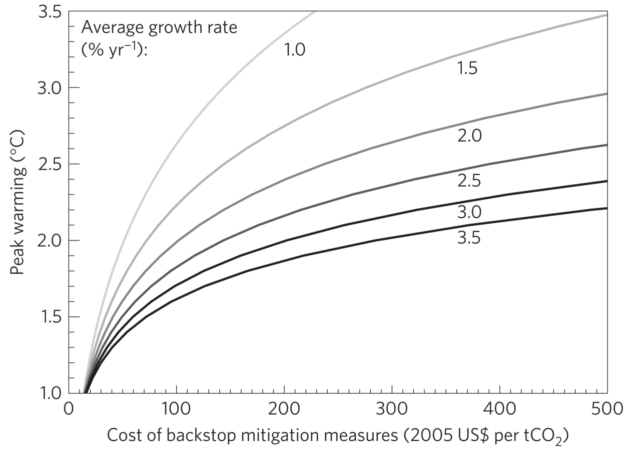

Figure 1 | The relationship between peak warming, final mitigation costs and economic growth. The figure shows the cost of a backstop mitigation technology (or combination of technologies) capable of reducing net CO_2 emissions to zero that is required to achieve various levels of peak warming, assuming that a consumption-maximizing decision is taken on technology deployment. Average emissions are assumed to be 75% of their 2014 level between now and when emissions reach zero, average future economic growth as shown and other parameters and assumptions given in the Methods.

Second, the central role played by $\tilde{g}/\bar{E}$ highlights the importance of the carbon intensity of growth, which is naturally defined as the ratio of CO_2 emissions to the rate of consumption growth, or E_t/g_t, where $g_t = (\mathrm{d}W_t/\mathrm{d}t)/W_t$. This phrase has also been used to refer to the carbon intensity of new production, or $\mathrm{d}(E_t/W_t)/\mathrm{d}t$ (ref. 25), but the distinction is important: what matters for peak warming is the total emissions used to achieve a given rate of economic growth, not the marginal change in emissions associated with new production. Emission reduction measures that reduce the long-term rate of economic growth could be environmentally counterproductive if they impair the ability of future generations to reduce emissions to zero. Conversely, measures that permanently reduce emissions while only temporarily reducing the rate of consumption growth have a positive impact, because they would increase g/E in future. Countries with relatively high per-capita emissions and moderate economic growth have, on this analysis, a particular responsibility to invest in reducing the cost of the backstop technology, A_B, to reduce peak warming.

Finally, the existence of at least one technology capable of reducing net CO_2 emissions to zero is crucial. This is important, because we still do not know what this technology is, never mind what it will cost to deploy at the necessary scale. Some properties are evident. It is not simply a substitute for fossil energy in a particular application, such as power generation: it is a completely effective substitute in every application[24], including those for which fossil energy is most attractive, such as high-density transport fuels. Given the vast range of services provide by fossil fuels, the simplest hypothesis is that the backstop represents the cost of atmospheric CO_2 removal. This explains the recent finding that the availability of carbon capture and sequestration (CCS), which, combined with biomass energy (BECCS), plays the role of the backstop in many aggressive mitigation scenarios, is the key determinant of the cost of maintaining temperatures below 2 °C (refs 23,26). Our results suggest that the cost of CO_2 removal will remain critical under higher scenarios.

Even if a perfect substitute for fossil fuels were developed, if it were to cost more than the marginal cost of extraction of the cheapest fossil fuel, some fossil CO_2 emissions would continue in the absence of a complete global ban on fossil fuel extraction and use. Stabilizing temperatures would require these recalcitrant emissions to be compensated for by atmospheric CO_2 removal. This is why the cost of CO_2 removal and disposal is likely to determine the marginal cost of reducing net CO_2 emissions to zero even if other measures are responsible for the bulk of emission reductions: complete substitution for fossil fuels in all applications requires complete global compliance, whereas large-scale deployment of CO_2 removal does not[27,28].

