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Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy

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A number of recent studies have found a strong link between peak human-induced global warming and cumulative carbon emissions from the start of the industrial revolution, while the link to emissions over shorter periods or in the years 2020 or 2050 is generally weaker. However, cumulative targets appear to conflict with the concept of a 'floor' in emissions caused by sectors such as food production. Here, we show that the introduction of emissions floors does not reduce the importance of cumulative emissions, but may make some warming targets unachievable. For pathways that give a most likely warming up to about 4°C, cumulative emissions from pre-industrial times to year 2200 correlate strongly with most likely resultant peak warming regardless of the shape of emissions floors used, providing a more natural long-term policy horizon than 2050 or 2100. The maximum rate of CO_2-induced warming, which will affect the feasibility and cost of adapting to climate change, is not determined by cumulative emissions but is tightly aligned with peak rates of emissions. Hence, cumulative carbon emissions to 2200 and peak emission rates could provide a clear and simple framework for CO_2 mitigation policy.

Keywords: cumulative emissions; emissions floors; rate of warming; climate change

1. Introduction

A substantial fraction of the carbon dioxide (CO_2) emitted into the atmosphere by human activity remains there, in effect, for centuries to millennia. Changes in ocean chemistry, which can be described through the Revelle buffer factor [1], limit oceanic removal of CO_2 [2], while the potential for terrestrial vegetation to take up CO_2 is also predicted by some models to fall as the climate warms [3],

although the size of this feedback is uncertain [4]. Complete removal of these anthropogenic emissions may require long time scales [4], or assistance from large-scale air-capture technologies [5–7].

If the above properties of the carbon cycle are real and enduring, then it is likely that bringing future emissions to zero would not reduce temperatures except in the very long term. Rather, once temperatures have peaked, they would remain almost steady [8–10]. Several recent studies have sought to exploit this observation in order to provide a simple link between levels of cumulative emissions and future warming [11–14].

Allen *et al.* [11] considered the cumulative carbon emissions summed between pre-industrial times and 2500, linking them to peak warming. Meinshausen *et al.* [13] examined multi-gas pathways and used a cumulative emissions metric between years 2000 and 2050 to relate to the probability of exceeding a 2°C target, rather than the amount of warming. The German Advisory Council on Global Change [15] argued for a cumulative limit between 2010 and 2050, while Matthews *et al.* [12] argued that warming by a given date is proportional to cumulative emissions to that date.

These papers show how cumulative emissions provide a tractable, well-constrained and concise metric for use by policy-makers interested in avoiding some level of peak global warming. The recent Copenhagen Accord [16] contains an aim of limiting warming to no more than 2°C, and draws on earlier targets from the EU and G8 [17,18]. Though not specified in the Copenhagen Accord, this 2°C warming limit is usually presumed to be relative to pre-industrial levels [19]. Using the results in Allen *et al.* [11], a 2°C limit on the most likely peak CO_2-induced warming could be achieved by limiting cumulative emissions to one trillion tonnes of carbon (1 TtC).

Cumulative emission targets represent the sum of emissions over time, and therefore these cumulative emissions could be distributed over time in a number of ways. For example, an early peak in emissions could be followed by a relatively slow rate of post-peak decline, or a later peak could be followed by a much more rapid decline [20]. One real-world difference between the pathways is that it may not be technically or politically feasible, or economically desirable, to decrease emissions at rates much in excess of 3 or 4 per cent per year, so that peaking later may not be viable, assuming a 2°C warming target [21].

In this paper, we address the problem of CO_2-induced warming. This is a central but not exhaustive component of potentially dangerous anthropogenic interference with the climate system. Most multi-gas pathways of future radiative forcing currently in the literature describe a total anthropogenic warming that either approximately equals or exceeds CO_2-induced warming [22]. This is because of the warming effect of non-CO_2 greenhouse gases usually equalling or exceeding the cooling effect of aerosols. Hence, avoiding dangerous levels of CO_2-induced warming is a necessary, albeit not always sufficient, condition for avoiding potentially dangerous anthropogenic interference in the climate system.

Most of the largest non-CO_2 anthropogenic forcing agents are distinct from CO_2 in having much shorter effective lifetimes in the climate system. Hence, although warming induced by non-CO_2 forcing agents may affect CO_2 through temperature–carbon-cycle feedbacks, it is difficult to arrive at a comprehensive framework for treating the cumulative impact of all anthropogenic forcings in terms of a single CO_2-equivalent metric [23]. The exception is nitrous oxide (N_2O),

which has an atmospheric lifetime comparable to, albeit different from, that of CO_2 and, crucially, longer than the response time of the physical climate system. Hence, it could be argued that nitrous oxide emissions should be considered in the same framework as CO_2, and, throughout this paper, CO_2 could be replaced by the combination of CO_2 and N_2O. Predicting long-term emissions of N_2O, given current rapid developments in agricultural technology, is even more difficult than predicting CO_2 emissions. Thus, for the sake of simplicity, we focus on CO_2 alone, and do not consider the issue of what fraction of these long-term emissions might be made up of N_2O, although we note that, in several other papers considering the impact of emissions over the very long term, this fraction is substantial.

In this paper, we explore how cumulative emission targets relate to more widely known policy targets, such as limiting emission rates in 2020 or 2050. First, we analyse the relative skill of different emission measures to predict the resultant future peak warming, comparing cumulative emissions over a range of periods and actual emission rates at years 2020 and 2050.

Second, we investigate whether the cumulative emissions metric still holds for a class of emission pathways that do not assume that all emissions can be mitigated over the coming centuries. It is often argued that it may not be technically, economically or politically feasible to eliminate emissions of all greenhouse gases while, for example, preserving global food security [24]. This limit has been referred to as an 'emissions floor' [25,26]. It is difficult to estimate a compelling emissions floor, either in terms of its size (in gigatonnes of carbon per year ($GtC \, yr^{-1}$)), or in terms of the extent to which it can reduce over time as new technologies become available. Nevertheless, it makes sense to consider the possibility that it may prove prohibitively expensive to reduce emissions beyond some positive level, particularly when the impact of N_2O is also included. Thus, in this paper we examine the effects of emissions floors on the basic arguments behind cumulative emissions framings of climate change. We use the following conventions: if the emissions floor is constant, then we refer to it as a 'hard floor'. If, on the other hand, society is able to continue to reduce residual CO_2 emissions, eventually to the point where net emissions are zero, then we call this a 'decaying floor'.

Third, we recognize that mitigation alone will not avoid all potential impacts of climate change, even if global warming does remain below 2°C [27,28]. Since some adaptation will be required in the future, policy-makers also need information on the rates of future climate change. This will determine how quickly a response is needed. Neither the cumulative total metric nor 2°C warming targets provide information on short-term rates of change in global warming [29]. Here, we analyse correlations between rates of CO_2-induced warming and short-term emission rates, noting that warming rates are also strongly influenced by non-CO_2 climate-forcing agents.

2. Methods

Our method consists of deriving a range of idealized CO_2 emission pathways and using a simple coupled climate–carbon-cycle model to estimate the resulting climate change. As many parameters in the model are uncertain,

a likelihood-based method is used to identify the values that give the best agreement with observations of the recent past or model studies with more complex coupled climate–carbon-cycle models [11].

For the majority of this paper, we run one simulation for each selected emission pathway, using the parameters that were previously found to give the best agreement with observations and more complex models. The model is run between the years 1751 and 2500. By running large ensembles containing hundreds of different emission pathways, we can begin to analyse trends across emission pathways. This method allows us to ask questions, such as: 'What is it about an emission pathway that controls the resulting peak rate of global mean temperature increase?'

