Drivers of peak warming in a utility-maximising world

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We consider the implications of the linear relationship between cumulative carbon emissions and global temperatures[1,2,3] for peak warming in an idealised integrated assessment[4,5] framework. Under conventional assumptions about climate damage, economic growth, mitigation decisions and discounting, peak warming is determined by only two quantities that are directly affected by near-term mitigation policy: the cost of a 'backstop' mitigation technology that reduces net carbon dioxide emissions to zero; and the growth productivity of carbon, or the ratio between the average rate of economic growth and average emissions between now and the time of peak warming. This highlights the importance of maintaining economic growth in a carbon-constrained world and investing in backstop technologies, such as large-scale carbon dioxide removal, in any utility-maximising strategy to limit peak warming.

Under a traditional utility-maximising approach to climate policy, the benefits minus the costs of climate mitigation are maximised by reducing 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 criticised for comparing incommensurable costs,[7] conflicting with basic notions of human values[8] or rights,[9] benefit-cost analysis remains a useful tool for assessing the relative importance of different elements in climate policy. Most integrated assessment studies focus on the "opening game", or drivers of mitigation policy in the immediate future. Here we focus on the "end game", identifying drivers of peak warming in a utility-maximising framework. 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:

$$S_t = W_t D_0 T_t^{\gamma}$$

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 the damage done, as a fraction of global consumption, by 1°C warming and γ determines how impacts accelerate with rising temperatures. Other functional forms are used to represent non-linear climate change or impacts,[10,11] but at the level of precision of aggregate impacts, most can be approximated by some combination of D_0 and γ.

S represents aggregate impact on consumption, not welfare: 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. A disaggregated model in which welfare impacts on rich and poor regions or social groups are computed separately might give a different value for D_0, but still the same overall functional form for S,[12] except in the case that impacts are predominantly on regions or social groups whose incomes are decoupled from the overall growth of global consumption. This might happen in principle, but does not happen in the majority of integrated assessment calculations, so the crucial assertion that impacts scale with global consumption is almost ubiquitous.

Under conventional Ramsey discounting, the SCC is defined as

$$\mathrm{SCC}_{t_1} = \int_{t=0}^{\infty} \delta S_{t+t_1} e^{-rt} dt$$

where δS_{t+t_1} is the marginal impact on S at time $t + t_1$ resulting from the emission of one tonne of carbon dioxide ($\mathrm{CO_2}$) at time t_1 and r is the consumption discount rate, $r = \rho + \eta g$, where ρ is the pure rate of time preference, η is a measure of aversion to inequality and g is the consumption growth rate. If g is only marginally affected by climate change, which is clearly contestable,[13] we have

$$\delta S_{t+t_1} = \left(\frac{\partial S}{\partial T}\right) \delta T_{t+t_1} = \gamma D_0 W_{t+t_1} T_{t+t_1}^{\gamma-1} \delta T_{t+t_1}$$

In the long run, the cumulative impact of climate change on consumption through its impact on g might be very substantial[14] but our focus here is on drivers of the SCC at any given time, for which this impact can also be approximated by adjusting the values of D_0 and γ.

Finally, the observation that global temperatures increase in line with cumulative $\mathrm{CO_2}$ emissions suggests a very simple expression for the temperature perturbation at time $t + t_1$ resulting from the emission of an additional tonne of $\mathrm{CO_2}$ at time t_1:

$$\delta T_{t+t_1} = T_{\mathrm{TCRE}} (1 - e^{-k_s t})$$

where the Transient Climate Response to Cumulative Carbon Emissions, T_{TCRE}, is approximately constant and k_{s} is the rate constant for the "fast" component of the thermal adjustment of the climate system to radiative forcing,[15] which is of order a decade or less. The invariance of T_{TCRE} over a range of cumulative emissions from zero to 10,000 billion tonnes of $\mathrm{CO_2}$ ($\mathrm{GtCO_2}$) arises from the approximate cancellation between the logarithmic relationship between $\mathrm{CO_2}$ concentrations and radiative forcing and the increasing airborne fraction of emissions due to saturation of carbon sinks.[16]

This expression applies to $\mathrm{CO_2}$-induced warming. The simplest way to accommodate other agents is to assume that future total anthropogenic warming remains, as now, approximately 10% greater than $\mathrm{CO_2}$-induced warming and adjust T_{TCRE} accordingly. Although $\mathrm{CO_2}$ emissions dominate long-term warming, other agents could add up to 0.5°C to peak temperatures even under stringent mitigation scenarios.[1]

