The Transient Response to Cumulative CO₂ Emissions: a Review

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Abstract The transient climate response to cumulative CO₂ emissions (TCRE) is a metric of climate change that directly relates the primary cause of climate change (cumulative CO₂ emissions) to global mean temperature change. The metric was developed once researchers noticed that the cumulative CO₂ versus temperature change curve was nearly linear for almost all Earth system model output. Here, recent literature on the origin, limits, and value of TCRE is reviewed. TCRE appears to emerge from the diminishing radiative forcing per unit mass of atmospheric CO₂ being compensated by diminishing efficiency of ocean heat uptake and the modulation of airborne fraction of carbon by ocean processes. The best estimate of the value of TCRE is between 0.8 to 2.5 K EgC⁻¹. Overall, TCRE has been shown to be a conceptually simple and robust metric of climate warming with many applications in formulating climate policy.

Keywords Climate change · TCRE · CCR · Carbon budget

Introduction

In the quarter-millennium since the invention of the coal fuelled steam engine, burning of fossil fuels and land use changes have lead to the emission of ~550 Pg of carbon

(Pg C) to the atmosphere [17]. The resultant change in atmospheric composition from these emissions, along with the emission of other greenhouse gasses and aerosols, has altered the radiative balance of the Earth, causing warming of the Earth system [35]. To better understand the effect of greenhouse gas emissions on the Earth system, numerical models have been developed that incorporate representations of the global carbon-cycle, radiative forcing from greenhouse gasses and aerosols, absorption of heat by the Earth system and the fluid dynamics of the atmosphere and oceans [5]. Surprisingly, despite the great complexity of the system, simulations with these Earth System Models (ESMs) consistently show that the change in global mean near-surface air temperature is nearly proportional to cumulative CO₂ emissions (e.g. [6, 13, 24]). The constant of proportionality between these two quantities has been designated the Transient Climate Response to Cumulative CO₂ Emissions (TCRE) [5, 15].

TCRE is a convenient metric of climate change as it directly relates the most used index of climate change (change in near surface air temperature) to the primary cause of climate change (cumulative CO₂ emissions). Closely related to the concept of TCRE is the cumulative warming commitment (CWC) [1], a metric which quantifies the relationship between peak warming and cumulative emissions. ESMs suggest that peak warming is also nearly proportional to cumulative emissions of CO₂ [1] and therefore CWC is a constant for a given climate model. The warming that occurs after emissions cease, often called the Zero Emissions Commitment (ZEC) (e.g. [23]), is in many ESM simulations zero or negative (e.g. [23, 29, 38, 40]), in such cases CWC is equal to TCRE.

A clear distinction has not always been made between the ratio of warming to cumulative CO₂ emissions whilst CO₂ emissions continue and this ratio following cessation

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of emissions (e.g. [14, 24]). As the temperature trajectory of ESMs varies from cooling to significant continued warming following cessation of CO₂ emissions (e.g. [10, 22]), there is need to distinguish this post-cessation phase of climate change from the change that occurs while emissions continue. Therefore, in this manuscript, TCRE will be used to denote the relationship between cumulative CO₂ emissions and warming while emissions of CO₂ continue. I recommend that the relationship between cumulative emissions and peak warming (CWC), and cumulative emissions and warming at some distant time in the future be referred to using unique names such as those proposed by Frölicher and Paynter [10].

TCRE is related to the more abstract concept of transience climate response (TCR), which describes the warming at the point in time when atmospheric CO₂ concentration is doubled from the pre-industrial concentration in an idealized experiment [5]. Although TCR is a good metric for comparing climate models [5], it has limited practical application as one must know the relationship between cumulative CO₂ emissions and atmospheric concentration of CO₂ to relate TCR to human activities (e.g. [4]). TCRE incorporates these carbon cycle uncertainties into its definition and therefore provides a conceptually simple way to relate CO₂ emissions to the consequences of those emissions.