(a) Emission pathways

We use emission pathways that follow the algorithm outlined by Allen *et al.* [11]. This gives the rate of change of future emissions according to the equations below:

$$
E_a = \begin{cases}
H(t) & \text{for } t < t_0, \\
a\mathrm{e}^{bt} & \text{for } t_0 \leq t < t_1, \\
c\mathrm{e}^{dt^2 + ft} & \text{for } t_1 \leq t < t_2, \\
g\mathrm{e}^{ht} & \text{for } t \geq t_2,
\end{cases}
$$

where E_a is the carbon emissions in year t, $H(t)$ is historical emissions data, a, b, c, d, f, g and h are constants, and t_0 is the year at which historical data are replaced by emission pathways. The parameters b and h, representing the initial rate of exponential growth and final rate of exponential decline, depend on the specification of the emission pathways and are allowed to vary between emission pathways; t_1 and t_2 are the times of transitions, and also vary between emission pathways. The remaining constants are determined by the requirement that emissions are continuous everywhere, and that rates of change of emissions are continuous, where $t > t_0$.

Note that E_a is measured in tonnes of carbon, as opposed to tonnes of CO_2. To convert to tonnes of CO_2, one would simply multiply our emissions and cumulative emission values by a factor of 44/12.

To create the emission pathways, we select a number of values of parameters b, h, t_1 and t_2. Each combination of these parameters represents a different possible emission pathway. We select parameter options such that there are 12 750 possible emission pathways of the type outlined here. We choose the ranges of the parameters to give a range of emission pathways with cumulative emissions to 2200 between 0.7 and 3 TtC. We choose the parameters so that the majority of emission pathways have a maximum rate of emissions decline of less than 4 per cent per year, but we also consider a smaller number of pathways that decrease by up to 10 per cent per year.

We also develop a new set of pathways, extending those described above. These pathways have 'emissions floors' to represent the emissions that are potentially technologically, economically or politically unfeasible to mitigate. Although these are expressed in terms of CO_2 alone, they could also be assumed to include the impact of the other principal long-lived anthropogenic radiative forcing agent, N_2O. Including the impact of further non-CO_2 forcing agents is difficult. Because
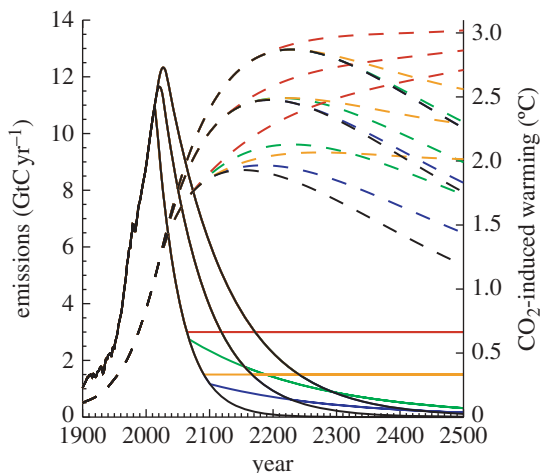
Figure 1. Fifteen emission pathways and their resulting temperature trajectories. The emission pathways are in solid lines, and can be read off the left axis, while the temperature trajectories are in dashed lines, and can be read off the right axis. The 15 emission trajectories are created by combining three possible pathways, shown here in black, with five possible emissions floors, shown here in coloured solid lines, as outlined in §2*a*. The upper, middle and lower plumes of overlapping coloured dashed temperature trajectories correspond to the black emission profiles that peak the highest, the second highest and the lowest, respectively. The three emission pathways in red solid line with the highest constant emissions floors have red dashed resultant temperature trajectories. The same correspondence applies for the other colours of emissions floors and their resultant temperature trajectories. The upper, middle and lower black curves have cumulative totals to 2500 of 2, 1.5 and 1 TtC, respectively.

of their very much shorter lifetimes, these emissions do not accumulate in the system, as does CO_2. We use two types of emissions floors: a hard floor, F_H, and a decaying floor, F_D. These two floors take the forms

$$F_H \geq A$$

and

$$F_D \geq B \exp\left(-\frac{t - t_{2050}}{\tau}\right),$$

where A and B are constants with units of gigatonnes of carbon per year (GtC yr^{-1}) and represent the size of the emissions floor in the year 2050 ($t = t_{2050}$), and τ is a time constant set to 200 years. Emissions floors are caps below which emissions are not able to fall, so for all t, where $t = t_0$, we take whichever is the larger of $E_a(t)$ and $F(t)$ to be our emissions pathway. If we take into account five alternative emissions floors, namely (i) no floor, (ii) low hard floor, (iii) high hard floor, (iv) low decaying floor and (v) high decaying floor, which could apply to each of the 12 750 possible pathways described above, we have 63 750 possible emission pathways. We do not use all of these possible pathways, but rather pick a random subset of a few thousand pathways to investigate with the simple coupled climate–carbon-cycle model. Fifteen of these pathways are plotted in figure 1, alongside their resulting warming trajectories as simulated by the simple model outlined below.

(b) Models

Following Allen *et al.* [11], our analysis is based on a simple combined climate–carbon-cycle model with a time step of one year. The model uses a three-component atmosphere–ocean carbon cycle, in which we assume that the atmospheric CO_2, measured by a concentration C, can be split into three components, C_1, C_2 and C_3. Physically, C_1 can be thought of as representing the concentration of CO_2 in long-term stores such as the deep ocean; $C_1 + C_2$ as representing the CO_2 concentration in medium-term stores such as the thermocline and the long-term soil-carbon storage; and $C = C_1 + C_2 + C_3$ as the concentration of CO_2 in those sinks that are also in equilibrium with the atmosphere on time scales of a year or less, including the mixed layer, the atmosphere itself and rapid-response biospheric stores. Each of these components, C_1, C_2 and C_3, is then associated with some fraction of the emissions into the atmosphere, E, and a particular removal mechanism:

$$\frac{\mathrm{d} C_3}{\mathrm{d} t} = b_3 E,$$

$$\frac{\mathrm{d} C_2}{\mathrm{d} t} = b_1 E - b_0 C_2$$

and

$$\frac{\mathrm{d} C_1}{\mathrm{d} t} = b_4 E - b_2 \int_0^t \frac{\mathrm{d} C_1(t')}{\mathrm{d} t'} \frac{\mathrm{d} t'}{\sqrt{t - t'}},$$

where b_3 $(= 0.1)$ is a fixed constant representing the Revelle buffer factor, and b_1 is a fixed constant such that $b_1 + b_3 = 0.3$ [11]; b_1 represents the fraction of atmospheric CO_2 that would remain in the atmosphere following an injection of carbon in the absence of the equilibrium response and ocean advection; b_0 represents an adjustable time constant, the inverse of which is of order 200 years. The third equation in our simple carbon-cycle model, which relates to C_1, accounts for advection of CO_2 into the thermocline and land–biosphere; b_2 represents an adjustable diffusivity, while $b_1 + b_3 + b_4 = 0.85$ is the fraction of CO_2 that would remain in the atmosphere within a year of a pulse injection [11].

