Annual Review of Environment and Resources

Net Zero: Science, Origins, and Implications

Myles R. Allen,[1,4] Pierre Friedlingstein,[2,3]
Cécile A.J. Girardin,[1] Stuart Jenkins,[4]
Yadvinder Malhi,[1,5] Eli Mitchell-Larson,[1]
Glen P. Peters,[6] and Lavanya Rajamani[7]

[1]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, United Kingdom; email: myles.allen@ouce.ox.ac.uk

[2]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, United Kingdom

[3]Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, CNRS-ENS-UPMC-X, Paris, France

[4]Department of Physics, University of Oxford, Oxford, United Kingdom

[5]Leverhulme Centre for Nature Recovery, University of Oxford, Oxford, United Kingdom

[6]CICERO Center for International Climate Research (CICERO), Oslo, Norway

[7]Faculty of Law, University of Oxford, Oxford, United Kingdom

Annu. Rev. Environ. Resour. 2022. 47:849–87

First published as a Review in Advance on
August 26, 2022

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112320-105050

Keywords

carbon budget, net zero, climate neutrality, nature-based solutions, greenhouse gases, carbon markets, Paris Agreement

Abstract

This review explains the science behind the drive for global net zero emissions and why this is needed to halt the ongoing rise in global temperatures. We document how the concept of net zero carbon dioxide (CO_2) emissions emerged from an earlier focus on stabilization of atmospheric greenhouse gas concentrations. Using simple conceptual models of the coupled climate–carbon cycle system, we explain why approximately net zero CO_2 emissions and declining net energy imbalance due to other climate drivers are required to halt global warming on multidecadal timescales, introducing important concepts, including the rate of adjustment to constant forcing and the rate of adjustment to zero emissions. The concept of net zero was taken up through the 5th Assessment Report of the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change (UNFCCC) Structured Expert Dialogue, culminating in Article 4 of the 2015 Paris Agreement. Increasing numbers of net zero targets have since been adopted by countries, cities, corporations, and investors. The degree to which any entity can claim to have achieved net zero while continuing to rely on distinct removals to compensate for ongoing emissions is at the heart of current debates over carbon markets and offsetting both inside and outside the UNFCCC. We argue that what matters here is not the precise makeup of a basket of emissions and removals at any given point in time, but the sustainability of a net zero strategy as a whole and its implications for global temperature over multidecadal timescales. Durable, climate-neutral net zero strategies require like-for-like balancing of anthropogenic greenhouse gas sources and sinks in terms of both origin (biogenic versus geological) and gas lifetime.

Contents

1. NET ZERO EMISSIONS AND GLOBAL WARMING

Article 4 of the Paris Agreement, building on the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (1) and the United Nations Framework Convention on Climate Change (UNFCCC) Structured Expert Dialogue (2), states, "In order to achieve the long-term temperature goal set out in Article 2 [Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C], Parties aim…to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (3, p. 4). Announcements made in the buildup to the 26th UN Climate Change Conference of the Parties (COP26) meeting in Glasgow in 2021, particularly India's declaration for net zero emissions by 2070, China's announcement in 2020 of carbon neutrality by 2060, and those of other major developing countries, including Brazil, Nigeria, and South Africa, mean that more than 90% of the world economy is now covered by some form of target aiming for net zero emissions between 2050 and 2070 (4). Given that little more than a decade has passed since the first papers were published indicating the need for net zero carbon dioxide (CO_2) emissions to halt global warming (5) and introducing the concept of an atemporal carbon budget (6–9), the adoption of these net zero goals represents remarkably rapid progress for an international environmental issue. This progress both reflects real and growing concern about the impacts of global warming and is an example of effective translation of novel scientific findings into national and international policy, brokered by the IPCC. Challenges remain, however, most obviously in the lack of detail regarding how these midcentury net zero targets are defined and are to be achieved, what they mean in the context of the long-term temperature goal of the Paris Agreement, whether all net zero declarations are collectively consistent, and the extent to which they reflect a fair and differentiated approach to net zero. In this article, we review the science behind net zero, taking a historical perspective to explain how the concept emerged, how it was conveyed into policy, and some of the issues that remain unresolved.

As we discuss in Section 4, the term net zero is generally applied to all greenhouse gases (GHGs) aggregated in some way but does not include non-GHG climate forcers such as aerosols, although the scientific origins of the concept of net zero lie in the need for net zero CO_2: To avoid ambiguity, we refer to these two usages as net zero GHG and net zero CO_2, respectively. Climate neutrality[1] was defined by the 2018 IPCC Special Report on 1.5°C (SR1.5) (10, 11) as a state in which human activities result in no net effect on the climate system, although this term was not used in the IPCC 6th Assessment Report (AR6) (12) because multiple definitions were in use. In this review, we propose that climate neutrality could be used more specifically to denote a situation in which human activities cause no additional increase or decrease of the global average surface temperature over multidecadal timescales. This definition is precisely analogous to carbon neutrality, which corresponds in normal scientific usage to net zero CO_2 emissions. In the context of multiple GHGs discussed in Section 4, climate neutrality corresponds to sustained net zero CO_2-warming-equivalent emissions. We suggest that converging on this definition of climate neutrality would be helpful in the context of policy focused on limiting warming, since climate neutrality, by definition, is then achieved at the time of peak warming.

The SR1.5 (10, "Summary for Policymakers," para. A.2.2) stated, "Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*)." The AR6 (12, "Summary for Policymakers," para. D.1) went further: "[L]imiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions." Global warming here refers to the human-induced change in global average surface temperature relative to preindustrial conditions, and radiative forcing is the net energy imbalance in the climate system caused by some external driver, such as an increase in GHG concentrations, before temperatures adjust to that driver.

We can express these statements quantitatively in a simple equation relating human-induced global warming ΔT over a multidecadal time interval Δt to CO_2 emissions and non-CO_2 radiative forcing:

$$\Delta T \approx \kappa_E \overline{E_C} \Delta t + \kappa_F \left(\Delta F_N + \rho \overline{F_N} \Delta t \right), \qquad 1.$$

---

[1] Climate neutrality is a state in which the net impact of a combination of anthropogenic climate forcing agents causes no additional warming or cooling of the climate system. We suggest this as an intuitive definition of climate neutrality, since it corresponds to the same climate impact as carbon neutrality in a CO_2-only scenario. Other definitions, such as net zero greenhouse gas emissions aggregated using a specific greenhouse gas metric, have also been proposed.

where $\overline{E_C}$ is the average rate of CO_2 emissions over that time interval, ΔF_N is the change in global non-CO_2 radiative forcing between the decade prior to the beginning and the decade prior to the end of that time interval, and $\overline{F_N}$ is the average non-CO_2 radiative forcing over that time interval. The origins of the various terms in Equation 1, including the use of decadal averages in this definition of ΔF_N, are explained in this review.

Rate of adjustment to constant forcing (RACF): fractional rate of change of global average surface temperature associated with a multidecadal period of constant radiative forcing

If non-CO_2 radiative forcing is negligible, Equation 1 implies that warming over any time interval, including from preindustrial to present or from now to the time of peak warming in the future, is determined by cumulative CO_2 emissions over that interval, $\overline{E_C}\Delta t$. If CO_2 emissions are reduced to and held at net zero ($\overline{E_C} = 0$), studies using more comprehensive models of the climate–carbon cycle system indicate that we can expect little if any additional CO_2-induced warming (13), at least over a multidecadal time interval (14), although further warming may occur on longer timescales (15).

We explain in Section 2 why Equation 1 is expected to be approximately true, and the coefficients κ_E, κ_F and ρ approximately constant, for mitigation scenarios that limit warming to 1.5–3°C: κ_E is the transient climate response to emissions (TCRE) (16, 17), formally assessed by the AR6 to be 0.45(±0.18)°C per trillion tonnes of CO_2 ($TtCO_2$) emitted; κ_F is the transient climate response to forcing (TCRF), or the sum of the fast components (18, 19) of the climate response to any forcing change; and ρ is the rate of adjustment to constant forcing (RACF), or the fractional rate at which temperatures change in the decades after forcing stabilization (20, 21). The RACF depends on past forcing as well as the climate response, but a representative maximum value of (300 years)$^{-1}$, or 0.3% per year, is consistent with best-estimate values of other climate system properties when forcing has primarily increased in recent decades (22, 23). A TCRF of $\kappa_F = 0.42(\pm 0.10)$°C per W/m^2 is consistent with this RACF and other climate system properties assessed by the AR6. [The TCRE and TCRF values are similar because in these units the radiative forcing due to a constant emission of CO_2, or the CO_2 absolute global warming potential (AGWP) divided by the time horizon, is slightly less than unity, meaning a constant emission of CO_2 over a period of 50 to 100 years starting in year zero leads to a radiative forcing at the end of this period of approximately 1 W/m^2 per $TtCO_2$ emitted, as we explain in Section 4.] As we shall see in Section 2, the RACF also plays a key role in understanding the need for net zero CO_2 emissions to limit CO_2-induced warming, because it also represents the fractional rate at which forcing has to decline over multidecadal timescales to maintain stable surface temperatures. Despite its simplicity, Equation 1 summarizes two decades of climate–carbon cycle research, so we propose to structure our review around it.