It is straightforward to show (see Methods Summary), in this utility-maximising framework, that there is a unique relationship between peak temperature T_1 and only two quantities that we can influence through mitigation policy in the near future: the cost, S_{B}, of the 'backstop' technology that removes the last tonne of global emissions, or the MAC as emissions reach zero; and the ratio between the average rate of economic growth $\bar{g}$ and average emissions $\bar{E}$ between now and the time emissions reach zero:

$$\mathrm{S_B} = AT_1^{\gamma-1}\exp\left(\frac{\bar{g}}{\bar{E}}\frac{(T_1 - T_0)}{T_{\mathrm{TCRE}}}\right)$$

where γ, A 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 $\bar{g}$ in the meantime, but it does assume that consumption continues to grow, and the SCC with it.

The figure shows how S_{B}, the required cost of a backstop technology capable of reducing net CO_2 emissions to zero, varies as a function of peak warming and average rates of future economic growth, assuming that this technology is available and deployed when the benefits outweigh the costs, and using geophysical and economic parameters given in the Methods Summary, an $\bar{E}$ of 90% of today's emission rate (hence assuming some further increase followed by decline) and a subjective discount rate at the time of peak warming of $r - g =$ 1.5% per year.

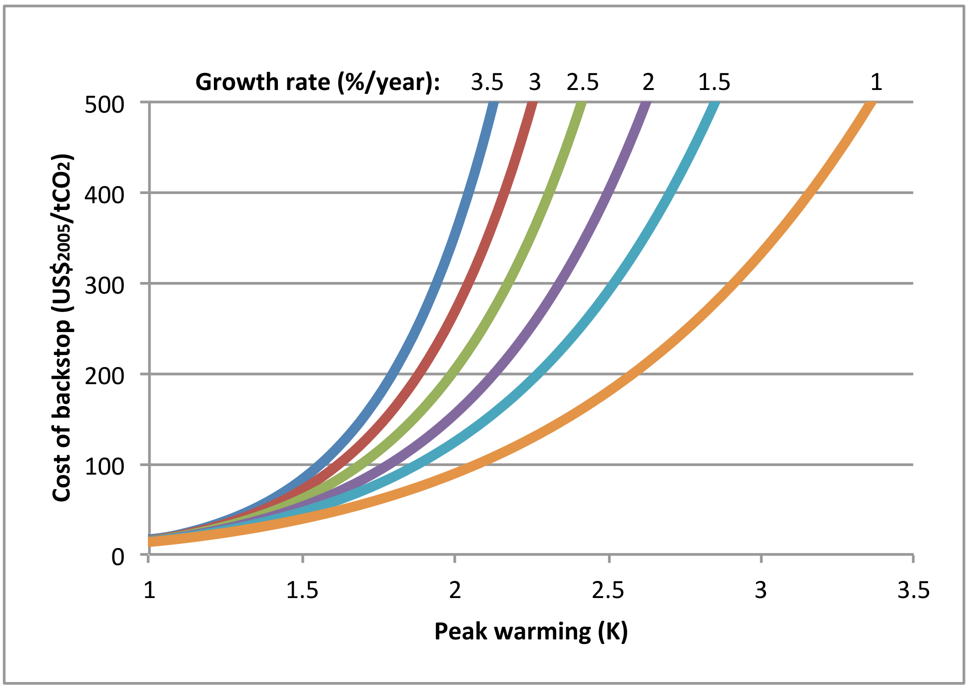

Figure: The relationship between economic growth, final mitigation costs and peak warming. The figure shows the cost of a backstop mitigation technology capable of reducing net CO_2 emissions to zero that is required to achieve various levels of peak warming for a range of rates of average future economic growth, assuming a utility-maximising decision is taken on technology deployment, average emissions of 36 $GtCO_2$/year between now and when emissions reach zero, a subjective discount rate at the time of peak warming of 1.5%/year and other parameters given in the Methods Summary.

The figure illustrates a number of points. First, growth matters: in a utility-maximising framework, for any S_{B}, the faster we can grow the world economy while not allowing average emissions to rise, the faster the monetary value of the social cost of carbon rises and the sooner our descendants will, if they choose to maximise utility, reduce emissions to zero. They might, of course, decide to stabilise temperatures at a lower level, sacrificing global consumption for the sake of minimising impacts on vulnerable societies or ecosystems. Conversely, they might be insufficiently well organised to deploy abatement measures as they become socially cost-effective, or crucial technologies might not be available at the scale required when needed.