The surface temperature response, T, to a given change in atmospheric CO_2 is calculated from an energy balance equation for the surface, with heat removed either by a radiative damping term or by diffusion into the deep ocean. It is described by

$$a_1 \frac{\mathrm{d} T}{\mathrm{d} t} = a_3 \ln\left(\frac{C}{C_0}\right) - a_0 T - a_2 \int_0^t \frac{\mathrm{d} T(t')}{\mathrm{d} t'} \frac{\mathrm{d} t'}{\sqrt{t - t'}}.$$

Here, a_1 is a fixed heat capacity, which we approximate as the effective heat capacity per unit area of a 75 m ocean mixed layer; a_3 corresponds to a doubling of atmospheric CO_2 levels causing a forcing of $3.74\,\mathrm{W\,m^{-2}}$; and C_0 is the pre-industrial concentration of CO_2 [30]; a_0 and a_2 are both able to vary, and control the climate sensitivity, and rate of advection of heat through the thermocline, respectively. This is a simple energy balance equation, where the term on the left-hand side represents the thermal inertia of the system; the first term on the

right-hand side (r.h.s.) is the atmospheric CO_2 forcing, the second term on the r.h.s. is a linearized temperature feedback, and the third term on the r.h.s. is a diffusive term representing the flux of heat into the deep ocean.

Finally, we represent the climate–carbon-cycle feedback by adding an extra, temperature-dependent component to the total anthropogenic emissions emitted each year (E_a):

$$E = E_a + b_5 T',$$

where T' is the temperature anomaly above an exponentially weighted running mean with a time constant of 100 years, and b_5 is the adjustable carbon-cycle feedback parameter. Since the industrial revolution, models showing this feedback have been largely linear; however, this linearization is unlikely to hold for temperatures greater than 3–4°C above pre-industrial temperatures. Further, the equation is unreliable for decreases in temperature, but these are not considered here.

Together, these equations make up the simple coupled climate–carbon-cycle model that we use throughout this paper. Figure 1 shows the temperature trajectories simulated by this model for 15 sample emission pathways.

(c) Likelihoods

For the majority of this paper, we use 'best-guess' parameters for each of the variables in the model; however, in §3c, we use a range of parameters to sample uncertainties. We varied five parameters in this coupled climate–carbon-cycle model in order to sample their uncertainties, while we kept the rest constant. The five parameters that we varied are a_0, a_2, b_0, b_2 and b_5. We did not vary the other parameters in the model because their fractional uncertainties are much smaller than those of the five parameters listed above.

We constrained these five parameters with five 'observations' (either direct, or based on more complex model simulations). These are (i) observed attributable CO_2-induced twentieth-century warming, (ii) global heat capacity, inferred from the combination of ocean warming and ocean heat uptake, (iii) historical record of atmospheric CO_2 concentrations, (iv) the rate of advection of CO_2 in the deep ocean, based on the C^4MIP family of climate–carbon-cycle general circulation models (GCMs) and models of intermediate complexity, and (v) the climate–carbon-cycle feedback parameter, again estimated from the C^4MIP family of models [11]. We require C^4MIP to help with some of these quantities in the absence of true observations of the carbon cycle. We assigned each of the constraints a log-normal distribution from estimates in the literature, as detailed by Allen *et al.* [11].

For each combination of the five model parameters, we operated the simple climate–carbon-cycle model, and calculated and then multiplied together the likelihoods for each of the constraints to create a single likelihood for each parameter combination. The parameter combinations that better reproduce the constraints are then more likely, and the parameter combination that best reproduces the constraints is considered to be our best guess, or the most likely [31].

In most of this paper, we only use this best-guess parameter combination in the coupled climate–carbon-cycle model. In §3*c*, however, we use several thousand parameter combinations to create 'likelihood profiles'. Figure 1 shows 15 warming trajectories calculated using best-guess parameters.

3. Results

(*a*) *A comparison of different types of emission targets*

We compare the performance of a range of emissions and cumulative emission targets in estimating peak CO_2-induced warming. We do this comparison by constructing an initial set of 395 different emission pathways, each with a zero emissions floor, which have been randomly selected from the 12 750 possible pathways with no emissions floor outlined in §2*a*. Once we have randomly selected our 395 emission pathways, we use the simple coupled climate–carbon-cycle model described in §2*b* to estimate quantities such as the most likely peak warming for each pathway. We use these results to analyse the usefulness of each of six emission metrics of interest. We consider cumulative carbon emissions (i) from pre-industrial times to the time of peak warming and (ii) from year 2010 to year 2050. We also consider the actual emissions rates at (iii) year 2020 and (iv) year 2050. Additionally, we consider (v) the peak emissions rate and (vi) the year in which emissions peak.

The performance of each emission metric is shown in figure 2, where the emission metrics are plotted against the peak warming. The bars in the plot indicate the range for each metric in pathways with resultant values of peak warming at or very near to 2 and 3°C. Black bars consider only the pathways represented by black crosses with 'rate of emissions decline' less than 4 per cent. The grey bars include both black crosses and grey diamonds, corresponding to emission pathways with rates of decline as high as 10 per cent. For example, in figure 2*d*, pathways with a resultant warming of 2°C have emissions in year 2050 between 4.5 and 6.4 GtC yr^{-1}, giving a range of 1.9 GtC yr^{-1}.

Based on the metrics presented in figure 2, we conclude that, for cases with no emissions floor, the strongest correlation across all pathways occurs between peak warming and the cumulative emissions from pre-industrial times to the time of that peak warming, as shown in figure 2*a*. The correlation is almost as strong if cumulative emissions out to 2500 are considered (shown in black squares in figure 3*a*) because the vast majority of the emissions in these zero emissions floor pathways have occurred by the time of peak warming. Note that, because of the idealized nature of the climate model used here, it may not be quantitatively reliable above 3–4°C of warming.

An interesting feature of the tight correlation present in figure 2*a* is the curvature, which is due to the functional form of CO_2 forcing. Forcing due to CO_2 is proportional to the logarithm of the fractional change in atmospheric CO_2 since the pre-industrial era [30]. If the forcing were linear, the model used in this paper suggests that there would be a more linear relationship between cumulative emissions and peak warming [12].