2. CO_2-INDUCED WARMING: FROM STABILIZING CONCENTRATIONS TO NET ZERO EMISSIONS

The cumulative impact of CO_2 emissions on global temperature and the consequent need for net zero emissions to halt global warming are now so central to climate policy that it may seem surprising that these concepts were relatively novel only a decade ago—and also that the scientific community took a surprisingly long time to recognize their significance. It is an interesting example of how overall framing determines the research agenda and how even a relatively minor separation of disciplines can obscure results. The two disciplines in question were the physical climate modeling community, investigating the global temperature response to changing atmospheric concentrations of GHGs, and the carbon cycle modeling community, exploring the relationship between CO_2 emissions and atmospheric CO_2 concentrations. Understanding how these two fields of research came together also helps illustrate the limitations of Equation 1.

Prior to the late 2000s, the overarching framing of research on climate change mitigation was, in the words of the UNFCCC in 1992 (24, Article 2, p. 4), "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Scenario developers (25–28) and the carbon cycle modeling community (29–32) understood their role to be identifying emission pathways consistent with different concentration pathways and stabilization levels. Meanwhile, the physical climate modeling community focused on characterizing the equilibrium response to indefinite stabilization of GHG concentrations at some level, as characterized by the equilibrium climate sensitivity (ECS), or the long-term warming response to a doubling of atmospheric CO_2 concentrations (33, 34). Relatively few early papers (35) explicitly combined these emissions-to-concentrations and concentrations-to-warming steps.

A persistent challenge emerged with placing a robust and useful upper bound on the ECS value (36–39): From the time of the Charney Report in 1979 (33) to the IPCC 3rd Assessment in 2001 (40), the canonical uncertainty range for the ECS remained 1.5–4.5°C. The IPCC 4th Assessment raised the lower bound to 2–4.5°C in 2007 (41), only for the IPCC 5th Assessment to lower it again to 1.5–4.5°C in 2013 (1). The problem was not only that the ECS was uncertain but also that the uncertainty itself was contestable, particularly the upper bound, because of the nonlinear relationship between the ECS and the quantities that could be observed (42–44).

While these debates continued, two separate developments suggested a different way forward. First, the transient climate response (TCR), a measure of the warming at the time of CO_2 doubling in response to exponentially increasing CO_2 concentrations, was shown to be more robustly constrained by both models and observations than was the ECS because it depended on better-understood aspects of the climate response (45) and was more directly related to quantities that could be observed, including the increase in global average surface temperature to date (46, 47). A conceptual model emerged (48) representing the global temperature response to radiative forcing by two components: a fast adjustment on a timescale of a few years, characterized by the TCR, and a slow adjustment to equilibrium on a timescale of several centuries, characterized by the ECS (18). Second, our understanding of the global carbon cycle was maturing: Although CO_2 emissions had long been recognized (49) to have an effectively permanent impact, CO_2 did not simply accumulate in the atmosphere, with the relationship between emissions and concentrations also characterized by various adjustment rates, including centennial timescales (50). We illustrate these points and their implications in the following sections, which also allow us to explain the origin of the simple relationship between emissions, radiative forcing, and global temperature expressed by Equation 1.

2.1. The Global Temperature Response to Radiative Forcing

The response of global average surface temperature T_s, relative to a preindustrial equilibrium, to any externally imposed energy imbalance or effective radiative forcing F was found in the 2000s to be well characterized by a simple two-layer energy balance model:

$$C_s \frac{\mathrm{d}T_s}{\mathrm{d}t} = F - \lambda T_s - \gamma\,(T_s - T_d) - \lambda'\,(T_s - T_d) \qquad 2.$$

and

$$C_d \frac{\mathrm{d}T_d}{\mathrm{d}t} = \gamma\,(T_s - T_d), \qquad 3.$$

where C_s and C_d are the effective heat capacities of the land plus near-surface ocean and the deep ocean, respectively, and T_d is the effective deep-ocean temperature departure from preindustrial equilibrium. F is the effective radiative forcing, meaning the global average planetary energy imbalance that would give this surface temperature response on multiyear timescales (all these quantities are effective because warming and forcing are nonuniform). For CO_2, effective and actual radiative forcing are similar, but for spatially nonuniform drivers such as aerosols, they may be different (51). Hence, the only variable in Equations 2 and 3 that represents a directly observable quantity is T_s.

On the right-hand side of Equations 2 and 3 λ is the equilibrium sensitivity parameter, or the additional rate of energy radiation to space per degree of global warming for a planet in equilibrium; γ represents ocean overturning processes that transport heat between the surface and deep ocean; and λ' represents the additional rate of energy radiation to space resulting from the fact that the planet is not in equilibrium [λ' was originally introduced (52) as an efficacy of ocean heat uptake, but we feel this representation is clearer because this term does not actually correspond to an ocean heat uptake].

This two-layer model was originally introduced (53) (with $\lambda' = 0$) in 2000 as a simpler (and in some respects more realistic) alternative to earlier diffusive models of ocean heat uptake (54). A nonzero λ' was added later to characterize the behavior of more complex models. This increase in complexity explains the lack of progress in constraining the ECS, or F_{2x}/λ, where F_{2x} is the radiative forcing resulting from a doubling of CO_2. Because F_{2x} is characterized to within approximately ±10% by long-established (55, 56) radiative transfer calculations, most of the uncertainty in the ECS, and hence uncertainty in the stabilization level of GHGs consistent with avoiding any particular level of warming, arises from uncertainty in λ.

Early estimates of the ECS were based solely on the spread of results from atmosphere–ocean general circulation models, but as models proliferated, it became clear that uncertainties in different processes contributing to the additional energy radiated to space per degree of warming were approximately additive (39), yielding a symmetric distribution of uncertainty in λ and consequently a weak upper bound on the ECS. This problem remains to this day, with some of the most advanced and (in all other respects) physically realistic models in the latest Coupled Model Intercomparison Project phase 6 (CMIP6) displaying ECS values above the accepted current range of uncertainty. It is still frequently cited as evidence of a substantial warming in the pipeline that would occur if atmospheric concentrations of GHGs were stabilized at their current levels (57). This constant concentration commitment is, however, not the same as the future warming under no additional emissions (58), or zero emissions commitment (ZEC), although they are still often (59) confused with each other.

Given the difficulty of constraining the ECS with climate models, interest turned to constraining it with observations, but problems arose here as well. The initial rate of warming (in degree Celsius per year) in response to a steadily increasing forcing (in Watt per square meter per year), which is more or less what has been observed over recent decades, is inversely proportional to $(\lambda + \gamma + \lambda')$, so without knowledge of γ and λ', this rate alone does not provide information on λ. To address this problem, papers emerged in the early 2000s (37, 60) combining information on observed rates of warming with new datasets (61) of ocean heat content change. If the rate of total ocean heat content change is equated with the sum of the left-hand side of Equations 2 and 3, the equations can be added together to eliminate the γ-dependent term, providing a constraint on the effective climate sensitivity, $F_{2x}/(\lambda + \lambda')$.

This constrains the ECS itself if, and only if, it is assumed that $\lambda' = 0$, or that the strength of atmospheric feedbacks does not change under global warming. Unfortunately, evidence emerged (52, 62) in the mid- to late-2000s that feedbacks could be expected to change not only in the future but consistently in the direction of the net feedback weakening as the climate system came back into equilibrium ($\lambda' > 0$). Given there was no realistic prospect of any observational constraint on λ', this was, in effect, the end of the road for efforts to provide a useful upper bound on the ECS and hence determine a safe stabilization concentration of atmospheric GHGs. Throughout this period there were calls (63, 64) to pay more attention to the TCR, given the limited relevance of the ECS to the temperature response to any scenario other than a hypothetical forcing stabilization.

Observed climate change provided a much more robust constraint on the transient response to a relatively rapidly increasing forcing, since this was actually being observed (42). Hence, in 2006, peak warming in response to a scenario in which the CO_2 concentration (or radiative forcing in general) peaks and subsequently declines was proposed as a more robust focus for climate policy than equilibrium warming in response to atmospheric stabilization (65). The reason for this result is clear from an alternative way of presenting the two-layer model, which clarifies some more general properties of the climate response to any radiative forcing. Equations 2 and 3 can be rewritten (66, 67) as

$$\frac{\mathrm{d}\mathbf{T}}{\mathrm{d}t} = \mathbf{J}\mathbf{T} + \frac{\mathbf{F}}{C_s} \equiv \begin{pmatrix} -(\lambda + \gamma + \lambda')/C_s & (\gamma + \lambda')/C_s \\ \gamma/C_d & -\gamma/C_d \end{pmatrix} \begin{pmatrix} T_s \\ T_d \end{pmatrix} + \begin{pmatrix} F/C_s \\ 0 \end{pmatrix}. \qquad 4.$$

If the matrix $\mathbf{E}$ consists of the eigenvectors of the Jacobian $\mathbf{J}$, arranged column-wise, $\mathbf{E}^{-1}$ is its inverse, σ_j is the jth eigenvalue, and $c_j = E^{-1}_{j0} E_{0j}/(\sigma_j C_s)$, then the response to any radiative forcing $F(t)$ can be decomposed (68) into $M = 2$ components, each associated with an adjustment timescale $s_j = \sigma_j^{-1}$ (assuming effective heat capacities are expressed in Watt-years per square meter per degree Celsius and a 1-year time interval):

$$T_s(t) = \sum_{j=1}^{M} \frac{c_j}{s_j} \int_{t'=0}^{t} F(t') \exp\left(-\frac{t - t'}{s_j}\right) \mathrm{d}t'. \qquad 5.$$

To a good approximation, with $M = 2$, the fast timescale $s_1 \approx C_s/(\lambda + \lambda' + \gamma)$ and the slow timescale $s_2 \approx C_d(\lambda + \lambda' + \gamma)/(\lambda\gamma)$, as may be verified by considering the initial response to any forcing (assuming a large C_d) and the slow adjustment to equilibrium with a constant forcing (assuming a small C_s), respectively. Crucially, both adjustment timescales, s_1 and s_2, depend on climate system properties (radiative feedbacks to space and their dependence on disequilibrium) that are unrelated to ocean mixing timescales.