Second, the ratio between the geometric mean rate of economic growth $\bar{g}$ and the arithmetic mean of future emissions $\bar{E}$ emerges as a critical parameter, illustrating the "Malthusian optimism" of such integrated assessment calculations. Provided consumption continues to grow exponentially while emissions do not, then eventually our descendants will find it is in their interest to stabilise climate. The expectation of sustained exponential consumption growth over a period of changing climate and stabilising population is contestable, but even if it is not assumed explicitly, it typically emerges from most integrated assessment calculations.

The central role played by $\bar{g}/\bar{E}$ highlights the importance of carbon productivity[17] in mitigation policy, with a twist: what matters is not so much the growth of carbon productivity, or the difference between the consumption and emission growth rates, but the growth productivity of carbon, or the consumption growth achieved per unit of emissions. If consumption growth is assumed, then the only way of increasing $\bar{g}/\bar{E}$ is by decreasing emissions, so this framework in no way detracts from the need for short-term decarbonisation. It does, however, support the contention that measures should be assessed in terms of their impact on the growth productivity of carbon rather than their impact on emissions *per se*. Measures to reduce emissions that also reduce the rate of economic growth, as well as likely being politically unacceptable, could also be environmentally counterproductive if they impair the ability of future generations to reduce emissions to zero. That said, measures that permanently reduce emissions while only temporarily reducing the rate of consumption growth have a positive impact, since they would increase g/E in future.

Finally, the existence of a backstop technology, capable of reducing net carbon dioxide 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, 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, or some combination of artificial or biomass-based air capture with either geological sequestration or remineralisation. This explains the recent finding that the availability of carbon capture and sequestration, which, combined with biomass energy, plays the role in the backstop in many aggressive mitigation scenarios, is the key determinant of the cost of maintaining temperatures below 2°C.[18,19] Our results suggest that the cost of CO_2 removal will also 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.[20,21]

Estimates of the cost of CO_2 removal and disposal vary from less than \$200 to over \$1000/tCO$_2$[18] and depend heavily on how costs may change as these technologies are deployed at scale (accounting for the land and freshwater requirements for biomass energy with carbon capture and sequestration, for example). Fortunately, the convex relationship between SCC_{t_1} and T_1 means that peak warming is, in a utility-maximising calculation, surprisingly insensitive to the cost of the backstop technology, provided growth can be maintained in a world of constrained emissions. The reason is that, if the social cost of carbon is a temperature-dependent multiple of global consumption W_t, and W_t doubles every 30 years or so, then a doubling of the cost of the backstop technology implies only a few decades' delay in deployment. If future growth is maintained at 2.5% per year without emissions (averaged over time) rising substantially above present-day levels, then a \$200/tCO$_2$ cost of CO_2 removal would imply temperatures peaking around 2°C, while \$400/tCO$_2$ would imply peak temperatures around 2.3°C, with these parameters. The cost of the backstop technology becomes much more important in a low-growth world. It also becomes important at low values: if large-scale CO_2 removal can actually be achieved for as little as \$100/tCO$_2$,[22] then the prospects of maintaining global temperatures below 2°C, under these assumptions, are good even at relatively low rates of economic growth.

Despite, or rather because of, its simplicity, this framework allows us to illustrate some important factors determining peak warming in a utility-maximising world. Some may find our conclusions so counter-intuitive they lead them to question utility-maximisation as a policy objective or the assumption of sustained exponential consumption growth. But since these are ubiquitous features of integrated assessment calculations, it remains helpful 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] This is understandable, given the need for immediate policy advice. But as a result, peak warming emerges as a consequence of a numerical calculation, with the role of assumptions about 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. This note suggests that the converse may be true: focussing exclusively on short-term emission reduction may be distracting us from what really matters for peak warming.[21]

Methods Summary:

The SCC at time t_1 is a function of both the size of the world economy and the expected temperature after t_1

$$\mathrm{SCC}_{t_1} = \gamma D_0 T_{\mathrm{TCRE}} \int_{t=0}^{\infty} W_{t+t_1} T_{t+t_1}^{\gamma-1} (1 - e^{-k_s t}) e^{-rt} dt$$