Climate targets to limit the magnitude of anthropogenic climate change are usually framed in terms of keeping warming below a chosen temperature change threshold. The most widely cited threshold being 2 K of warming relative to pre-industrial times (e.g. [7]). A consequence of peak global temperature change being nearly proportional to cumulative emissions of CO₂ is that for a given temperature threshold there is a corresponding and finite budget of cumulative CO₂ emissions compatible with such a goal. This budget is independent of the time and rate of the emission of CO₂ [26, 38]. The conceptual simplicity of TCRE and of carbon budgets lead to the prominent presentation of these concepts in working group one of the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5) [17, 35].

Since the articulation of the concept of TCRE in 2009 further research has focused on the physical origin of TCRE (e.g. [14, 21, 31]), quantifying the magnitude, uncertainty and limitations of the concept (e.g. [6, 13, 16, 20, 29]). Here, I review recent advances in the understanding and limits of TCRE with a focus on work published between years 2013 to 2015 and pioneering earlier works.

The Discovery of TCRE

TCRE was conceptualized in three papers published in the boreal spring of 2009 [1, 15, 24]. Matthews et al. [24]

defines what is now thought of as the TCRE, although in that paper the metric was given the name: “Carbon-Climate Response”. TCRE combines the concepts of carbon sensitivity (the increase in atmospheric CO₂ concentration from the emission of CO₂), the climate sensitivity (the physical response of the climate to an increase in atmospheric CO₂ concentration) and the feedbacks between these two processes into a single metric. Mathematically, the concept is described as:

$$\Lambda = \frac{\Delta T}{E} = \frac{\Delta T}{\Delta C_a} \times \frac{\Delta C_a}{E}, \quad (1)$$

where Λ is TCRE, ΔT is the change global mean near surface temperature, E is cumulative emissions of CO₂ and C_a is the carbon content of the atmosphere. For the convenience of readers, all variables are defined in text and in Table 1.

Matthews et al. [24] showed that TCRE is nearly constant in time and emerges as a property of all of the ESMs and intermediate complexity Earth System Models (EMICs) that participated in the Coupled Climate-Carbon Cycle Model Intercomparison Project (Fig. 1). A finding that has been confirmed for the latest generation of ESMs (Fig. 1b, [13]) and EMICs (Fig. 1c).

The work by Gregory et al. [15] was an effort to unify the feedback frameworks developed for physical and the

Table 1 Definitions of variables used in this manuscript

Variable	Units	Definition
Λ	K EgC ⁻¹	TCRE
T	K	Temperature
E	Eg	Cumulative emissions of CO ₂
C_a	Eg	Carbon content of the atmosphere
α	–	Airborne fraction of CO ₂
θ	Wm ⁻² EgC ⁻¹	Linearized radiative forcing factor
C_o	Eg	Original carbon content of the atmosphere
λ	W m ⁻² K ⁻¹	Climate feedback parameter
κ	W m ⁻² K ⁻¹	Ocean heat uptake efficiency
F	W m ⁻²	Radiative forcing
N	W m ⁻²	Planetary heat uptake
R	W m ⁻²	e-fold radiative forcing from CO ₂
ϕ	W ⁻² m ⁴ K ⁻² a ⁻¹	Ocean heat uptake parameter
l	–	Land-borne fraction of carbon
I_U	Eg C	Undersaturation of the ocean
I_B	Eg C	Initial carbon inventory of the ocean-atmosphere system
V	m ³	Volume of the ocean
$\overline{DIC}$	Eg m ⁻³	Mean ocean Dissolved Inorganic Carbon
R_v	–	Revelle buffer factor

Fig. 1 Cumulative emissions versus temperature curves for: **a** C⁴MIP simulations [8, 24], **b** CMIP5 Earth System Models [13], and intermediate complexity ESM simulations [6, 40]. C⁴MIP models were forced with the A2 SRES scenario [28], CMIP5 ESMs with the idealized 1 % increasing atmospheric CO₂ concentration scenario, and EMICs with representative concentration pathways [27]. Panels have been reproduced from panels a, f, and h of Fig. 12.45 in Collins et al. [5]

carbon cycle feedbacks to climate change. As part of this effort, Gregory et al. [15] derived a metric equivalent to the transient climate response that took into account carbon cycle feedbacks. The name given to this new metric was the TCRE, although this metric was defined in a different manner than the concept was eventually defined by the IPCC [5]. The original definition given by Gregory et al. [15] is:

$$\Lambda = \frac{\alpha C_o \theta}{\lambda + \kappa}, \quad (2)$$

and accounting for this change in definition the [15] TCRE is described by:

$$\Lambda = \frac{\alpha \theta}{\lambda + \kappa}. \quad (3)$$

where α is airborne fraction of CO₂, θ is a linearized radiative forcing factor, C_o is the original carbon content of the atmosphere, λ is the climate feedback parameter and κ is the ocean heat uptake efficiency. Note that the original definition of TCRE has units of K while the revised definition has units of K EgC⁻¹.

Allen et al. [1] added to the conceptualization of TCRE and of carbon budgets by developing the concept of CWC, a metric similar to TCRE but relating cumulative emissions to peak temperature following cessation of emissions. Allen et al. [1] found that CWC is nearly proportional to cumulative emissions of CO₂, which suggests that the concept of a finite budget of cumulative CO₂ emissions holds even if warming continues after emissions cease. This property is crucial for the robustness of finite carbon budgets as some climate models simulate continued warming (or even continued build up of atmospheric CO₂) after cessation of anthropogenic CO₂ emissions (e.g. [12, 22]).

The Physical Origin of TCRE

Why TCRE should be nearly constant over a large range of cumulative carbon emissions is not intuitively obvious. Of the parameters identified by Gregory et al. [15] in the definition of TCRE, radiative forcing, ocean heat uptake and airborne fraction of CO₂ are all expected to change on timescales relevant to TCRE (e.g. [35]). Radiative forcing from CO₂ is a nonlinear function of CO₂ concentration, ocean heat uptake is expected become less efficient over time and ESM simulations suggest that airborne fraction of carbon should evolve in time (e.g. [35]). Therefore, changes in these quantities must cancel one-another out to maintain a near constant TCRE. Matthews et al. [24] inferred that the TCRE arises from: (1) saturation of carbon sinks leading to a higher airborne fraction of CO₂ cancelling out the reduction in radiative forcing per unit change in atmospheric CO₂ (due to the near logarithmic relationship between CO₂ concentration and radiative forcing) and (2) the uptake of heat and carbon by the ocean being linked to the same deep-ocean mixing processes. The first effect was invoked to explain why TCRE is independent of scenario followed, a concept referred to here as independence from the rate of CO₂ emissions. The second effect was invoked to explain why TCRE does not change much in time, time independence. However, a detailed analysis was not included in Matthews et al. [24] to support this hypothesis. The second point in particular has been

challenged by detailed modelling of ocean carbon and heat uptake [11].

Three recent studies have engaged in a detailed analysis of the physical basis of TCRE [14, 21, 31]. Raupach [31] investigated TCRE using a simplified climate model that can be configured in a spectrum of complexity from fully coupled set of nonlinear equations to fully linearized approximation of these equations. TCRE emerges both in the fully linearized version of the model (consistent with the definition of TCRE presented by Gregory et al. [15]) and in the fully coupled version of the model. However, the intermediate uncoupled versions of the model did not exhibit a linear relationship between cumulative CO₂ emissions and temperature change. The study concludes that in general TCRE arises from a combination of (1) positive carbon-climate feedbacks increasing the airborne fraction of carbon; (2) weakening radiative forcing per unit CO₂ at higher atmospheric concentrations of CO₂ and (3) contributions from non-CO₂ radiative forcing. Notably without the contribution from non-CO₂ radiative forcing the simulated TCRE remains approximately constant until 1700 Pg C of CO₂ have been emitted to the atmosphere.