The coefficients c_j represent components of the equilibrium warming response to a 1 W/m^2 radiative forcing associated with each adjustment timescale, so their sum $\sum c_j = \lambda^{-1}$. Algebraic derivation of c_j in terms of coefficients of Equations 2 and 3 (67, 68) is rather involved, but they are straightforward to calculate numerically from the Jacobian $\mathbf{J}$ and readily generalized (69) to a multilayer model, $M > 2$. It has been recently argued (19) that the behavior of more complex models to sudden forcing changes is better reproduced by three response timescales, although we focus here on $M = 2$ for simplicity because it captures the response (70) on decadal and longer timescales. For any value of M and reasonable choices of parameters, notably $C_d \gg C_s$, the effective deep-ocean temperature anomaly is dominated by the slowest timescale, s_M, so

$$T_d(t) = \frac{\sum c_j}{s_M} \int_{t'=0}^{t} F(t') \exp\left(-\frac{t - t'}{s_M}\right) \mathrm{d}t'. \qquad 6.$$

This is useful for calculating $\lambda'(T_s - T_d)$ and hence net heat uptake to interpret ocean heat content changes given a range of values for λ'.

The advantage of reformulating the layer model (Equations 2 and 3) in terms of response timescales is that if $M = 2$ and we focus on timescales much longer than s_1 and much shorter than s_2, $T_s(t)$ in Equation 5 is well approximated (67) by one component proportional to the forcing, subject to a few years' delay, and a second component proportional to the time-integrated forcing:

$$T_s(t) \approx \kappa_F \left[F(t - s_1) + \rho \int_{t'=0}^{t} F(t')\ \mathrm{d}t' \right], \qquad 7.$$

where $\kappa_F = c_1$ is the TCRF and ρ is the RACF [$\rho = c_2/(c_1 s_2)$ in this limit], as may be verified by considering the response to a ramp forcing increase (21). Total warming is proportional to a rapid adjustment to recent forcing, averaged over the past $2s_1$ years (to give an average delay of s_1 years), plus a component proportional to integrated forcing since forcing anomalies began.

Hence, the temperature change in response to a slowly varying forcing over a multidecadal time interval consists of one component proportional to the forcing change (calculating ΔF between the decade prior to the beginning and the decade prior to the end of the time interval accounts for the delay s_1 given that this is typically of the order of 5 years) and a second component proportional to the average forcing multiplied by the length of the time interval, $\bar{F}\Delta t$, or the change in time-integrated forcing over that time interval:

$$\Delta T = \kappa_F \left(\Delta F + \rho \bar{F} \Delta t\right). \qquad 8.$$

The second and third terms on the right-hand side of Equation 1 have emerged.

The TCRF, κ_F, is simply the sum of the fast (subdecadal) components of the climate response to any forcing. With units of degree Celsius per Watt per square meter, κ_F is a more general property of the climate system than is the TCR, which is defined (71) as the warming observed at the time of CO_2 doubling (i.e., after 70 years) in a scenario in which CO_2 increases at 1% per year starting from equilibrium. The TCRF is approximately the TCR divided by F_{2x}, but not identically so because 70 years is not negligible relative to the centennial adjustment timescale. Most papers ignore this small difference and estimate TCR from any multidecadal transient forcing change (43, 47).

The RACF, ρ, is the fractional rate at which temperatures increase in the decades after forcing is stabilized, or the fractional rate at which forcing needs to decline to stabilize temperatures [halt global warming (10)] over a multidecadal timescale, giving $\Delta T = 0$ in Equation 1. The RACF is clearly an important quantity for net zero policy but is only determined directly by climate system properties in the limiting case that forcing has increased from zero much faster than the RACF itself, so the deep ocean has yet to begin to adjust. In this case, $\rho = \rho_{max} \equiv c_2/(c_1 s_2)$. This expression also applies for $M > 2$ provided there is only one centennial response time, all other response times are subdecadal, and c_1 is replaced by κ_F, the sum of the subdecadal components. If some component of the forcing has increased on a timescale comparable to the RACF, then $\rho < \rho_{max}$ because the deep ocean will have begun to equilibrate. Despite this dependence of ρ itself on the forcing scenario, the maximum RACF, ρ_{max}, is useful because it represents the rate of forcing decline that guarantees stable or declining temperatures whatever the past forcing history. For a forcing that has increased recently, as is the case for both aggregate and most individual components of non-CO_2 forcing, the RACF will be close to ρ_{max}.

Figure 1*a* shows the response of this simple two-component system to a linear increase in forcing to F_{2x} over 70 years, after which forcing is held constant. In **Figure 1*b***, forcing declines exponentially at a fractional rate ρ_{max} after year 70, yielding approximately stable surface temperatures. Consistent with Equation 7, the fast component of the response (orange dashed line) is well characterized by the forcing times the TCRF (orange dotted line) subject to a small delay, $T_1 = c_1 F(t - s_1)$), while the slow component, or the product of the TCRF, RACF, and integrated forcing, $T_2 = c_1 \rho_{max} \int F(t)\mathrm{d}t$, is identical to the purple dashed line.

While the maximum RACF is related to the ECS (22), $\rho_{max} = (\mathrm{ECS} - \mathrm{TCR})/(\mathrm{TCR} \times s_2)$, it also depends on the TCR and centennial response time, s_2. More specifically, it depends on the realized warming fraction (RWF), or TCR/ECS ratio (72, 73): $\rho_{max} = (1 - \mathrm{RWF})/(\mathrm{RWF} \times s_2)$. Hence, a temporary forcing stabilization does not constrain the ECS, nor does the ECS fully constrain the RACF. Given its policy significance, there is a clear need for research directly constraining the RACF: The SR1.5 (10, Section 1.2.4) remarked that the RACF was "less than 1%

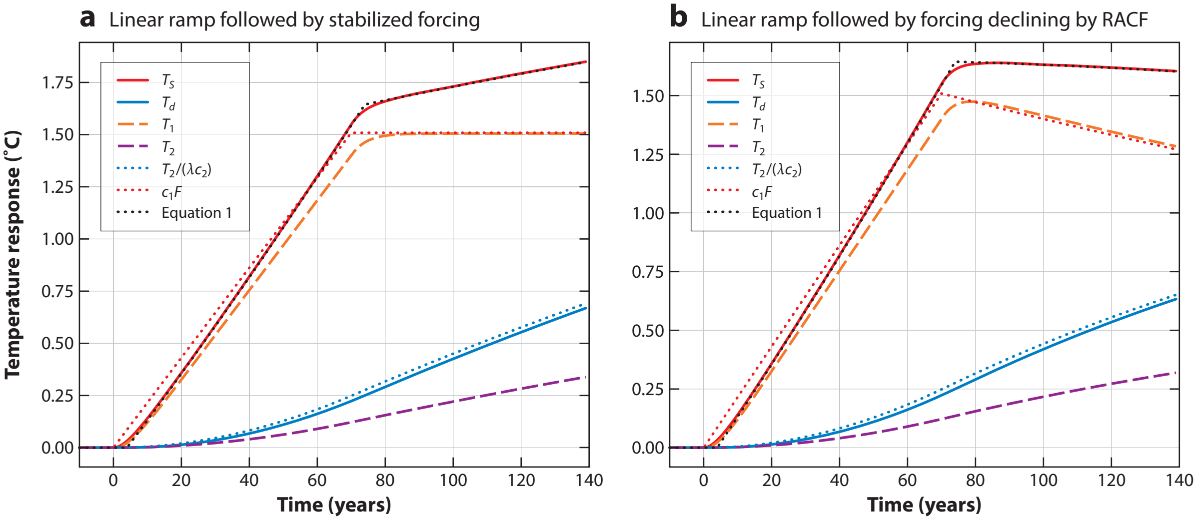

Figure 1

(*a*) Response of a two-component climate model to a linear increase in forcing to F_{2x} over 70 years, after which forcing is held constant. (*b*) As in panel *a*, except forcing declines exponentially at the rate of adjustment to constant forcing (RACF) after year 70, showing how the decline in T_1 and continued increase in T_2 combine to give approximately constant surface temperatures. Solid red and blue lines show surface and effective deep-ocean temperatures, T_s and T_d. Dashed orange and dashed purple lines show the two components of the response, T_1 and T_2, where $T_1 + T_2 \equiv T_s$. The blue dotted line shows the approximation to T_d in terms of T_2 in Equation 6, the red dotted line shows the transient climate response to forcing (TCRF) times the forcing, and the black dotted line shows T_s implied by Equation 1. See the Python code used to generate Figure 1 in the **Supplemental Material**.

per year," but lack of specific research prevented a stronger statement in either the SR1.5 or the AR6.

Supplemental Material >

2.2. The Radiative Forcing Response to CO$_2$ Emissions

While the physical climate research community was busy failing to constrain the ECS, our understanding of the carbon cycle response to CO$_2$ emissions was maturing, although still focused almost exclusively on quantifying emissions consistent with different "stabilization scenarios" (26; 41, Section 3.1.2). Stabilization referred to concentrations, not temperature, such was the prevalence of the UNFCCC (24), Article 2, framing. In particular, it was recognized that a sizeable fraction of CO$_2$ emitted through the burning of fossil fuels effectively persisted in the active carbon cycle (combined atmosphere, oceans, and terrestrial biosphere) indefinitely, holding up atmospheric concentrations for centuries to millennia (49, 74, 75). This finding had long been recognized as an inevitable consequence (76) of the Revelle buffer factor: Solution of additional CO$_2$ into the oceans necessarily results in conversion of carbonate (CO_3^{2-}) ions into bicarbonate (HCO_3^-) ions to conserve alkalinity. Because only approximately 10% of oceanic dissolved inorganic carbon is in the form of carbonate, the effective size of the oceanic carbon reservoir is approximately 10 times smaller than what might be inferred from the total amount of dissolved inorganic carbon in the oceans, so fossil CO$_2$ emissions have a substantial and irreversible impact on atmospheric concentrations (77).