Estimates of the cost of CO_2 removal and disposal[26] vary from less than US$ 200 to over US$ 1,000 per tCO_2 and depend heavily on how costs may change as these technologies are deployed at scale (accounting for the land and freshwater requirements for BECCS, for example). The convex relationship between SCC_{t_1} and T_{max} means that peak warming is, in a benefit–cost-maximizing calculation, relatively insensitive to the cost of the backstop technology at higher levels of peak warming and higher growth rates. This may be understood as an instance of 'Malthusian optimism': if the SCC is a temperature-dependent multiple of global consumption W_t, and W_t doubles every 30 years, then a doubling of the cost of the backstop technology implies only a few decades' delay in its deployment. The cost of the backstop technology becomes much more important in a low-growth world or for lower levels of peak warming. This is particularly germane to discussion[29] of limiting warming to "well below 2 °C". Achieving this, under the conditions shown in Fig. 1, would seem to require either very optimistic assumptions about future rates of economic growth, or for the cost of backstop mitigation options such as large-scale CO_2 removal[30] to be reduced to US$ 100 per tCO_2 or less. Alternatively, future decision makers might assign a higher value to climate damages, by adopting a lower growth-corrected discount rate or higher values of D_0 or γ (perhaps motivated by welfare and equity considerations), or to reduce emissions below the level indicated by benefit–cost maximization (on precautionary grounds, for example).

Despite, or rather because of, its simplicity, this framework allows us to illustrate some important factors determining peak warming in a consumption-maximizing world. We do not address whether consumption maximization should be a policy objective or the assumption of sustained exponential consumption growth: the aim is simply to make their implications clear. The focus of integrated assessment is often on the initial carbon price trajectory, which is strongly dependent on the discount rate employed today[5]. As a result, peak warming emerges as a consequence of a numerical calculation, with the role of backstop technologies, economic growth and the discount rates employed by future generations not always transparent. Discussion of backstop mitigation options, such as CO_2 removal, is often dismissed as a distraction from the need to reduce emissions now. The analysis described above suggests that the converse may be true: focusing exclusively on short-term emission reduction may be distracting us from what really matters for peak warming.

Methods

Methods and any associated references are available in the online version of the paper.

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Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints.

Competing financial interests

The author declares no competing financial interests.

Methods

The invariance of T_{TCRE} over a range of cumulative emissions from zero to over 5,000 $GtCO_2$ arises from the approximate cancellation of the logarithmic relationship between CO_2 concentrations and radiative forcing, and the increasing airborne fraction of emissions due to saturation of ocean and land carbon sinks[19]. The temperature response to a CO_2 pulse remains near its peak value, which emerges within about a decade, for a century or more in comprehensive Earth system models because of the cancellation between the 'recalcitrant' component of the thermal response[16] and the slow uptake of carbon by the deep ocean and adjustment of land carbon sinks[18]. Hence rapid adjustment to a constant temperature set by the TCRE is an adequate representation provided $r-g$ focuses on sub-century timescales. Temperatures can decline after their peak in simplified models if important climate–carbon cycle feedbacks are omitted[17].

Under the assumptions given in the main text, the monetary value of climate change impacts due to a warming of δT at time $t+t'$ is given by

$$\delta S_{t+t'} = \left(\frac{\partial S}{\partial T}\right)\delta T_{t+t'} = \gamma D_0 W_{t+t'} T_{t+t'}^{\gamma-1}\delta T_{t+t'} \quad (6)$$

Hence the SCC at time t is a function of both the size of the world economy and the expected temperature after t

$$\text{SCC}_t = \gamma D_0 T_{\text{TCRE}} \int_{t'=0}^{\infty} W_{t+t'} T_{t+t'}^{\gamma-1}\left(1-e^{-k_s t'}\right)e^{-rt'}\,dt \quad (7)$$

If global consumption (inflation-adjusted output minus investment) is rising exponentially at a rate g (which may be affected by climate change), so $W_{t+t'} = W_t e^{gt'}$, and temperatures are rising or falling linearly at a rate T', so $T_{t+t'} = T_t + T't'$, then

$$\text{SCC}_t = \gamma W_t D_0 T_{\text{TCRE}} \int_{t'=0}^{\infty}\left(T_t + T't'\right)^{\gamma-1}\left(1-e^{-k_s t'}\right)e^{-(r-g)t'}\,dt' \quad (8)$$

For relatively slow rates of warming, such that $T'/T_t \ll r-g$ (necessarily the case in all but the most aggressive geoengineering scenarios as temperatures approach their peak), this gives

$$\text{SCC}_t = \gamma W_t D_0 T_{\text{TCRE}} T_t^{\gamma-1}\left[\left(\frac{1}{r-g} - \frac{1}{k_s + r-g}\right) + \frac{(\gamma-1)T'}{T_t}\left(\frac{1}{(r-g)^2} - \frac{1}{(k_s+r-g)^2}\right)\right] \quad (9)$$

This expression can be used to identify approximate benefit–cost-maximizing emission paths, provided the impact of climate change on growth can be neglected over the discounting timescale $(r-g)^{-1}$. For example, if $k_s \gg r-g$ and T' is small, then setting $\text{SCC}_t = \text{MAC}_t = A_E W_t / E_t$ gives the expression for long-run emissions in equation (4). Note that if $\gamma = 1$, the SCC scales exactly with W_t, making it constant in terms of welfare[5].