For figure 2*b*–*f*, grey diamonds, representing emission pathways with a maximum rate of decline between 4 and 10 per cent, generally appear to the right and below the black crosses, representing emission pathways with peak
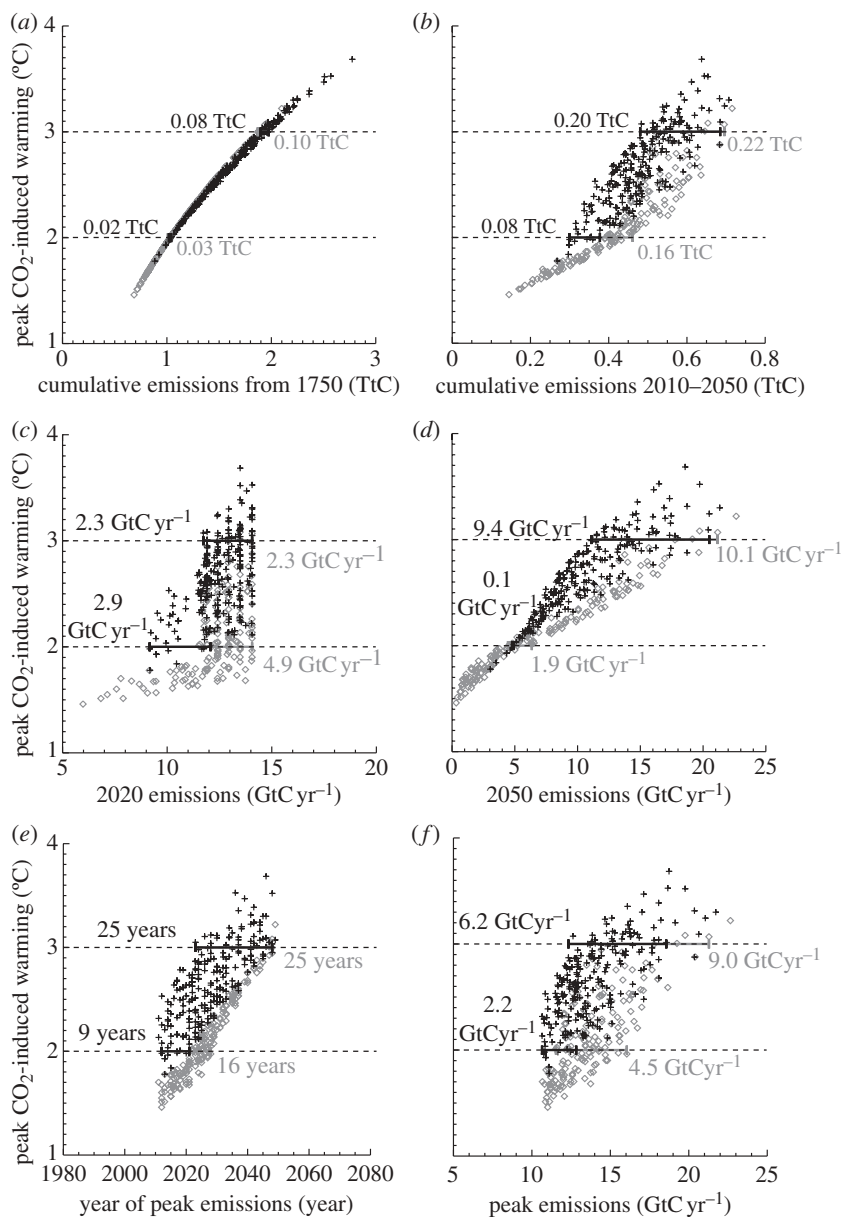
Figure 2. Scatter plots showing the relationship between most likely peak CO_2-induced warming and various global carbon emission metrics for 395 emission pathways. The x-axis for each panel shows: (a) emissions time-integrated between 1750 and 2500, (b) emissions time-integrated between 2010 and 2050, (c) emissions in the year 2020, (d) emissions in the year 2050, (e) the year in which emissions peak, and (f) the peak or maximum in emissions. Black crosses indicate emission pathways in which the maximum rate of emissions decline is less than $4\% \, yr^{-1}$; grey diamonds indicate the converse. The bars show the spreads of the metrics for pathways with a resultant peak warming of $2°C$ or $3°C$. The black bars show the spread in pathways with peak rates of emissions decline less than 4%, while the grey bars show the spread in all emission pathways. We see that the strongest correlation is in (a), between peak warming and cumulative emissions between 1750 and 2500.

rates of decline between 0 and 4 per cent. For a given peak warming, and so for a given cumulative total, pathways with a faster rate of emissions decline will have relatively more of their cumulative total emitted sooner than for pathways with slower rates of decline. As a result, these rapidly declining pathways will have higher cumulative emissions between 2010 and 2050, higher 2020 emissions, higher peak emissions and a later year of peak emissions. This effect also holds for 2050 emissions above $5\,\mathrm{GtC\,yr^{-1}}$. For emission pathways with cumulative emissions less than 1 TtC, corresponding to a peak warming of 2°C, 2050 emissions occur once the pathway has been declining exponentially for a considerable period, and so rapidly declining pathways will have relatively lower emissions in 2050.

The correlation between peak warming and cumulative emissions between year 2010 and 2050, which is the emissions metric used by the German Advisory Council on Global Change [15], is plotted in figure 2b. We see that the correlation here is not as good as in figure 2a. Emissions before 2010 are not allowed to vary across emission pathways, so there can be no contribution to the spread in peak warming from this historical time period. The majority of the spread comes from the variation in post-2050 emissions, which will have a significant impact on peak temperatures, but which by definition are not included in 2010–2050 metrics. We see that, in cases where post-2050 emissions are small, the spread is much tighter, as shown by those pathways with cumulative emissions less than 0.3 TtC between 2010 and 2050. This is because the majority of future cumulative emissions in these pathways are emitted before 2050. This means that, up to roughly 1.8°C, the cumulative emissions between 2010 and 2050 has some skill in predicting peak CO_2-induced warming, but this skill is reduced for higher temperatures.

We also consider whether there is predictive skill in using the actual emission rates at a particular year; here we use year 2020 and year 2050. The former year is chosen because most of the Copenhagen Accord emission reduction pledges are quoted for this year [16]. The latter is chosen because several reduction targets for 2050 have also been presented [17,32]. Figure 2c,d shows 2020 and 2050 emissions against peak warming. As in Lowe *et al.* [33], we find that emissions in the year 2020 are not a good indicator of peak warming, because they are largely a function of current emissions, and are not a key determinant of cumulative emissions.

For figure 2d, year 2050 emissions do seem to be a good indicator at lower rates of emission, particularly at values that cause roughly 2°C of warming or less. However, we found 2050 emissions to be a less good indicator of peak resultant warming at higher rates of emission. This is in part a consequence of the choice of pathways, as we have considered only smooth pathways with a single maximum and exponential tails (see §2a for more detail on how the emission pathways are chosen). A wider range of functional forms to describe emission pathways would be expected to reduce the strength of the relationship between 2050 emissions and peak warming.

We also compare the peak emission rate and the year of peak emissions with the peak CO_2-induced warming. As shown in figure 2e,f, the spread is very large for both of these metrics, and there is little correlation, except for the rapidly declining emission pathways (grey diamonds) appearing to the right of the slowly declining pathways (black crosses), as explained earlier.

Under the assumption that society will work to avoid crossing a key temperature threshold, from figure 2a, the cumulative emission metric confirms that we have a choice of high emissions soon followed by rapid decarbonization, or

more stringent emission cuts occurring soon with a lower rate of decarbonization in the future. As in Allen *et al.* [20], this actually forces the many potential emission pathways considered here, which have the same cumulative total, to cross around the middle of the twenty-first century. Lower cumulative totals, and thus pathways with these features that result in lower levels of warming, leave less flexibility, and thus all pathways must intersect in roughly the same place. At higher cumulative totals, there is more flexibility about when carbon is emitted, and therefore pathways do not cross in the same place, resulting in the wider spread of pathways at warmer peak temperatures. Thus, pathways with lower rates of emission in 2050 are likely to result in a similar amount of peak warming, while higher rates of emission in 2050 can lead to varying levels of peak warming, as seen in figure 2*d*.

(b) The effect of emissions floors

In figure 1, we calculated the warming trajectories not only for emission pathways with zero emissions floors, but also for pathways with non-zero floors. We show in figure 2 that cumulative emissions to the time of peak warming are tightly correlated with peak CO_2-induced warming for the case with no emissions floors, and here we investigate whether emissions floors affect this correlation. Figure 3 shows the impact of emissions floors on different cumulative emission metrics, and each of the panels has the same form as figure 2*a*.

We have plotted most likely peak temperatures as a function of four different cumulative emission metrics: year 1750–2500 (figure 3*a*), year 1750 to the time at which peak warming occurs (figure 3*b*), year 1750–2100 (figure 3*c*) and year 1750–2200 (figure 3*d*).

In figure 3*a*, we can see that pathways with larger emissions floors are shifted to higher cumulative totals. This occurs because the cumulative totals include contributions for portions of the emissions floor that are emitted after the time of peak warming, which can have no effect on peak warming, as illustrated by the green curves in figure 1.