The implications of this millennial-timescale airborne fraction (AF) (defined as the additional CO$_2$ loading in the atmosphere over any time interval as a fraction of total cumulative emissions over that time interval) were that stabilizing temperature (5) and precipitation (13) on multicentury to millennial timescales would eventually require near-zero CO_2 emissions and that the more CO_2 is released in total, the higher this eventual equilibrium warming would become (78). As far back as 1978, Siegenthaler & Oeschger (49) observed, with considerable prescience, that "if a maximum CO_2 increase of 50% above the preindustrial concentration is tolerable…we may burn in total over the next centuries not much more than 10% of the known fossil fuel reserves" (p. 394). Their paper focused, however, on the impact of emissions on the long-term steady-state concentration of CO_2, noting that unless fossil fuels were burned gradually, much higher concentrations of CO_2 would occur before this level was reached. It was not immediately obvious whether and how the requirement for net zero emissions also applied to halting global warming on multidecadal timescales. As we show below (Equation 15), halting warming requires a dynamic balance between declining CO_2 concentrations and ongoing oceanic thermal adjustment that may occur at a temperature different from the long-term static equilibrium.

To explain why this is so, we use the standard impulse response model of atmospheric CO_2 concentrations, $C_a(t)$, responding to CO_2 emissions, $E_C(t)$:

$$C_a(t) = C_0 + \sum_{i=1}^{N} a_i \int_{t'=0}^{t} E_C(t') \exp\left(-\frac{t-t'}{\alpha\tau_i}\right) \mathrm{d}t', \qquad 9.$$

where C_0 is the preindustrial concentration (generally taken as 278 ppm), and the a_i are empirically determined partition coefficients representing the fraction of an emitted pulse of CO_2 that leaves the atmosphere on timescales τ_i. These also include the conversion from tonnes of CO_2 to parts per million, so $\sum_i a_i = 0.13$ ppm per one billion tonnes of CO_2 ($GtCO_2$). The τ_i range from a few years, representing the rapid mixing of atmospheric CO_2 into the near-surface ocean, to effectively infinite, corresponding to the millennial-timescale AF. The coefficient α is a state-dependent factor (79) that can be used to capture nonlinearity in the response. When this type of model was originally introduced in the 1990s (35), it was intended only as a linearization, so α was set to unity. Such a linear impulse response model, however, necessarily predicts a monotonically declining AF under constant emissions, whereas more complex models have long been known (80) to show a constant or increasing AF. A declining AF combined with the long-established logarithmic dependence of CO_2-induced radiative forcing on CO_2 concentrations,

$$F = \frac{F_{2x}}{\ln(2)} \ln\left(\frac{C_a}{C_0}\right), \qquad 10.$$

meant that a linear impulse response model necessarily predicted some decline in warming per tonne of CO_2 emitted over time, and consequently, if coupled to the model of the temperature response to forcing represented by Equation 5, temperatures eventually decline following net zero CO_2 emissions.

The first study (to our knowledge) to model the response to net zero CO_2 emissions using such a simplified framework was by Friedlingstein & Solomon in 2005 (81). They found a more complex response than indicated by Equation 1, with an initial temperature overshoot followed by this temperature decline. This overshoot arose because that study used a single multidecadal time constant to characterize the thermal response to radiative forcing rather than partitioning it into fast and slow components. Independently, Shine et al. (82), whose study was also published in 2005, used a slightly more complex model that captured the slow and fast components of the temperature response and was (again to our knowledge) the first to document an approximately linear relationship between cumulative CO_2 emissions and warming on multidecadal timescales. Using a conventional energy balance model (83) coupled to a linear impulse response model of the carbon cycle, but considering small perturbations about a background state of constant atmospheric composition (hence implicitly linearizing the logarithmic relationship between CO_2 concentrations and radiative forcing), Shine et al. (82, table 2) gave estimates of the warming response to a constant CO_2 emission over time horizons of 20, 100, and 500 years of 0.0095, 0.0494, and 0.2 K per $GtCO_2$ per year, respectively. This quantity [the absolute global temperature-change potential for a sustained emission ($AGTP_S$)], once divided by the time horizon, is simply another name for the TCRE, giving values of 0.47, 0.49, and 0.4 K/$TtCO_2$, almost identical to modern TCRE estimates. This may have been the first paper to document the cumulative impact of CO_2 emissions on global temperature and hence the need for net zero CO_2 emissions to halt global warming, but because the focus of that paper was on comparing other GHGs to CO_2, Shine et al. did not draw attention to this result despite, in hindsight, its evident policy significance.

In the meantime, more complex models were being developed to capture the nonlinear response of the carbon cycle (84–88), in particular the increase in AF over time (89) as marine and biospheric sinks saturate. Warming itself also introduces new sources [e.g., increased soil decomposition, forest dieback, carbon from thawing permafrost (90)] and causes some sinks to weaken or reverse, becoming net carbon sources (warming leading to enhanced bacterial respiration in soils and transitions in vegetation cover). An increase in AF due to such feedbacks is consistently predicted (89) by coupled climate–carbon cycle models (91). Whereas some regional weakening of terrestrial sinks has been recently observed (92), there has been no significant increase in the observed net AF over recent decades (93–95).

A constant AF is consistent with a linear impulse response ($\alpha = 1$) under exponentially increasing emissions, $E(t) = E_0 e^{rt}$, in which case the AF is given by $\mathrm{AF} = \sum_i a_i r/(r + \tau_i^{-1})$. Emissions have only recently departed from an approximately exponential increase for the period over which relatively precise observations of the AF are available, so observations alone do not determine whether α is state dependent. When combined with model-based estimates of the response to a pulse injection of CO_2 into near-present-day concentrations, however, observations indicate (80, 96) a time-dependent impulse response, with the AF increasing with both warming and the accumulation of CO_2 in the oceans and biosphere (97, 98).

Equation 1 assumes that, in the absence of any non-CO_2 forcing, $\Delta T = \kappa_E \overline{E_C} \Delta t$, so warming is simply proportional to cumulative CO_2 emissions and κ_E, the TCRE, is constant. A linear relationship between cumulative CO_2 emissions and CO_2-induced warming (constant TCRE) is a consistent emergent feature of coupled Earth system models (6, 8, 16) found to hold up to cumulative emissions of 6,000 $GtCO_2$ (99), or warming up to approximately 3°C, before becoming weakly concave (100) (declining TCRE). This linearity can arise only from a cancellation (101) between the concave (logarithmic) relationship between atmospheric CO_2 concentrations and radiative forcing, and the convex relationship between CO_2 emissions and concentrations arising from an increasing AF (102). This may be partly accidental: There is a physical basis for a cancellation between logarithmic radiative forcing and declining oceanic CO_2 uptake (103–105), but this does not encompass the more complex response of the biosphere.

Although a constant TCRE is a helpful simplification, and may be exploited (106, 107) to provide observational constraints on future warming, it is not necessary for net zero CO_2 emissions to be consistent with no further CO_2-induced warming nor is a constant TCRE essential to the concept of a finite remaining carbon budget. What is important is the existence of a monotonic, path-independent (108) relationship between cumulative CO_2 emissions and CO_2-induced warming. The assumption of a constant TCRE starts to break down under both large cumulative (109) and strongly negative emissions (110). Studies to date suggest active CO_2 removal is slightly less effective at drawing down global temperatures than positive CO_2 emissions are at driving them up. Hence, the concept of a remaining carbon budget makes the most sense as allowable emissions to limit peak warming to a specific level, consistent with the unitary interpretation of the long-term temperature goal of the Paris Agreement (see Section 5), rather than a budget to limit warming to a particular level by a specific year, possibly after a temperature overshoot (111).

The simplest system (67) to explain why the TCRE is approximately constant, and the limitations of this linear relationship between cumulative CO_2 emissions and global temperature, is to assume the nonlinearities represented by α in Equation 9 and the logarithmic forcing in Equation 10 cancel perfectly. If that is the case, then

$$F_C(t) = \sum_{i=1}^{N} \mu_i \int_{t'=0}^{t} E_C(t') \exp\left(-\frac{t-t'}{\tau_i}\right) \mathrm{d}t', \qquad 11.$$

where the μ_i are simply the partition coefficients a_i scaled such that $\sum \mu_i$ is a time-averaged radiative efficiency of CO_2 in Watt per square meter per tonne. If we are focusing on interdecadal timescales, we can separate the forcing response to CO_2 emissions into an interannual-to-decadal component and a centennial component, with aggregate coefficients μ_1 and μ_2 and representative timescales τ_1 and τ_2, respectively. This separation of timescales is not as clear as in the case of the thermal response to forcing, so approximations are less accurate but serve to illustrate principles. In physical terms, $\mu_1 + \mu_2$ is the radiative forcing due to a unit-mass increase in the amount of CO_2 in the atmosphere, and μ_2 is the component of that forcing that persists for century or longer timescales. Importantly, τ_2^{-1}, the slow carbon adjustment rate (SCAR), is an average of all centennial and longer adjustment rates weighted by their respective μ_i. With one centennial adjustment timescale τ_c and one infinite timescale, with partition coefficients μ_c and μ_∞, respectively, such that $\mu_2 = \mu_c + \mu_\infty$, then $\tau_2 = \tau_c(\mu_c + \mu_\infty)/\mu_c \approx 400$ years.