MacDougall and Friedlingstein [21] explore the origin of TCRE using analytical analysis supported by an EMIC. The analysis begins from the classical linear temperature response equation:

$$F = \lambda \Delta T + N, \quad (4)$$

(e.g. [36]), where F is radiative forcing and N is planetary heat uptake. This relationship is combined with the [24] definition of TCRE (1) and approximations for radiative forcing:

$$F = R \ln \left(1 + \frac{\alpha E}{C_o} \right), \quad (5)$$

[37], and ocean heat uptake:

$$N = \frac{\Delta T}{\sqrt{\phi t}}, \quad (6)$$

where R is the e-fold radiative forcing from CO₂, ϕ is the ocean heat uptake parameter and t is time. Further, MacDougall and Friedlingstein [21] assume that carbon is emitted to the atmosphere at a constant rate (r) and that the airborne fraction of carbon is constant in time. The second assumption is approximately correct in simulations with a constant rate of emissions of CO₂ to the atmosphere and where the emission rate is below ~ 20 Pg C a⁻¹ [20, 21, 29]. With these approximations and assumptions the relationship for TCRE becomes:

$$\Lambda = \frac{R\alpha}{\lambda C_o} \ln \left(1 + \frac{\alpha E}{C_o} \right) \left(\frac{C_o}{\alpha E} \right) \left(\frac{1}{1 + \sqrt{\frac{r}{\phi \lambda^2 E}}} \right). \quad (7)$$

The relationship is simplified using Taylor series approximation of the hyperbolic arctangent form of the logarithm [18] to give:

$$\Lambda \approx \frac{R\alpha}{\lambda C_o} \left(\frac{1}{1 + \sqrt{\frac{r}{\phi \lambda^2 E}} + \frac{\alpha E}{2C_o} + \sqrt{\frac{\alpha^2 r E}{4C_o^2 \phi \lambda^2}}} \right). \quad (8)$$

As TCRE is near constant over a large range of cumulative emissions the terms in the denominator of Eq. 8 must change with increasing cumulative emissions in ways that cancel out. The point at which changes in the terms cancel out exactly is where the derivative of Eq. 8 is zero. For the parameter values used in MacDougall and Friedlingstein [21], the derivative is zero at 677 Pg C of cumulative CO₂ emissions and TCRE is within 95 % of its peak values between 200 and 2100 Pg C. The second term in the denominator of Eq. 8 is equivalent to $\frac{\kappa(E)}{\lambda}$, the ocean heat uptake efficiency normalized to the climate feedback parameter, while the third term in Eq. 8 is simply the atmospheric carbon content normalized to twice the original atmospheric carbon content. The relationship states that when the rate of emissions and the airborne fraction is constant it is the diminishing ability of the ocean to absorb heat that is compensating for the diminishing radiative forcing per unit CO₂ to create a near constant value for TCRE. If the assumption of constant rate of emissions is replaced by exponentially increasing rate of emissions, an increase in the airborne fraction at higher emission rate is needed to maintain a constant TCRE. Examples of the analytical relationships derived in MacDougall and Friedlingstein [21] and in Gregory et al. [15] are shown in Fig. 2.

For TCRE to be independent of the rate of CO₂ emissions, the airborne fraction of CO₂ must change in a way that compensates for the effect of r on TCRE (8). MacDougall and Friedlingstein [21] provides evidence from EMIC simulations that the ocean uptake of carbon is modulating airborne fraction to produce this effect. Goodwin et al. [14] focuses on this oceanic effect in their analytical description of TCRE. Goodwin et al. [14] take advantage of the functional form of the ocean-atmosphere carbon equilibrium equation to derive an analytical equation for TCRE. The ocean-atmosphere equilibrium equation is:

$$\ln \left(\frac{C_a}{C_o} \right) = \frac{E(1-l) + I_U}{I_B}, \quad (9)$$

where l is the land-borne fraction of carbon, I_U is the undersaturation of the ocean. That is, the difference between the ocean dissolved inorganic carbon (DIC) at a given point in time and the ocean DIC at equilibrium, in addition to any changes in organic matter and calcium carbonate fluxes from the ocean biosphere. I_B is the initial carbon inventory

Fig. 2 Temperature versus cumulative CO₂ emissions curves (**a** and **c**) and TCRE curves (**b** and **d**) for various analytical descriptions of the climate system. r is the rate of CO₂ emissions and α is the airborne fraction of carbon. Figure reproduced from MacDougall and Friedlingstein [21]

of the ocean-atmosphere system, taken to be a constant and defined as:

$$I_B = C_{\text{atm}} + \frac{V \overline{DIC}}{R_v}, \quad (10)$$

where V is the volume of the ocean, $\overline{DIC}$ is mean ocean DIC and R_v is the Revelle buffer factor. Combined with Eq. 4, this gives a analytical expression for TCRE of:

$$\Lambda = \frac{R_v}{\lambda I_B} \left(1 - \frac{N}{F}\right) \left(1 - l + \frac{I_U}{E}\right). \quad (11)$$