We find that if a hard or non-varying emissions floor becomes too large, then the emissions cannot balance the natural processes that remove carbon from the atmosphere. At present, the precise value of the emissions when the floor becomes too large is uncertain, although we highlight that it may be model-specific. This is illustrated by the red curves in figure 1. Consequently, for large hard emissions floors, atmospheric levels of CO_2 continue to rise throughout our 750-year simulation, and are still increasing at the end of the experiment, along with associated levels of mean global warming. Extending this analysis to include pathways with cumulative emissions of more than 3 TtC, a resultant warming of more than 3–4°C, or cases in which temperatures fail to peak by 2500 would be possible in principle, but would take us outside the range of pathways for which such a simple model is appropriate. Hence, we have not plotted cases where temperatures do not peak by 2500 in figures 3 or 4, since we are unable to project when they would peak. All pathways with no floor, and all pathways with a decaying floor, have peaked by 2500; however, some pathways with a hard emissions floor have not.
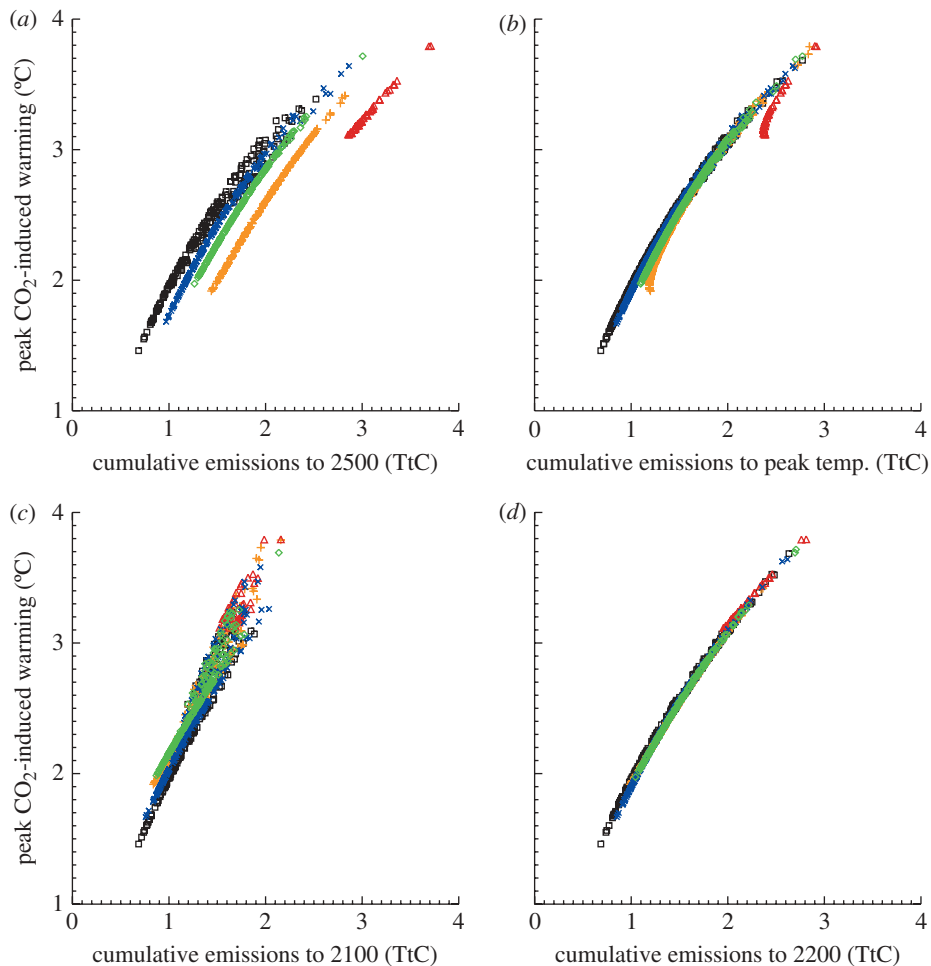
Figure 3. Most likely peak warming as a function of cumulative emissions for different emissions floors. The type of cumulative emission metric varies between the plots: cumulative emissions to (*a*) 2500, (*b*) the time of peak warming, (*c*) 2100, and (*d*) 2200. The panels in this figure are as figure 2*a*, but with different floors preventing emissions from dropping below certain values at certain times. The emissions floors used here are the same as those in figure 1, and use the same colour code. The black squares represent pathways in which no floor is present, so emissions are allowed to fall to zero. The yellow crosses and red diamonds indicate pathways in which a 'hard' floor is set at 1.5 or 3 $GtC\,yr^{-1}$; in these pathways, emissions are unable to fall below the floor and so remain at these values indefinitely. The blue crosses and green diamonds are pathways with an exponentially decreasing emissions floor, which has a decay time of 200 years. The blue crosses pass through 1.5 $GtC\,yr^{-1}$ in the year 2050, while the green diamonds pass through 3 $GtC\,yr^{-1}$ in that year. We observe the strongest correlation in (*d*), between peak warming and cumulative emissions to 2200.

The observational constraints are much more effective in constraining the short- and medium-term response of the climate–carbon-cycle system than they are at constraining the multi-century response. Hence, it is inherently hard to determine whether, after a significant injection of CO_2 into the atmosphere,

certain emissions floors will cause temperatures to stabilize, decline or continue rising. Additionally, when considering an emissions floor, it could be argued that temperatures will be rising or falling so slowly that their trend could be reversed by actively intervening in the carbon cycle, or simply reducing or increasing emissions by an amount substantially smaller than has already been achieved in reaching that floor. The maximum rate of increase of CO_2 concentrations beyond 2200 associated with the emission pathways in figure 1 is 28 ppm by volume per century (ppmv per century). The rate of associated warming shown in figure 1 beyond 2200 is at most 0.27°C per century. In contrast, the associated maximum rates in 2100 are a concentration rise of 99 ppmv per century and a warming of 0.88°C per century. It could be argued that a society capable of achieving the kind of rates of emission reduction in the year 2100 that are assumed under these pathways would almost certainly be able to convert a static emissions floor into a decaying one if it were necessary to do so. Hence, it could be argued that the scenario of very rapid reductions followed by a completely stable ('hard') floor in CO_2 emissions is unlikely to occur, although the role of N_2O in very long-term emissions is potentially an issue here. Methane could also influence temperatures over the very long term, as could anthropogenic aerosols and other short-lived forcing agents. However, any agent with a lifetime shorter than the response time of the physical climate system must be treated in a very different way to CO_2, since such emissions do not effectively accumulate in the atmosphere over multi-decadal time scales.

Figure 1 shows that the size and types of emissions floors determine how temperatures will behave after they peak. Several studies have suggested that near-zero emissions are required to stabilize temperatures [10,14]. Our simple model's simulations suggest that temperatures will peak then fall slowly under near-zero emissions (figure 1), but this result is acutely sensitive to model structure. At present, there appears to be insufficient understanding and suitable observations of the carbon cycle to constrain behaviour during the regime when temperatures decline. In light of this lack of observational constraints, we do not feel confident in relying upon the simple model's simulations long after the time at which temperatures peak.

Figure 3b shows peak warming plotted against cumulative emissions integrated between the year 1750 and the time of peak warming. The correlation in this figure is much better than that in figure 3a. Figure 3b shows that a decaying emissions floor does not significantly alter the shape of the relationship between cumulative emissions and peak temperature, as the peak warming is still a function of the cumulative emissions. Emissions floors do, however, affect the lower ends of the curves with low values of cumulative emissions. Consider two emission pathways, both with a cumulative total of 1 TtC, but one with a decaying emissions floor, and one with no emissions floor: the pathway without an emissions floor will cause a temperature peak earlier than the pathway with the decaying floor, as the emissions floor causes emissions to be emitted over a longer time period. Consequently, in the case with an emissions floor, there will have been more time for carbon to be removed from the atmosphere, presumably resulting in slightly lower atmospheric concentrations at the end of our simulation period than in the no-floor case. As forcing is a function of atmospheric concentrations, the case with no emissions floor and higher CO_2 concentrations will result in a higher peak temperature.