Under these simplifications, the interdecadal (timescales longer than τ_1 and shorter than τ_2) response to a constant emission of E_0 tonnes of CO_2 per year starting in year zero is given by

$$F_C(t) = \mu_1 E_0 \tau_1 + \mu_2 E_0 \tau_2 \left(1 - \exp\left(-\frac{t}{\tau_i}\right)\right) \approx \mu_2 E_0 t + \mu_1 E_0 \tau_1 - \frac{\mu_2 E_0 t^2}{2\tau_2}. \qquad 12.$$

The first term in the approximation on the right-hand side is the largest, so on timescales longer than s we can approximate $\mathrm{d}F/\mathrm{d}t \approx \mu_2 E_0$, $\int F_C \,\mathrm{d}t \approx \mu_2 E_0 t^2/2$, and $F_C(t-s) = F_C(t) - s\mathrm{d}F/\mathrm{d}t$. Using these approximations, we can rearrange Equation 12 as

$$E_0 t = \int_{t'=0}^{t} E_C(t')\ \mathrm{d}t' \equiv C_E(t) \approx \frac{1}{\mu_2}\left[F_C\left(t - \frac{\mu_1\tau_1}{\mu_2}\right) + \frac{1}{\tau_2}\int_{t'=0}^{t} F_C(t')\ \mathrm{d}t'\right]. \qquad 13.$$

Having linearized Equation 11, the interdecadal-timescale forcing response to any emission time series may be represented by the superposition of responses to a series of constant emissions or removals starting at different times. Hence, the cumulative CO_2 emissions, $C_E(t)$, that cause a radiative forcing, $F_C(t)$, are equal to the sum of one term proportional to the radiative forcing subject to a small delay (of the order of years) and a second term proportional to the time-integrated radiative forcing. The fact that changes in CO_2-induced forcing appear, on these timescales, to occur before changes in cumulative CO_2 emissions may seem counterintuitive, but it arises from subdecadal component(s) of the impulse response in Equation 11 and explain why rates of warming appear to respond to changing CO_2 emission rates faster than would be implied by the short thermal timescale of adjustment to forcing, s_1, and why the peak warming response occurs relatively soon after a pulse emission (112).

Comparing Equations 7 and 13, CO_2-induced warming is proportional to cumulative CO_2 emissions, $T_C(t) = \kappa_E C_E(t)$, where $\kappa_E = \kappa_F \mu_2$, only if both subdecadal and centennial thermal and carbon cycle response times match up, so $s_1 = \mu_1\tau_1/\mu_2$ and $\rho = \tau_2^{-1}$, respectively. If they do not match up, then on short timescales the temperature response can lead or lag cumulative CO_2 emissions by a few years, $\nu = s_1 - \mu_1\tau_1/\mu_2$. This quantity is so negligible that it barely merits a name, but for the sake of completeness, we refer to it as the fast emissions adjustment timescale.

Likewise on long timescales, if $\rho > \tau_2^{-1}$, then sustained cooling accompanies net zero CO_2 emissions, whereas if $\rho < \tau_2^{-1}$, net zero CO_2 emissions result in sustained warming. This rate of adjustment to zero emissions (RAZE) is the RACF minus the SCAR, $o = \rho - \tau_2^{-1}$. This is the difference between two rates that are each less than approximately 0.3% per year, so the RAZE is close to zero and at most of the order of ±0.1% per year (we suggest the underappreciated omicron symbol is used to represent this small but persistent quantity). Hence, a more general expression for the temperature response to CO_2 emissions over a multidecadal time interval is

$$\Delta T = \kappa_E \left(\Delta C_E + o \overline{C_E} \Delta t \right), \qquad 14.$$

where $\Delta C_E = \bar{E} \Delta t$ is the change in cumulative CO_2 emissions over that time interval; $\overline{C_E}$ is the cumulative CO_2 emissions since preindustrial times, averaged over that time interval; κ_E is the TCRE; and o, the RAZE, is small (of the order of 1 in 1,000 years) and as likely positive as negative. The RAZE is a fractional rate of annual increase or decrease of global temperature anomaly, with units of fraction per year or percent per year. It is related to the ZEC (15), or the absolute amount of warming that occurs after emissions cease. In the case of only a single multicentury-timescale adjustment, a positive RAZE indicates a positive ZEC and vice versa, but as we discuss below, the value of the RAZE is less scenario dependent than the value of the ZEC.

Rate of adjustment to zero emissions (RAZE): fractional rate of change of global average surface temperature associated with a multidecade period of net zero CO_2 or CO_2-warming-equivalent emissions

As well as demonstrating the limitations of the simple relationship between cumulative CO_2 emissions and CO_2-induced warming expressed in Equation 1, these expressions explain why so many papers came close to identifying this relationship without actually doing so: Both long and short timescales in both thermal and carbon cycle responses must be modeled for it to emerge.

These concepts are illustrated in **Figure 2**. **Figure 2*a*** shows the warming response to a constant 40 $GtCO_2$ emissions sustained over 70 years, and **Figure 2*c*** shows the response to historical CO_2 emissions followed by emissions following the Shared Socioeconomic Pathway (SSP1-1.9) ambitious mitigation scenario (12) up to the date of net zero. Both cases are followed by net zero CO_2 emissions. The approximation in Equation 12 is evident in **Figure 2*a*,*b***: Shortly after emissions begin but on timescales much less than τ_2, the forcing leads cumulative CO_2 emissions by a few years, $\mu_1 \tau_1 / \mu_2$.

Forcing and temperature responses are simulated by the FaIR (Finite-amplitude Impulse Response) model (96), a simple but nonlinear climate model supporting four carbon cycle and three thermal response timescales that replicates the responses of more complex Earth system models with considerable fidelity. For the value of the TCR used, $s_1 = \mu_1 \tau_1 / \mu_2$ giving a zero fast emissions adjustment timescale, $\nu = 0$. Temperatures therefore increase in proportion to cumulative CO_2 emissions for all three values of the RACF with no delay (contrast the immediate temperature response to a sudden increase in emissions in **Figure 2*a*** with the slightly delayed response to a sudden increase in $\mathrm{d}F/\mathrm{d}t$ in **Figure 1*a***). Different choices of parameters within uncertainty ranges can introduce a small lead or lag between temperatures and cumulative emissions, but only of the order of a few years.

After emissions reach net zero, the impact of the RACF variations is more evident. All variations are well within the range of uncertainty in the RWF (72, 73), or TCR/ECS ratio, and might arise from variations in λ or λ', and thus are not necessarily related to any oceanic adjustment timescale. This is important, as it is often assumed that a slower thermal adjustment timescale, s_2, is necessarily related to a slower carbon cycle adjustment timescale, τ_2, because the same deep-ocean mixing timescales determine both. There will be some relationship, but because the RACF also depends on atmospheric radiative feedbacks that have no physical link to the carbon cycle, and because τ_2 also depends on the partitioning of the response between multicentury and infinite timescales, it cannot be assumed that the RACF will covary perfectly with the SCAR. Therefore, the RAZE, $o = \rho - \tau_2^{-1}$, can be positive, zero, or negative: Net zero CO_2 emissions can result in