Goodwin et al. [14] use simulations with an EMIC to show that an increase in the ratio of $\frac{N}{F}$ is being compensated for by a decline in the ratio $\frac{I_U}{E}$ to generate a near constant TCRE. As the term I_U is difficult to describe analytically combining the MacDougall and Friedlingstein [21] and Goodwin et al. [14] equations and reducing the variables to fundamental constants is a opportunity for future research.

In summary, analytical analysis and results from simple and intermediate complexity climate model experiments suggest that the TCRE arises from the diminishing radiative forcing per unit mass CO₂ being compensated for by diminishing efficiency of ocean heat uptake and the modulation of ocean uptake of carbon as a function of the emission rate of CO₂. The details of the oceanic modulation of TCRE remain poorly explained.

The Limits of TCRE

The proportionality between cumulative CO₂ emissions and temperature change has from the time of its original conceptualization been viewed as a first-order approximation, with the studies that first articulated the concept noting that the relationship becomes sub-linear at high cumulative emissions [24]. The recent model intercomparison studies that evaluate TCRE confirm that the approximate linearity of the cumulative emission versus temperature curve to be limited to a finite range of cumulative emissions (see Fig. 1a, b) [6, 13]. At high cumulative emissions, the temperature versus cumulative CO₂ emissions curve become more logarithmic in shape for most models (Fig. 1). This suggests that the logarithmic forcing from CO₂ is becoming the dominant term in the relationship. Analytical analysis of the climate system supports this limitation. The terms in the equations explored in MacDougall and Friedlingstein [21] only cancel out precisely at a single point. Away from this point, the cancellation is only approximate and grows ever less accurate. MacDougall and Friedlingstein [21] defined the notion of a TCRE window over which the TCRE remains within 95 % of its peak value. The size of the window is expected to vary depending on value of the climate system parameters characteristic to each climate model.

Several recent climate modelling studies have explored the degree to which TCRE is independent of the rate of CO₂ emissions [16, 20, 21, 29] and have produced varying conclusions. Nohara et al. [29] forced a fully coupled ESM with five idealized emissions pathways, all of which converged

on the same total of cumulative CO₂ emissions. In three of the pathways, carbon is emitted at a constant rate, one pathway is a pulse experiment and another is an overshoot experiment. Except for the overshoot experiment, all of the pathways yield the same value of TCRE. Krasting et al. [20] forced a fully coupled ESM with seven emission pathways all with constant rates of CO₂ emissions and all converging on the same total cumulative CO₂ emissions. The rate of emissions varied between 2 and 25 Pg C a⁻¹. The study found a complex relationship between TCRE and rate of emission with the highest TCRE for both the highest and lowest emission rates, and TCRE reaching a nadir at 5 Pg C a⁻¹. Herrington and Zickfeld [16] forced an EMIC with 24 emissions pathways converging at 1275, 2275, 3275, 4275 and 5275 Pg C. The pathways were defined by different peak rates of emissions to achieve each cumulative total, in addition to a pulse and an overshoot emission pathway for each cumulative CO₂ total. The study found that TCRE was consistent within each cumulative emissions total but declined from 1.9 to 1.7 K EgC⁻¹ as emissions tended toward higher cumulative totals.

Uptake of carbon by the terrestrial biosphere does not appear to play a primary role in the physical origin of TCRE [14, 21, 31]. However, when using a model version configured to have a strong positive terrestrial carbon cycle feedback, MacDougall and Friedlingstein [21] found that the TCRE varied by rate of emissions but only when the model was forced with highly idealized emission pathways. It is plausible that variation in land carbon uptake played a role in the variation in TCRE with CO₂ emissions rate found in the simulations of Krasting et al. [20]. However, a detailed analysis of the source of the variation in TCRE was not included in that study.