We can observe this phenomenon in figure 1 by comparing the lowest green and yellow emission pathways and temperature trajectories. The yellow emission pathway has a higher cumulative total than the green one, when integrated to the time when temperatures peak. Despite this higher cumulative total, the green curve has a higher peak warming than the yellow curve because its emissions are put into the atmosphere over a shorter time period. It is this phenomenon that causes the hard emissions floors to 'peel away' from the soft emissions floors in figure 3b.

In figure 3b, at the upper end of the curve, where cumulative totals are large, the existence of an emissions floor seems to make little difference to the peak temperature. This is because the fraction of the cumulative total that is part of the emissions curve is much larger than the fraction that is in the emissions floor. For the decaying emissions floor in particular, the floor will have decayed to near zero by the time that $E_a(t) = F_D(t)$, as the pathway will reach the floor at a later time than it would have if it had a smaller cumulative total. In general, if the cumulative emissions over the duration of the emissions floor are small compared with the overall emissions, then the floor is not particularly important. If the cumulative emissions over the duration of the floor are a large fraction of the cumulative total, then the level of the floor is a crucial determinant of peak warming. This phenomenon is illustrated in figure 1 by considering the upper yellow and black emissions and temperature curves. The emission pathway is so large that the yellow emissions floor does not affect it until 2240, and as a result the yellow and black temperature trajectories are indistinguishable until after temperatures have peaked. This illustrates why emissions floors have less impact on peak warming for pathways with high cumulative totals.

In figure 3c, we see that the correlation between peak warming and cumulative emissions to 2100 is relatively weak. The points furthest to the right of the plot, however, are all black crosses, representing emission pathways with zero emissions floors. This is because, for pathways with zero emissions floors, more of the total cumulative emissions have been emitted by 2100 than for pathways with non-zero emissions floors. We see in figure 1 that all of the 15 temperature trajectories are still warming beyond 2100, and all emission pathways are still emitting beyond 2100. These emissions beyond 2100 are not accounted for in this metric, but will influence the peak warming, which accounts for most of the lack of correlation in figure 3c.

The best correlation of all the panels can be observed in figure 3d. This suggests that cumulative emissions, when calculated between 1750 and 2200, are a strong indicator of most likely peak CO_2-induced warming regardless of the type of emissions floor chosen. This is presumably because most of the warming trajectories peak within a few decades of 2200. Those trajectories considered here that do not peak near 2200 have all warmed to within a small fraction of their peak warming by this date, and therefore the emissions emitted in these pathways after 2200 only serve to maintain temperatures, and not to induce more warming. This phenomenon is illustrated by the lowest yellow curve, which peaks in 2273, but has warmed to 99 per cent of its peak warming by 2200. This example illustrates how emissions after 2200 have a very small influence on an emission pathway peak temperature, provided the emissions floor is not so high that it prevents temperatures from peaking until beyond 2500. We

cannot be confident in the correlation between peak temperatures and cumulative emissions to 2200 for emission pathways that result in warming of more than 4°C, because peak temperatures will not necessarily occur near the year 2200 in these pathways.

One way this work can inform current policy targets is for policy-makers to view cumulative carbon emission budgets as spread over, say, four periods: (i) 2010–2020, (ii) 2020–2050, (iii) 2050–2100, and (iv) 2100–2200. Subject to the constraints and caveats outlined above, decision-makers have some flexibility in moving emissions from period to period; the important thing for a maximum temperature target is that the overall budget not be exceeded, since this is the primary determinant of peak warming. The inter-period flexibility regarding peak temperature targets ought to be of practical value to policy-makers, since it allows them to make informed trade-offs between near-term emissions and emissions in the longer term.

(*c*) *Likelihood profiles*

In §3*a*, we confirmed the very tight correlation between cumulative emissions and peak CO_2-induced warming, refined in §3*b* to consider the effect of non-zero emissions floors. We find that, even with non-zero emissions floors, cumulative emissions, particularly cumulative emissions to the year 2200, correlate well with the resultant peak warming below 4°C.

However, thus far, and in figures 2 and 3, our estimates have been of 'best-guess' or 'most likely' warming, as defined in §2*c*. In this section we estimate our level of confidence in these results.

We re-run our model but with perturbed parametrizations for each ensemble member. For each ensemble member, we can determine a relative likelihood through comparison against our knowledge of the historical record. As explained in §2*c*, models that better reproduced our constraints have higher relative likelihoods.

In figure 4, we do not plot the location of each ensemble member, but instead we plot the outline of the entire ensemble. This allows our likelihood profile to be independent of sampling strategy, provided that we have sufficiently explored parameter space.

For each emissions profile within 1 per cent of 1.0, 1.5 or 2.0 TtC cumulative emissions between 1750 and 2200, we calculate a likelihood profile, such that each panel in figure 4 actually contains dozens of likelihood profiles plotted on top of each other. All of these likelihood profiles are quite similar, which shows not only that the best-guess peak warming is independent of emission pathway for a given cumulative total, but also that the entire likelihood profile shares this property.

We repeat this process for each type of emissions floor so that we can compare likelihood profiles between types. By comparing the likelihood profiles for emission pathways with the same cumulative total but different emissions floors (e.g. the profiles in figure 4*d*–*f*), we find that the likelihood profile is unaffected by the type of emissions floor.