The linear relationship between cumulative carbon emissions and future temperatures implies that $T_t \approx T_0 + T_{\text{TCRE}}\bar{E}(t-t_0)$, where T_0 is global temperature today, at t_0, and $\bar{E}$ is the arithmetic mean of the annual emission rate between now and time t. Total consumption at time t is $W_t = W_0 e^{\tilde{g}(t-t_0)}$, where W_0 is total consumption today and $\tilde{g}$ is the geometric mean of the economic growth rate between now and time t. Combining these gives:

$$W_t = W_0 \exp\left(\frac{\tilde{g}}{\bar{E}}\frac{(T_t - T_0)}{T_{\text{TCRE}}}\right) \quad (10)$$

If t_1 is the time at which CO_2 emissions reach zero, and hence temperatures peak (so $T'=0$) at $T_{t_1} = T_{\max}$, then the SCC at time t_1 is:

$$\text{SCC}_{t_1} = \gamma\left[W_0 D_0 T_{\text{TCRE}}\left(\frac{1}{r-g} - \frac{1}{k_s + r-g}\right)\right] \times T_{\max}^{\gamma-1}\exp\left(\frac{\tilde{g}}{\bar{E}}\frac{(T_{\max}-T_0)}{T_{\text{TCRE}}}\right) \quad (11)$$

where the term in square brackets is the constant G in equation (5). The quantity $r-g$, or 'growth-corrected discount rate'[8,24], emerges as a key parameter. Under logarithmic utility and a single globally representative agent, this is simply the pure rate of time preference (PRTP). The value of the PRTP that matters for peak warming, however, is not that used today, or how the current generation values the welfare of its descendants, but how those alive at time t_1, when temperatures peak, value the welfare of their descendants. This cannot be specified today, but may be affected indirectly by near-term decisions.

Geophysical and economic parameters used in Fig. 1 are $\gamma = 2$, $W_0 = 75 \times 10^{12}$ 2005 US\$, $D_0 = 0.00267$ for the fractional loss of global consumption due to a 1 °C warming[31], $T_0 = 0.9$ °C (ref. 21) and $k_s = 0.12$ per year[1,16,17]. All of these are uncertain, but are not directly affected by climate policy. If $r-g = 1.5\%$, they indicate an SCC of US\$ 25 per tCO_2 in 2015 rising to over US\$ 100 per tCO_2 by 2050, within the broad range of other studies[11]. Figure 1 uses a mid-range T_{TCRE} of 0.00054 °C per $GtCO_2$ (0.002 °C per GtC), which is 20% higher than the ratio of total anthropogenic warming to cumulative CO_2 emissions so far[3,21], but 20% lower than the 'likely' upper bound for this ratio at the time of peak warming in 2 °C scenarios[1]. A spreadsheet is provided (Supplementary Information) to facilitate sensitivity analysis.

We do not assume that $\bar{E}$ is exogenous because this is a diagnostic model: for any combination of $\tilde{g}/\bar{E}$ and A_B, what $T_{\max}$ emerges? Average future emissions $\bar{E}$ between now and when they reach zero depend on the emission path. If emissions peak immediately and decline linearly, then $\bar{E} = E_0/2$, where E_0 is the 2014 emission rate (39 $GtCO_2$ per year[32]). If emissions follow a quadratic profile, continuing to rise for 33% of the time between now and when they reach zero, peaking 33% higher than today, then $\bar{E} = E_0$. In the mitigation scenarios (initialized in 2005, with policies in most cases beginning to take effect in 2010) considered by IPCC WGIII (ref. 23) that achieve zero CO_2 emissions before 2100 without significant radiative forcing overshoot, $\bar{E} = 0.6E_0$ on average, with a range of 0.3–0.9. Figure 1 shows an illustrative case $\bar{E} = 0.75E_0$, consistent with the observation that near-term projected decarbonization rates are generally slower than those achieved in many of the WGIII scenarios.

Figure 1 shows one set of choices for non-policy parameters. Increasing D_0 (to account for impact uncertainty, or the effect of consumption inequalities on welfare[13]) or γ (greater nonlinearity) would all shift the lines downwards: the worse climate change turns out to be, the sooner our descendants, if they maximize consumption, would deploy a backstop CO_2 removal technology at a given cost. Increasing T_{TCRE} (higher climate response, or higher ratio of total to CO_2-induced warming) or $r-g$ (growth-corrected discount rate at the time of peak warming) both shift the lines upwards: higher peak warming for a given backstop technology cost. See the spreadsheet in the Supplementary Information.

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