If global consumption (inflation-adjusted output minus investment) is rising exponentially at a rate g (which may be affected by climate change), so $W_{t+t_1} = W_1 e^{gt}$, and temperatures are rising or falling linearly at a rate T', so $T_{t+t_1} = T_1 + T't$, then

$$\mathrm{SCC}_{t_1} = \gamma W_1 D_0 T_{\mathrm{TCRE}} \int_{t=0}^{\infty} (T_1 + T't)^{\gamma-1} (1 - e^{-k_s t}) e^{-(r-g)t} dt$$

For relatively slow rates of warming, such that $T'/T_1 \ll r - g$, this gives

$$\begin{aligned}\mathrm{SCC}_{t_1} = \gamma W_1 D_0 T_{\mathrm{TCRE}} T_1^{\gamma-1} \Bigg[& \left(\frac{1}{r-g} - \frac{1}{k_\mathrm{s} + r - g}\right) \\ & + \frac{(\gamma-1)T'}{T_1}\left(\frac{1}{(r-g)^2} - \frac{1}{(k_\mathrm{s} + r - g)^2}\right)\Bigg]\end{aligned}$$

As an aside, this expression can be used to identify approximate benefit-cost-maximising emission paths avoiding iterative optimisation, provided the impact of climate change on growth is negligible.

The linear relationship between cumulative carbon emissions and future temperatures implies $T_1 \approx T_0 + T_{\mathrm{TCRE}} \bar{E} (t_1 - t_0)$, 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 t_1. Total consumption at time t_1 is given by $W_1 = W_0 e^{\bar{g}(t_1 - t_0)}$, where W_0 is total consumption today and $\bar{g}$ is the geometric mean of the economic growth rate between now and t_1. Combining these gives an expression for total consumption at time t_1:

$$W_1 = W_0 \exp\left(\frac{\bar{g}}{\bar{E}} \frac{(T_1 - T_0)}{T_{\mathrm{TCRE}}}\right)$$

If t_1 is the time at which CO$_2$ emissions reach zero and hence temperatures peak at T_1, then the Social Cost of Carbon at time t_1 is:

$$\mathrm{SCC}_{t_1} = \left[\gamma W_0 D_0 T_{\mathrm{TCRE}} \left(\frac{1}{r-g} - \frac{1}{k_\mathrm{s} - r + g}\right)\right] T_1^{\gamma-1} \exp\left(\frac{\bar{g}}{\bar{E}} \frac{(T_1 - T_0)}{T_{\mathrm{TCRE}}}\right)$$

where the term in square brackets is the constant A in the main text.

The quantity $r - g = \rho + (\eta - 1)g$, or 'subjective discount rate',[5] is a key determinant of near-term mitigation policy.[5,10,23] The question that really matters for peak warming, however, is not the value 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.

Typical geophysical and economic parameters are $\gamma = 2$, $W_0 = 75\times 10^{12}\ \mathrm{US\$}_{2005}$, $D_0 = 0.00267$ for the fractional loss in global welfare due to a 1°C warming,[24] $T_0 = 0.9$ °C and $k_\mathrm{s} = 0.12$ per year.[1] All of these are uncertain, but are not directly affected by climate policy. If $r - g = 1.5\%$, they indicate an SCC of \$25/tCO$_2$ in 2015 rising to over \$100/tCO$_2$ by 2050, within the broad range of other studies.[10] The figure uses a mid-range T_{TCRE} of 0.002/3.67 °C/GtCO$_2$, which is 20% higher than the ratio of total anthropogenic warming to cumulative CO$_2$ emissions to date[3,25], but 20% lower than the "likely" upper bound for this ratio at the time of peak warming in 2°C scenarios assessed in ref. 1.

Average future emissions $\bar{E}$ between now and when they reach zero depend on the emission path, but within limits. If emissions peak immediately and decline linearly, then $\bar{E} = E_0/2$, where E_0 is today's emission rate (~40 GtCO$_2$ per year). 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 $\bar{E} = E_0$. Most plausible paths would fall between these two: we use an illustrative conservative case $\bar{E} = 0.9E_0$.

The figure shows the implications of one set of choices for non-policy parameters. Increasing D_0 (to account for impact uncertainty, or the effect of consumption inequalities on welfare[12]) or γ (greater non-linearity) would all shift the lines to the left: the worse climate change turns out to be, the sooner our descendants, if they maximise utility, would deploy a backstop CO$_2$ removal technology at a given cost. Conversely, increasing T_{TCRE} (higher climate response, or higher ratio of total to CO$_2$-induced warming) or $r - g$, the subjective discount rate at the time of peak warming, both shift the lines to the right, implying a higher peak warming for any given backstop technology cost.

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