The concept of TCRE applies only to CO₂ and not to other greenhouse gasses and forcing agents (e.g. [24, 25]). The relatively short life times of many greenhouse gasses and the lack of a mechanism analogous to ocean modulation of airborne fraction of CO₂ mean that these gasses do not exhibit a simple relationship between their effect on global temperature and their cumulative emissions. Generally, non-CO₂ forcing agents should be accounted for in a separate “basket” from CO₂ [32, 33] as the warming from these agents dissipates within decades after their emissions cease while much the warming from CO₂ is expected to last many thousands of years (e.g. [30]).

Another limitation to the concept of TCRE was explored by Cherubini et al. [3]. This study looked at the effect of bio-energy CO₂ emissions on TCRE. The study found that because the plant material that fuels bio-energy production regrows with a characteristic timescale that the radiative forcing from these emissions decays in a similar manner to non-CO₂ greenhouse gasses. Cherubini et al. [3] concludes that emissions from bio-energy should not be added

to the cumulative emission total used to compute TCRE but instead be placed in another basket in an analogous manner to short lived greenhouse gasses.

Some studies have examined the relationship between cumulative emissions of CO₂ and metrics of climate besides temperature [16, 39]. These studies suggest that change in sea-ice cover and precipitation is close to linear functions of cumulative CO₂ emissions. While changes in the ocean meridional overturning circulation is not simulated to be a simple function of cumulative emission but exhibits complex dependence on the path of emissions [16, 39]. Herrington and Zickfeld [16] show that simulated transient thermosteric sea-level change is a function of both the rate of emissions and cumulative CO₂ emissions, consistent with Solomon et al. [34]. However, [16] suggest that thermosteric sea-level-rise becomes proportional to cumulative emissions after the system is allowed to evolve for centuries after emissions cease. Generally, these studies suggest that caution is warranted when extending TCRE to non-temperature metrics of climate change.

The Value of TCRE

The value of TCRE can be estimated both from climate model output (e.g. [6]) or from observations of the natural world (e.g. [13]). The most recent efforts to estimate TCRE from intercomparison of climate model output are Eby et al. [6] for EMICs and Gillett et al. [13] for ESMs. EMICs are intentionally simpler than ESMs in one or more ways but often include processes that are not yet represented in fully coupled ESMs and therefore may sample a larger part of the true Earth system uncertainty (e.g. [5]). For both efforts, TCRE was calculated from the 1 % compounded increase in atmospheric CO₂ concentration experiment at the time of the doubling of atmospheric CO₂ concentration. Calculating TCRE at this point in time makes it equivalent to the TCR. That is, $TCRE \equiv \frac{TCR}{2C_0}$. This definition of TCRE avoids complications from TCRE varying with emission rate in some ESMs and EMICs. The EMIC intercomparison found an inter-model range in TCRE of 1.4 to 2.5 K EgC⁻¹ [6], and the ESM intercomparison found an inter-model range in TCRE of 0.8 to 2.4 K EgC⁻¹. Notably in the ESM intercomparison, the two models that incorporate the nitrogen cycle have the largest values of TCRE [13] as these models simulate a smaller uptake of carbon into the terrestrial biosphere [2]. The high TCRE in the nitrogen cycle capable models may suggest that the true value of TCRE is on the high end of the inter-model range. However, uncertainty about the effect of nitrogen limitations in ESMs is considerable (e.g. [2]).

From the observational record Gillett et al. [13] calculate that TCRE is between 0.7 to 2.0 K EgC⁻¹ within

the 5 to 95 % uncertainty bound. Estimating TCRE from observed properties of the Earth system requires an estimate of the combined historical fossil fuel and land use change emissions, estimated change in global mean temperature relative to the pre-industrial climate, and an estimate of what fraction of this warming is attributable to changed in atmospheric CO₂ concentration. Attributing the fraction of warming from changes in atmospheric CO₂ concentration requires a knowledge of what fraction of historical radiative forcing is due to CO₂, other non-CO₂ anthropogenic forcing and natural forcing. This partitioning of forcing is derived from climate model output and therefore the observational constraint on TCRE is not truly independent of climate models. IPCC AR5 included a section describing TCRE [5] and summarizing evidence for its existence ([5] see Figure 12.45). The report gave an expert judgement of TCRE to be likely between 0.8 and 2.5 K EgC⁻¹.