We note that figure 4*c* only contains three likelihood profiles, as we only consider three emission pathways with a hard emissions floor and a cumulative total to 2200 of within 1 per cent of 1 TtC. Cumulative emissions to 2000 are approximately 0.5 TtC, and a 1.5 GtC yr^{-1} emissions floor between 2000 and
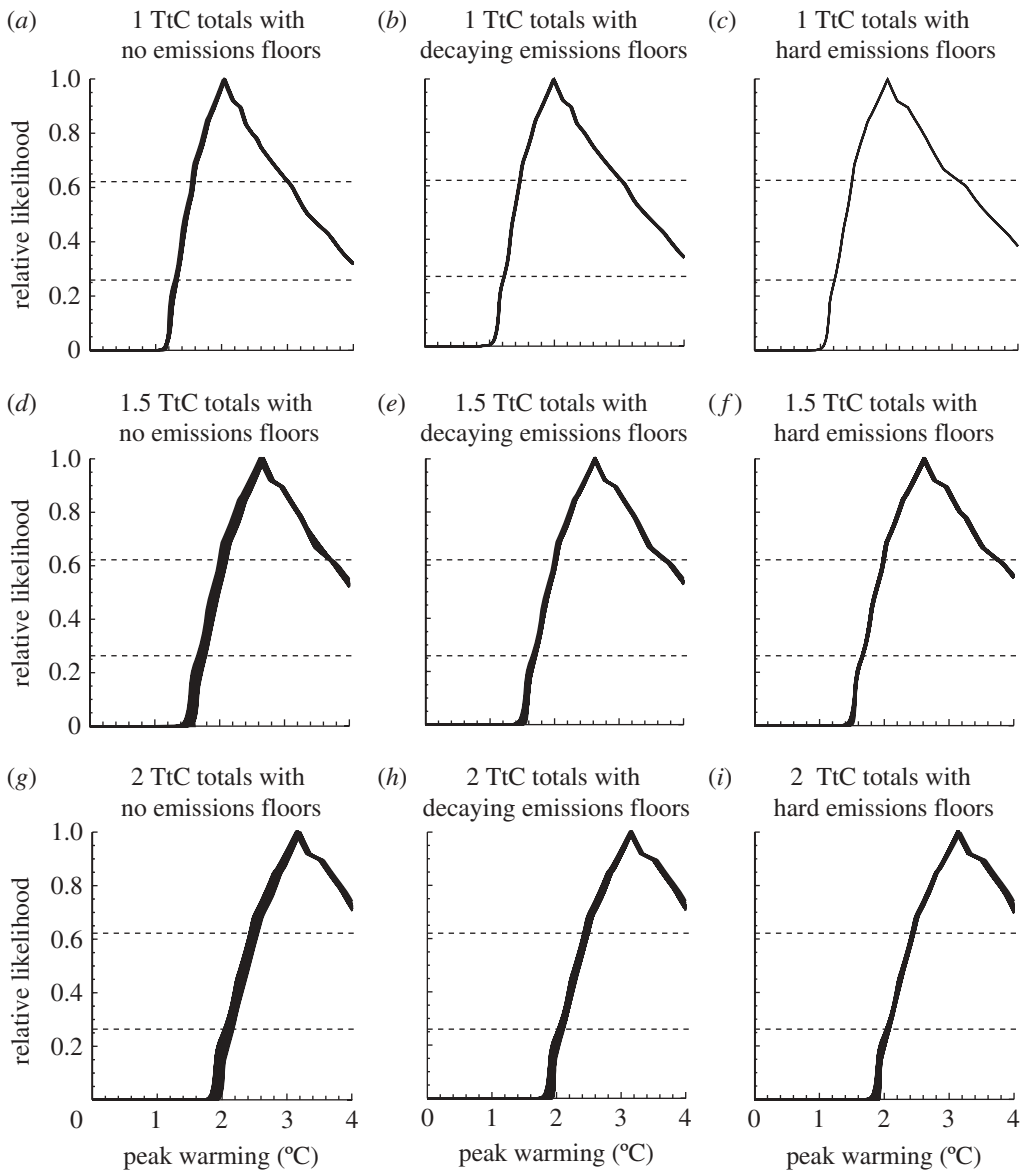
Figure 4. Peak warming for different cumulative totals and different emissions floors. These likelihood profiles are produced as outlined in §3*c* following Allen *et al.* [11]. Horizontal dotted lines show thresholds for the 17–83% and 5–95% confidence intervals [31]. Panels (*a,d,g*) have no emissions floor, so emissions are allowed to fall to zero. Panels (*b,e,h*) have a 'decaying' (i.e. exponentially decreasing with a 200-year lifetime, passing through $1.5\,GtC\,yr^{-1}$ in 2050) emissions floor. Panels (*c,f,i*) have a $1.5\,GtC\,yr^{-1}$ hard emissions floor. In each panel, we plot likelihood profiles over each other for every emission pathway with a cumulative total from 1750 to 2200 within 1% of the stated cumulative total. A sample emission pathway for each of the plots above is given in figure 1, alongside its resultant warming trajectory. The profiles with no emissions floors appear to be drawn thicker only because more emission profiles have been plotted upon one another. We see that the introduction of an emissions floor has little influence on the likelihood profile.

2200 has a cumulative total of 0.3 TtC, which leaves only 0.2 TtC remaining if the pathways are to have a cumulative total of 1 TtC. This forces the emissions profile to have a high rate of decline, which could make these profiles socio-economically unfeasible [21].

(*d*) *Constraining the rates of warming*

Thus far, we have only considered constraints on peak levels of global warming. A key objection to using peak warming targets in isolation is that the feasibility and cost of adapting to future climate change will also depend strongly on the rate of change and not just on the magnitude of global warming. In order to determine which factors constrain the maximum rate of warming, we use the same model experiments as reported in figure 2. Thus, we use only best-guess or most likely ensemble members, and we only consider emissions profiles with zero emissions floors. We now plot the peak rate of CO_2-induced warming as a function of the emission metrics, as illustrated in figure 5.

In figure 5, we find a very different set of correlations from those presented in figure 2. The main result, across all the panels in figure 5, is that the tightest linkage is between the peak rate of warming and peak emission rate. We now explain these results in more detail.

Though cumulative carbon emissions have a tight correlation with peak warming, figure 5*a* shows that they share only a very weak correlation with the peak rate of warming. The maximum rate of warming is instead controlled by the peak rate of emission, as indicated in figure 5*f*. The gradient of the points in figure 5*f* suggests that, for each extra $GtC\,yr^{-1}$ on the peak emission rate, the best-guess maximum rate of warming will increase by 0.016°C per decade.

It is known, however, that short-lived non-CO_2 greenhouse gases, such as methane, which we do not include in this paper, also influence atmospheric radiative forcing [34]. Although these gases have shorter lifetimes than CO_2 [34], they still have the potential to influence rates of warming beyond that induced purely by CO_2.

Figure 5*a* shows only a slight correlation, which occurs because the peak rate of emission and the cumulative emissions are not completely independent. Consider two emission pathways with different peak rates of emission and the same rate of emissions decline after the peak: the pathway with the higher peak will lead to a higher cumulative total, as shown in figure 5. As we cap the maximum rate of emissions decline to 10 per cent per year, higher peak emission rates will have a bias towards larger cumulative totals, which explains the correlation we observe in figure 5*a*.

The grey diamonds in figure 5 represent emission pathways that have a maximum rate of emissions decline of between 4 and 10 per cent per year, while the black crosses correspond to rates of decline between 0 and 4 per cent. For pathways with a cumulative total of less than 1 TtC and a rate of decline of less than 4 per cent per year, figure 5 shows only a limited range of possible rates of warming. This limited range of pathways all have a rate of warming less than 0.2°C per decade, which initially suggests that a cumulative emissions target could be used to constrain rates of warming, assuming that rates of decline are
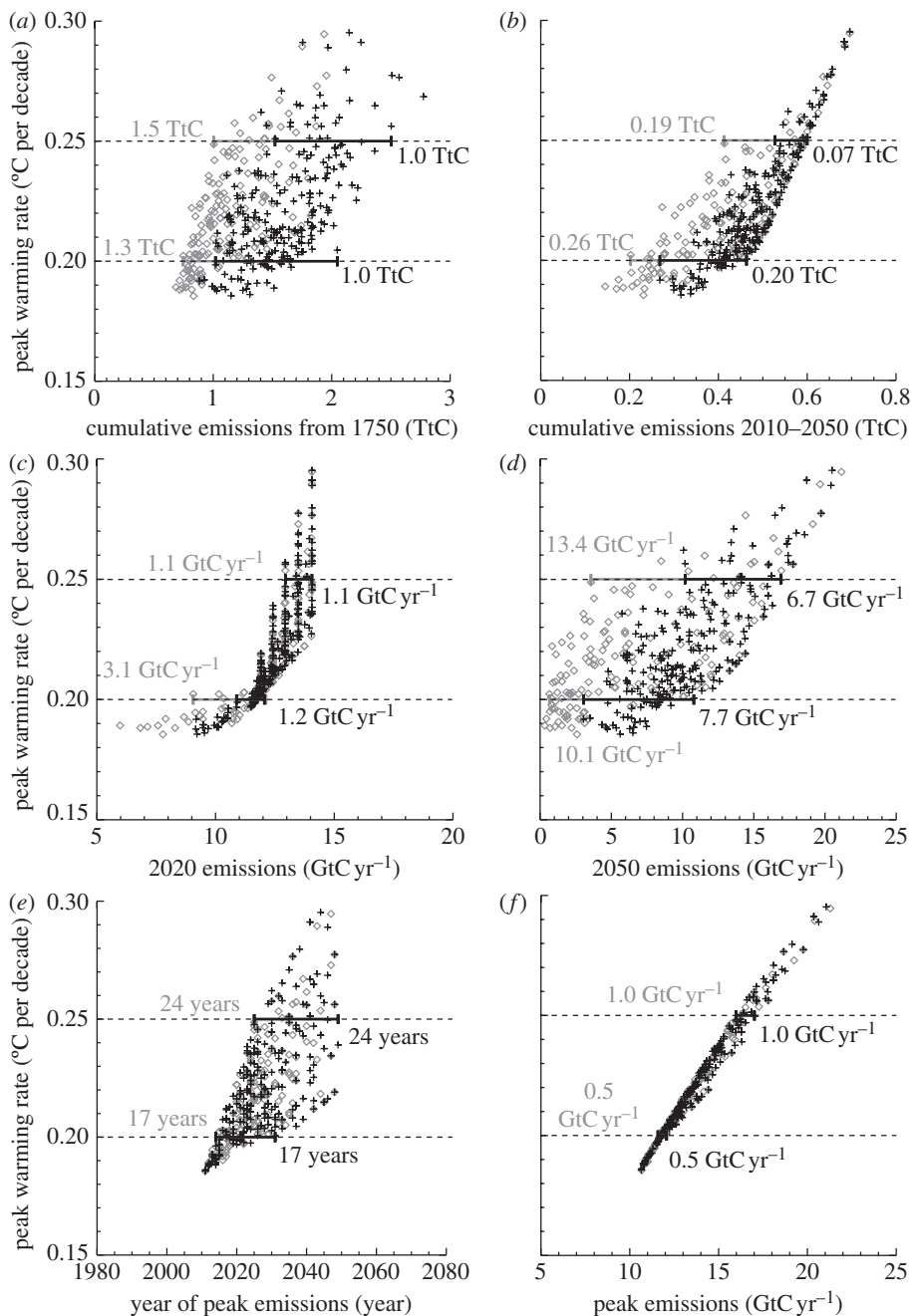
Figure 5. The correlation of emission metrics with most likely peak warming rate. This figure is like figure 2, but plotting against peak rate of warming instead of against peak warming. Again, black crosses indicate emission pathways in which the maximum rate of emissions decline is less than $4\% \, \mathrm{yr}^{-1}$; grey diamonds indicate the converse. The bars show the spread of the metrics for pathways with a resultant peak rate of warming of $0.2°C$ or $0.25°C$. The black bars show the spread in pathways with peak rates of emissions decline less than 4%, while the grey bars show the spread in all emission pathways. We see that the strongest correlation is in (*f*), between peak rate of warming and peak emission rate.