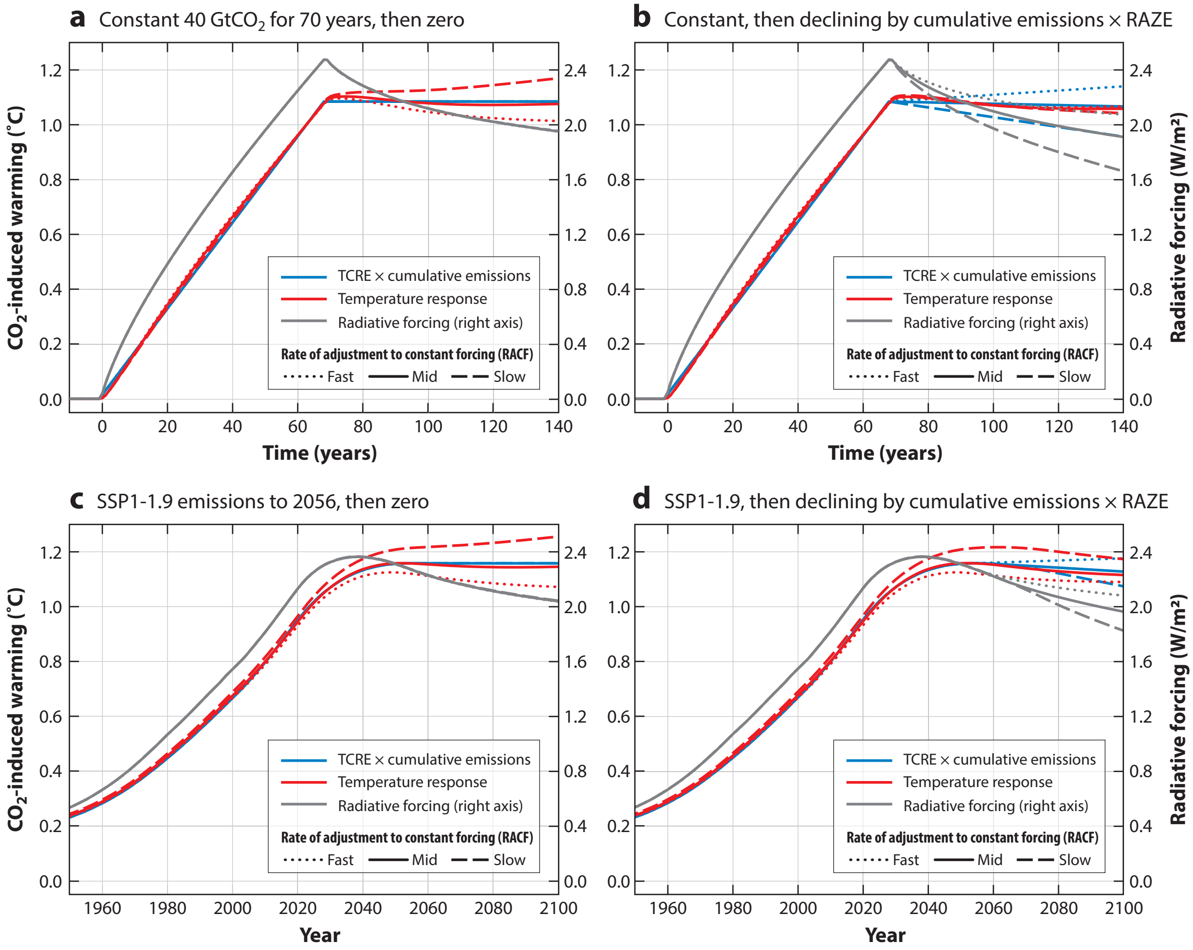

Figure 2

Temperature response to CO_2 emissions calculated with a simple nonlinear climate–carbon cycle model. (*a*,*c*) The graphs depict (*a*) constant emissions for 70 years and (*c*) historical emissions followed by the SSP1-1.9 ambitious mitigation scenario up to the date of net zero. Both cases are followed by zero emissions: Blue lines show cumulative CO_2 emissions multiplied by the TCRE, gray lines show CO_2-induced radiative forcing, and red lines show temperature responses for three values of the RACF, corresponding to the equilibrium climate sensitivity and realized warming fraction values well within current ranges of uncertainty. (*b*,*d*) Graphs are identical except emissions are reduced to a constant value of $E_{min} = -o C_E$ instead of zero, where C_E is cumulative emissions up to the date of net zero in panels *a* and *c*, respectively, and o is the RAZE, showing how a low level of ongoing emissions or removals can compensate for a nonzero RAZE to deliver approximately stable global average surface temperatures. Abbreviations: RACF, rate of adjustment to constant forcing; RAZE, rate of adjustment to zero emissions; SSP, Shared Socioeconomic Pathway; TCRE, transient climate response to emissions. See the Python code used to generate Figure 2 in the **Supplemental Material**.

Supplemental Material >

gradual warming, constant temperatures, or gradual cooling. Further research into the relationship between the RACF and the SCAR is urgently required because of their profound implications for net zero policy.

The ZEC was originally defined (113) as the difference between the long-term equilibrium warming, T_{eqm}, that concerned Siegenthaler and Oeschger, under which temperatures come into equilibrium with the irreversible increase in atmospheric CO_2 concentrations resulting from cumulative emissions C_E, and the warming that is manifest at the time emissions reach net zero, T_{zero}.

In our simplified framework, recalling that μ_∞ is the component of the radiative forcing due to a unit-mass emission of CO_2 that persists indefinitely and that μ_c is the component that declines on multicentury timescales,

$$\mathrm{ZEC} = T_{eqm} - T_{zero} \approx \left(\lambda^{-1}\right) \mu_\infty C_E - \kappa_E C_E = \left[(c_1 + c_2)\, \mu_\infty - c_1\, (\mu_c + \mu_\infty)\right] C_E, \qquad 15.$$

using the approximation $\kappa_E \approx c_1 \mu_2$ (the TCRE equals the TCRF times the forcing per tonne of CO_2 emitted that persists for centennial and longer timescales). Hence, the ZEC is zero if the RWF, $c_1/(c_1 + c_2)$, equals the fraction of multicentury-timescale CO_2-induced forcing that persists indefinitely, $\mu_\infty/(\mu_c + \mu_\infty)$. This appears to be approximately true, but there is no fundamental reason why it should be so.

Even for perturbations small enough that we can treat the entire problem as linear, the ZEC is scenario dependent, because it scales with C_E. Hence, the RAZE is a more fundamental climate system property than is the ZEC because there is a limit under which the RAZE converges to a scenario-independent value, $o_{max} = \rho_{max} - \tau_2^{-1}$. The RAZE is also easier to constrain, because like the ECS, quantifying the ZEC is in effect an infinite-timescale prediction. Finally, the RAZE is more directly relevant to policy because it determines the ongoing rate of CO_2 emissions or removals required to maintain stable temperatures on multidecadal timescales (see **Figure 2*b*,*d***).

Recognizing the limited policy relevance of the infinite-timescale ZEC, recent experiments such as the Zero Emissions Commitment Model Intercomparison Project (ZECMIP) (14) have sought to quantify the ZEC over specified multidecadal time intervals. In the main ZECMIP experiment, atmospheric CO_2 concentrations were increased at 1% per year, corresponding to a rapid increase in CO_2 emissions in the first decade followed by a more gradual increase to approximately 70 $GtCO_2$ per year. When diagnosed cumulative emissions reach 3,700 $GtCO_2$ (1,000 PgC), emissions cease and coupled climate–carbon cycle models are allowed to evolve freely. After an initial adjustment over the first couple of decades, 7 of 9 full-complexity and 9 of 9 intermediate-complexity Earth system models display a cooling trend sustained for at least the next 80 years. Fitting a straight line to the reported 25-, 50-, and 90-year ZEC values of all the full-complexity models and dividing by their respective TCREs give a mean and median RAZE of −0.06% per year with a standard deviation of 0.11% per year. Intermediate-complexity models display more consistently negative RAZEs, −0.16 ± 0.16% per year, although this latter range is strongly affected by two outlier models. If those two outlier models are excluded, the intermediate-complexity-model range of RAZE values resembles that of the full-complexity Earth system models. ZECMIP also found a shift toward more positive RAZE values with higher cumulative emissions, and Earth system feedbacks (114) or land-use changes (115) not fully represented in the current generation of models might also contribute additional warming, lending support to an approximate RAZE range of 0.0 ± 0.1% per year for cumulative emissions in the range of 3,000 to 6,000 $GtCO_2$, spanning most mitigation scenarios.

The focus of the ZECMIP experiment was on quantifying any potentially positive ZEC because this would affect remaining carbon budgets for limiting warming to specific temperature goals. But a negative RAZE is also relevant, since it opens the possibility of some ongoing CO_2 emissions being consistent with no further warming on interdecadal timescales. If emissions are reduced not to zero but to $-oT/\kappa_E \approx -oC_E$, where C_E is the cumulative CO_2 emissions since preindustrial times, then CO_2-induced warming remains approximately constant (**Figure 2*b*,*d***). Note that this residual emission rate can be either positive or negative (active CO_2 removal) because the sign of o is indeterminate. Scenarios meeting the goals of the Paris Agreement typically have to limit cumulative emissions to $<3{,}000$ $GtCO_2$. Because the RAZE is of the order of 0.1% per year, this ongoing emission or removal consistent with stable temperatures is of the order of

±3 $GtCO_2$ per year or less. The combination of natural climate variability and uncertainty over residual emissions and removals means that it might take many decades to establish the value of the RAZE and whether it is distinguishable from zero.

2.3. Implications for CO_2 Emissions Policy

This quantitative understanding of the physical origins of net zero has several implications for policy (116). First, carbon budgets determine warming only on multidecadal timescales. The question of precisely when the carbon budget for 1.5°C will be exhausted has received considerable attention (117), including in the SR1.5 (10) and the AR6 (12). Although much of the ambiguity in a carbon budget for 1.5°C of warming arises from expected non-CO_2 warming and the precise definition of warming levels, the fact that even CO_2-induced warming can lead or lag cumulative CO_2 emissions by a few years corresponding to the fast emissions adjustment timescale, ν, makes clear that temperatures should not be expected to reach a particular threshold temperature at precisely the date on which the relevant carbon budget is exhausted, but only within a decade on either side, even if the impacts of internal climate variability and other climate forcings are removed. Understanding this point is important to avoid unrealistic expectations of precision in relating carbon budgets to temperature outcomes.

Second, the observation that the RAZE is not necessarily zero, and hence that some ongoing CO_2 emissions or removals could turn out to be consistent with stable temperatures, though clearly significant, should not be overinterpreted. The RAZE is indistinguishable from zero on the basis of current evidence and is likely to remain so for the foreseeable future because it depends on poorly constrained centennial-timescale processes. Ongoing CO_2 emissions consistent with stable temperatures could be either positive or negative, even in the absence of nonlinearities. Including the impact of nonlinear Earth system feedbacks that are likely to emerge in the future, and therefore are not fully included in current estimates of the TCRE, such as increased carbon release from thawing tundra, would increase the likelihood that the RAZE is positive, requiring ongoing net CO_2 removal to limit warming.

Third, the possibility of a nonzero RAZE does not undermine the concept of a carbon budget consistent with a given level of warming at the time of net zero emissions, assuming emission reductions occur over a limited number of decades. The fact that o is of the order of one part in 1,000 years in Equation 14 means that there is a simple monotonic and near-linear relationship between cumulative CO_2 emissions and CO_2-induced warming as long as annual emissions remain larger than approximately 1/1,000th of cumulative emissions to date. This is also evident from **Figure 2**: Warming is proportional to cumulative emissions before the date of net zero for all three values of the RACF shown, despite different outcomes after that date. Hence, the observation that warming is proportional to cumulative CO_2 emissions does not imply that CO_2 emissions need to be exactly net zero to halt CO_2-induced warming, but it does imply they need to be approximately so. Currently, annual CO_2 emissions are 1/50th of cumulative CO_2 emissions, so they would have to be reduced by a factor of 10 to 20 and maintained at that level for decades before uncertainty in the RAZE becomes significant.