TCRE implies that transient climate warming is approximately a path-independent function of cumulative CO₂ emissions [24]. Combined with the notion that peak warming is also proportional to cumulative CO₂ emissions [1], this implies that there is a finite budget of fossil fuels that can be burned compatible with a given target for stabilizing global temperature [26, 38]. IPCC AR5 gave an uncertainty range for the carbon budget compatible with the commonly cited 2 K climate target based on their TCRE expert judgment range. Assuming that this range represents ± 1 standard deviation and that the uncertainty is normally distributed the CO₂ only carbon budget is 1570, 1210 and 1000 Pg C for > 33, > 50 and > 66 % probability of not breaching the 2 K target [5].

There have been two recent review papers exploring the consequences of carbon budgets for climate policy [9] and ethics [19]. Therefore, this review has focused on scientific aspects of TCRE and readers are encouraged to read these publications for recent reviews of the policy implications of TCRE.

Remaining Questions and Uncertainties

TCRE has proved a robust and useful metric of climate change, however, significant question remains about the physical origin of TCRE and the sensitivity of the metric to poorly contained parameters of the Earth system. In particular, the modulation of airborne fraction of CO₂ by the ocean is key to understanding the rate independence of the TCRE. To date, most climate model simulations that have supported detailed examinations of TCRE have focused either on scenarios where CO₂ emissions are constant [20, 21, 29] or where CO₂ emission rate increases monotonically [6, 13, 14, 31]. However, TCRE has been shown to be just as valid in scenarios where the emission rate

peaks and declines (e.g. [16, 40], Fig. 1c). Therefore, there is a need to examine the physical and chemical processes that govern the ocean uptake of heat and carbon in scenarios where emission rates are declining and incorporate this into our understanding of the near rate independence of TCRE.

Some ESMs suggest that TCRE has a small dependence on the rate of CO₂ emissions (e.g. [20]) while other ESMs show no such relationship (e.g. [29]). The origin of this discrepancy between models is an open question and should be a priority for future research.

Summary

The TCRE is a robust metric of climate warming that directly relates the primary cause of climate warming (anthropogenic CO₂ emissions) to the most used index of climate change (near surface global temperature change). The metric emerges almost universally from climate model output. For a given model, the metric is nearly constant and nearly independent of rate of CO₂ emissions. However, in some models, TCRE varies by emission rate up to ~ 10 % (e.g. [20]). In almost all models, the value of TCRE declines at high cumulative CO₂ emissions typically at values over ~ 2000 Pg C (e.g. [6, 13]). Exploration of the physical origin of TCRE shows that TCRE emerges from the diminishing radiative forcing per unit mass of atmospheric CO₂ being compensated by diminishing efficiency of ocean heat uptake and the modulation of airborne fraction of carbon by ocean processes. Analytical analysis suggests that TCRE should only be valid over a finite range of cumulative emissions as the changes in variables that cancel to create TCRE only exactly cancel at a single point.

TCRE has been estimated from observational data to be between 0.7 and 2.0 K EgC⁻¹ within the 5 to 95 % uncertainty bound [13]. The inter-model range in TCRE from fully coupled ESMs is 1.4 to 2.5 K EgC⁻¹ [13] and EMICs is from 0.8 to 2.4 K EgC⁻¹ [6].

The key policy implication of TCRE is that there is a finite budget of carbon that can be emitted to the atmosphere if global mean temperature is to be held below a chosen warming threshold. This budget is effectively independent of when and how fast CO₂ is emitted to the atmosphere and is estimated to be 1000 Pg C for a 66 % chance of staying below the 2 K global temperature change threshold [5].

TCRE is an emergent property of the Earth system that links the primary cause of climate change to the consequences of climate change in a conceptually simple manner. Therefore, TCRE and the closely related concept of carbon budgets will likely remain a useful tool for developing climate policy and explaining climate change to the general public until the use of fossil fuels is abolished.

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