kept at less than 4 per cent per year. However, these are CO_2-only pathways, and this range of warming rates would increase significantly if the possible range in non-CO_2 forcing pathways were included.

For a given peak rate of warming, and hence for a given peak emissions rate, pathways with a lower cumulative total or lower emissions in a given year must have a faster rate of decline after the peak. This phenomenon explains why all of the grey diamonds appear to the left of the black crosses in figure 5a–d. The grey diamonds are less visible in figure 5e,f because the black crosses have been plotted over the top of them.

In all of the emission pathways considered, emissions peaked between 2010 and 2050 by construction, and thus cumulative emissions between 2010 and 2050 are reasonably well correlated to peak emissions rate, particularly when we only consider pathways with rates of emissions decline between 0 and 4 per cent. This is indicated by figure 5b, where the black crosses are particularly well correlated.

The initially odd shape in figure 5c can be understood by considering the emission pathways of those points with peak rates of warming of 0.2°C per decade. We see that they have 2020 emissions of roughly $12\,\mathrm{GtC\,yr^{-1}}$. Figure 5$f$ also shows that a peak emission rate of $11.5\,\mathrm{GtC\,yr^{-1}}$ produces a peak rate of warming of 0.2°C per decade, suggesting that the emission pathways in figure 5c with 2020 emissions of 11.5 GtC are peaking around the year 2020. Thus, the points with rates of warming of more than 0.2°C per decade have peak years of emissions later than 2020, and are less affected by the rate of emissions in 2020. Similarly, points to the left of $11.5\,\mathrm{GtC\,yr^{-1}}$ generally peak before 2020, and therefore their emission peaks are largely controlled by the rate of emissions today, and not the emissions in 2020.

Figure 5d shows that the 2050 emissions do not correlate well with the peak rate of warming, as 2050 emissions are not influenced much by the peak emissions rate. There is a slight correlation, however, which can be explained by considering the same mechanism that causes the small correlation in figure 5a.

Because an emissions peak in the next decade will be heavily constrained by the rate of emissions today, figure 5e appears to have some correlation near the present day, which gets worse as we move into the future. The black crosses and the grey diamonds lie in the same region of figure 5e, which suggests that the peak rate of warming is not heavily affected by the emissions after the emissions peak.

Figure 5a–e appear to correspond with our principal finding that peak emissions rate determines the peak warming rate, which is illustrated in figure 5f. This means that only two emission targets—the peak rate and cumulative carbon emissions—are needed to constrain two key indicators of CO_2-induced climate change (peak warming and peak warming rate), as evidenced by the maximum-likelihood estimation method used above. We suggest that these targets could provide a simple and natural framework for specifying climate mitigation policy, and comparing the effect of different policies. Inclusion of short-term forcing agents within a rate-of-change target is a natural extension of this approach, and could provide a framework for including both emissions rates, or 'flows', as well as cumulative emissions, or 'stocks', into a set of climate targets that are better informed by current climate science than emissions rates in a given year or long-term concentrations.

4. Conclusions

A number of recent studies have considered the concept of cumulative carbon emissions and their relation to peak warming. Here, we consider how the concept of cumulative emissions interacts with other aspects of global change, such as emissions floors and rates of warming.

We consider other emission metrics, such as the emissions in year 2020 and 2050, and find that these cause a much wider range of magnitudes of resultant peak warming than metrics based on cumulative carbon emissions to the time of peak warming. For small cumulative totals, however, 2050 emissions can be a good indicator of peak warming; however, as soon as we consider 2050 emissions greater than around $5\,\mathrm{GtC\,yr^{-1}}$, this relationship breaks down. We also find that, for large cumulative totals in particular, cumulative metrics based on integrations over smaller time periods, such as 2010–2050, do not correlate with peak warming as well as cumulative emissions to a given date near the time of peak warming.

We extend the analysis of Allen *et al.* [11] of cumulative emissions to consider two types of emissions floors: 'hard' or constant floors, and exponentially decaying floors. In the situation that model temperatures peak before year 2500 and below 4°C, we find that cumulative emissions between pre-industrial times and year 2200 are highly correlated with that peak year, regardless of the type of emissions floor used. Floors do, however, provide a lower bound on cumulative totals at low values. We suggest that a natural geophysical time-frame for considering long-term climate policy is to the year 2200, instead of to the year 2100 as is often done today.

Cumulative emissions, however, say little about rates of global warming, which affect the cost and feasibility of societal and ecosystem adaptation in the short term. We show that maximum rates of CO_2-induced warming are much more closely correlated with peak emissions rates, and that, for each additional GtC per year on the peak emission rate, we will observe a best-guess increase of 0.016°C in the rate of warming per decade.

We also consider the short-term policy implications of our findings. The relationship between cumulative emissions and peak warming allows us to show how delaying mitigation in the short term creates the need for more rapid emission reductions later, in order to stay below a given cumulative emissions limit. Our findings relating to the rates of warming also show that only two emission targets (peak emission rate and cumulative carbon emissions to 2200) are needed to constrain two key indicators of CO_2-induced climate change: peak warming and maximum rate of warming. These targets could provide a simple and clear framework for specifying CO_2 mitigation policy over the next two centuries, and for comparing the effect of different policies.

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