Fourth, achieving whatever low level of emissions or removals is consistent with stable temperatures is likely to require substantial levels of active CO_2 removal to compensate for residual emissions. So if the RAZE turns out to be nonzero, only a minor recalibration of this removal effort would be required to compensate. Whatever the value of the RAZE, warming consistent with zero emissions would be indistinguishable from natural climate variability for decades. Hence, $o = 0$, or zero RAZE, is a pragmatic working hypothesis. We note, however, that no physical constraint has yet been identified that requires the RAZE to be greater than or equal to zero: Both ρ and τ_2

are uncertain quantities that depend on unrelated aspects of the climate–carbon cycle system and the results of the ZECMIP experiment suggest that, more likely than not, $o < 0$, or $\rho < \tau_2^{-1}$, for low warming levels. A low level of continued CO_2 emission could turn out to be consistent with no further CO_2-induced warming, although we are unlikely to discover this is the case until after temperatures have stabilized for several decades.

Fifth, even if the RAZE is zero, achieving net zero CO_2 emissions and thereby halting the CO_2-induced increase in global average surface temperature would not mean ending CO_2-induced climate change. The climate will continue to adjust for many centuries. Impacts would continue to evolve that depend on the pattern of surface warming, such as regional precipitation, on atmospheric CO_2 concentrations, such as ocean pH (118), or on the changing balance between warming and atmospheric CO_2 concentrations, which would include both global and regional precipitation (119) and sea-level rise (120).

In summary, the more cautious SR1.5 framing, that reducing CO_2 emissions to net zero would be sufficient to halt CO_2-induced warming on interdecadal timescales, is better justified by our current evidence base than is the stronger AR6 claim that limiting human-induced warming to any specific level requires reaching at least net zero CO_2 emissions. Results from the ZECMIP experiment and our understanding of underlying climate system properties suggest that the most that can be said at present is that halting CO_2-induced warming as likely as not requires reaching at least net zero CO_2 emissions, with this qualifier potentially becoming more likely than not at higher levels of warming under which net Earth system feedbacks are more likely to be positive.

3. THE ROLE OF THE TERRESTRIAL BIOSPHERE IN ACHIEVING CARBON NEUTRALITY

Protecting and nurturing the biosphere yield multiple benefits to human and ecological well-being and socioeconomic development, including climate. An ambitious program of sustainable management, protection, and restoration of ecosystems could reduce peak warming and could also have an important role in planetary cooling after temperatures have peaked (121), and it may be needed to compensate for emissions due to warming itself, arising from Earth system feedbacks. That said, the extent to which the biosphere can be relied upon to compensate for ongoing release of carbon from the lithosphere (solid Earth) in fossil fuel emissions remains unclear.

Agriculture, forestry, and other land use (AFOLU) activities currently contribute more than 10% of anthropogenic CO_2 emissions and play a larger role in methane and nitrous oxide emissions (see Section 4). These emissions will become increasingly important as energy and industrial process emissions decline in the transition to net zero (10). AFOLU has also contributed approximately one-third of historical emissions, such that carbon stocks in both standing biomass and soils in many regions of the world are severely depleted compared to prehistoric baseline levels (122).

However, forest regrowth and stimulated growth rates caused by CO_2 fertilization have also absorbed a substantial fraction of anthropogenic CO_2 emissions to date, presenting opportunities for enhancing terrestrial and coastal marine carbon stocks through afforestation and ecosystem restoration (122). Protecting ecosystems reduces the release of carbon (e.g., avoiding deforestation) and maintains the terrestrial carbon sink currently found in many intact ecosystems, such as tropical forests. Restoring ecosystems often results in enhancing carbon storage and carbon sinks (e.g., peatland restoration). Improving the management of agricultural and marine systems reduces carbon, methane, and nitrous oxide emissions (e.g., improving nutrient management) and sequesters carbon (e.g., trees in cropland) (123).

Nature-based solutions (NbS)[2] are activities that involve the protection, restoration, or management of natural and seminatural ecosystems, underpinned by biodiversity and implemented in a socially just context (122, 124). Several recent studies estimate the contribution that NbS could make to climate change mitigation if scaled up globally, yet there is still confusion around how much NbS could contribute to achieving net zero, as results have been estimated over various time frames, using different model assumptions, for different objectives (121, 123, 125–131). Estimates vary widely, as they depend on assumptions such as future trends in land sector demand (e.g., meat consumption) and supply (e.g., agricultural productivity) (128); the price of carbon, reflecting mitigation ambition (132); the carbon saturation point of mature ecosystems (123, 133) and the extent to which studies consider constraints on deployment of NbS related to economic and political feasibility, land rights, and local needs; and safeguards for food security and biodiversity (134).

An ambitious estimate of the global mitigation potential of NbS, including measures that are cost-effective (at an effective carbon price less than or equal to \$100 per tonne of CO_2 equivalent), ensure adequate global production of food and wood-based products, conserve biodiversity, respect land tenure rights, and consider biophysical constraints such as albedo and saturation of carbon uptake by old-growth forests, is provided by Griscom et al. (123). In this scenario, NbS help reduce global emissions at a rate of approximately 10 $GtCO_2$ $year^{-1}$, approximately half from avoided emissions and half from enhanced carbon sinks. This translates to reducing peak warming by approximately 0.1°C under a scenario consistent with a 1.5°C rise by 2055, by 0.3°C under a scenario consistent with a 2°C rise by 2085, or by 0.3°C in 2100 under an ongoing-warming scenario (121).

Moreover, there is additional mitigation potential from marine ecosystems. Although most models include coastal ecosystems (mangroves, saltmarshes, and seagrass), they exclude marine systems such as coral reefs, phytoplankton, and kelp forests and the role of marine fauna in facilitating or enhancing carbon sinks in pelagic and benthic environments (135, 136).

Going beyond biospheric net zero and compensating for ongoing fossil fuel emissions with enhanced uptake in the biosphere are attractive economically (132) and, if well managed (122), could provide multiple benefits, including restoring depleted biospheric carbon stocks, adapting to climate change, and supporting biodiversity. But relying on the biosphere to partially (or, worse, fully) compensate for continued production of CO_2 from burning fossil fuels carries risks, including rerelease of carbon to the atmosphere because land-use practices change, pathogen or invasive pest outbreaks (an acute problem in low-diversity forests such as temperate or island ecosystems), or risks due to climate change itself increasing the likelihood of carbon loss from ecosystems.

Protecting intact ecosystems is a priority, as their ecological integrity likely makes them more resilient, increasing their ability to act as long-term carbon sinks (127). Properly managed, most resilient ecosystems are likely to continue to act as carbon sinks long past the point when net zero emissions are achieved and global temperatures peak. Utilizing carbon uptake by intact ecosystems to offset continued fossil fuel emissions in support of net zero claims is, however, problematic because this uptake is often an indirect consequence of past emissions and is therefore already accounted for as a natural sink in the Earth system models used for the definition of carbon budgets and classification of emission scenarios (see Section 5).

Moreover, with further warming, the impact of nonlinear Earth system feedbacks is likely to emerge and may increasingly destabilize ecosystems, undermining their long-term mitigation

---

[2] Nature-based solutions are actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic, and environmental challenges effectively and adaptively while providing human well-being, ecosystem services and resilience, and biodiversity benefits.

potential (92). These Earth system feedbacks are not fully included in current estimates of the potential contribution of the terrestrial and coastal marine biosphere to achieving net zero. For example, the carbon sink in the Amazon forest appears to be diminishing as tree mortality rates increase, likely as a consequence of increasing frequency of severe drought events (92) and increasing atmospheric water deficits (137). Increased fire spread in Amazonia is also contributing to an increase in carbon emissions from the biome as a whole. These effects reduce the climate change mitigation potential of forests and other vegetation prone to fires, which needs to be considered when assessing the effect of forest-related NbS on net CO_2 emissions.

These risks highlight a broader question regarding the appropriate role of NbS and biospheric removals more generally in achieving net zero. Currently, they are widely considered a low-cost means of offsetting ongoing fossil fuel use, with considerable potential co-benefits. But as long as the net flux of carbon out of the biosphere remains positive, even if some of that flux is a consequence of historical warming, it could be argued that the first priority for NbS is stabilizing the carbon in the biosphere itself, and only when this has been achieved can NbS be considered a potential way of compensating for fossil CO_2 release. Even then, as Fankhauser et al. (138, p. 16) stated, “Achieving net zero through an unsustainable combination of fossil fuel emissions and short-term removals is ultimately pointless. Carbon emissions and removals must balance over multi-decadal timescales” (see **Figure 3**).

Hence, although there is an urgent need to invest in NbS now, not least to slow and reverse biospheric degradation, by midcentury negative emissions technologies and practices may need to shift away from biological storage to near-permanent geological storage (139).

It is essential that interventions claiming to be NbS are themselves sustainable. Mitigation options such as bioenergy with carbon capture and storage (BECCS) have benefits that are limited to carbon sequestration, potentially require vast areas of land that would not then be available for food production or nature protection or restoration, and do not provide the multiple long-term benefits of NbS (140). Without stringent environmental safeguards (which may in turn make it uneconomic), BECCS lacks ecological integrity and is therefore less likely to be resilient in the face of a rapidly changing climate.

Beyond climate benefits, there is mounting evidence that natural and seminatural ecosystems support our economies and societies in multiple ways, such as providing food, clean water, and shelter, protecting against the impacts of extreme events such as floods, droughts, and heatwaves (141, 142), and addressing various sustainable development goals and increasing the resilience of local communities (143, 144). As such, they should be a central component of climate adaptation plans.

4. FROM CARBON TO CLIMATE NEUTRALITY: NET ZERO WITH MULTIPLE GREENHOUSE GASES

The relationships described in Sections 2.1 and 2.2 allow a straightforward incorporation of non-CO_2 GHGs and other climate forcers into our understanding of how global emissions affect global temperatures (77, 145). Unlike CO_2, most other climate forcers can be characterized by a single atmospheric residence time τ, ranging from a few days to a decade for short-lived climate forcers (SLCFs), such as black carbon and methane, to over a century for nitrous oxide. Radiative forcing due to the sustained emission of E_0 tonnes per year of such a climate forcer, starting in year zero, is given by Equation 11 with $N = 1$:

$$F(t) = \int_{t'=0}^{t} \mu E_0 \exp\left(-\frac{t-t'}{\tau}\right) \mathrm{d}t' = \mu E_0 \left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \qquad 16.$$

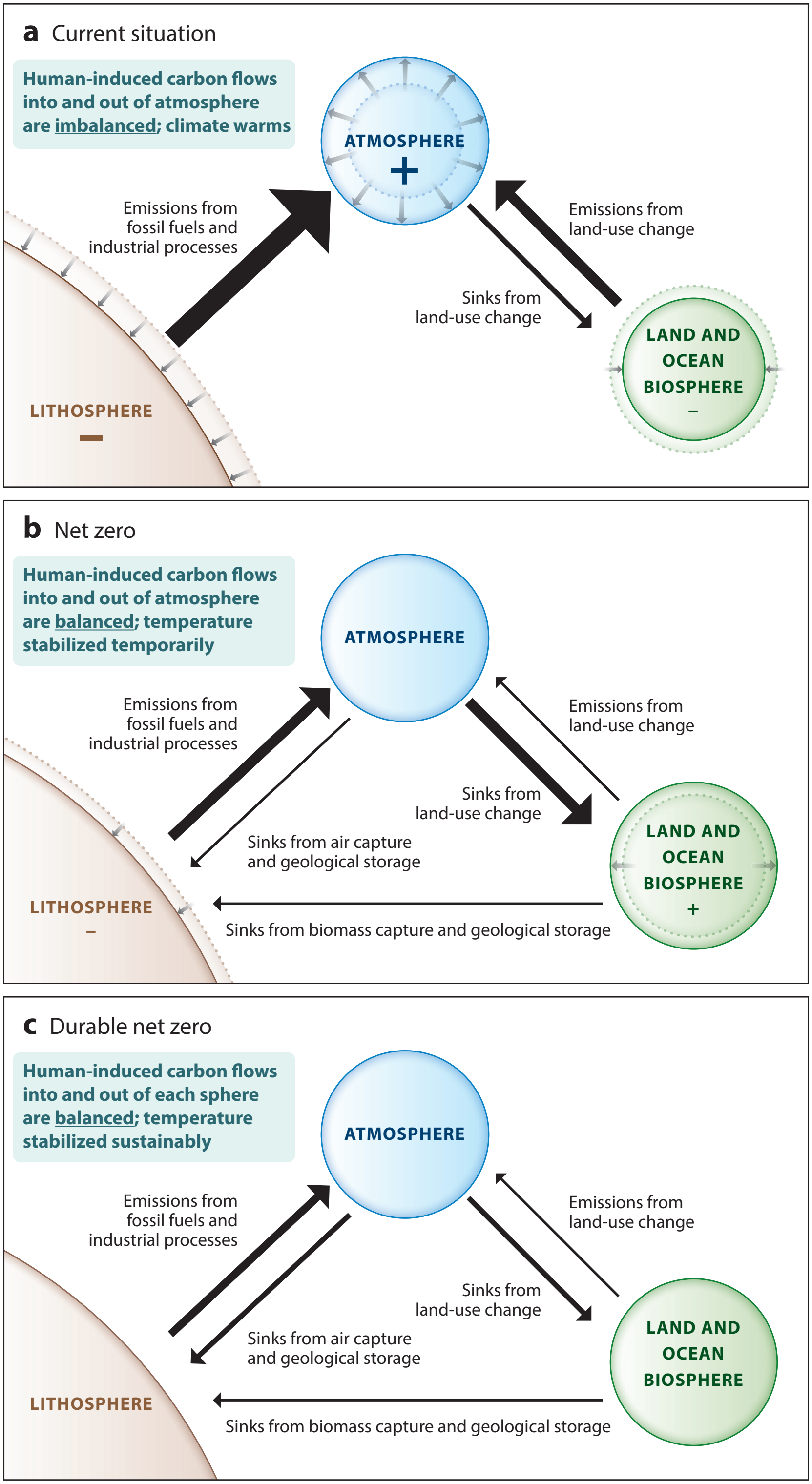

Figure 3

Schematic showing the transition to a durable net zero. Arrows indicate human-induced fluxes of carbon, primarily in the form of CO_2, between the lithosphere (solid Earth), atmosphere, and land and ocean biosphere. (*a*) The current situation, with large fluxes out of both the lithosphere and the biosphere into the atmosphere. Outward- and inward-pointing arrows indicate carbon flows are imbalanced, with carbon stocks increasing in the atmosphere and decreasing in both the biosphere and lithosphere. (*b*) A temporary net zero regime in which net flows into and out of the atmosphere are balanced, but there is still a net flux from the lithosphere into the biosphere. (*c*) A durable net zero regime in which all fluxes are balanced. Figure adapted from Reference 138; copyright 2022 Springer Nature Ltd. Panels may be viewed as individual files in the **Supplemental Material**.

Supplemental Material >

where μ is the radiative efficiency (146) expressed as the forcing due to a unit-mass increase in the amount of that climate forcer in the atmosphere. The quantity $F(H)/E_0 = \mathrm{AGWP}_H$, the AGWP for that forcer over a time horizon H years (82). The AGWP_H of a particular climate forcer divided by the AGWP_H of CO_2 is called its global warming potential (GWP_H).

CO_2-warming-equivalent (CO_2-we) emissions: the quantity of CO_2 emissions that would have the same impact on global temperature as a combination of CO_2 and non-CO_2 climate forcing agents

Because Equation 16 is linear, we can express the forcing response to an arbitrary emissions time series as the superposition of responses to constant emissions starting at different times in the past. Furthermore, for SLCFs expressed as CO_2-equivalent by dividing emissions by their GWP_H, we can replace μ in Equation 16 with the AGWP_H of CO_2, A_H, provided the SLCF lifetime $\tau_S \ll H$ (because the quantity in square brackets is then approximately unity for $t = H$). Hence, forcing due to any SLCF is proportional to an exponentially weighted trailing average of the rate of emissions of that SLCF, with the exponential timescale given by the forcer lifetime or, for slowly varying emission rates, SLCF emissions E_S subject to a delay of the order of τ_S:

$$F_S(t) \approx A_H E_S(t - \tau_S). \qquad 17.$$

Long-lived climate forcers (LLCFs), or any forcer with $\tau_L \geq H$ such as nitrous oxide, if also expressed as CO_2-equivalent using GWP_H, behave like CO_2.

It is conventional to use the 100-year global warming potential (GWP_{100}) to calculate CO_2-equivalent emissions, which we refer to as CO_2-e_{100} to avoid ambiguity. As it happens, all SLCFs behave similarly to each other if reported as CO_2-e_{100} because all SLCF lifetimes are much less than 100 years (this is not the case for other metrics such as GWP_{20}). Hence, the temperature response to a mixture of LLCFs and SLCFs, all expressed as CO_2-e_{100}, is (substituting Equation 17 into Equations 1 and 7)

$$T(t) \approx \kappa_E \int_{t'=0}^{t} E_L(t')\ \mathrm{d}t' + \kappa_F A_{100}\left[E_S(t - \tau_S - s_1)\ +\ \rho \int_{t'=0}^{t} E_S(t')\ \mathrm{d}t'\right], \qquad 18.$$

where E_L and E_S are aggregate emissions of LLCFs and SLCFs, respectively, with E_L including CO_2, and τ_S is the emissions-weighted average SLCF lifetime. Warming ΔT over a multidecadal time interval Δt is therefore, to a good approximation,

$$\Delta T \approx \kappa_E \overline{E_L} \Delta t + \kappa_F A_{100}\left(\Delta E_S + \rho \overline{E_S} \Delta t\right) \approx \kappa_E \left[\overline{E_L} \Delta t + 85 \Delta E_S + 0.28 \overline{E_S} \Delta t\right], \qquad 19.$$

where $\overline{E_L}$ and $\overline{E_S}$ are average rates of aggregate LLCF and SLCF emissions, respectively, over that time interval, and ΔE_S is the change in SLCF emission rates between the beginning and the end of that time interval, assuming all emissions are expressed as CO_2-e_{100}. To account for the $\tau_S + s_1$ delay from a change in SLCF emission rate and the temperature response, ΔE_S can be defined as the difference between the average emissions over the decade prior to the beginning and the decade prior to the end of the time interval Δt for very-short-lived SLCFs ($\tau_S \leq 1$ year), and the average emissions over the 20 years prior to the beginning and the 20 years prior to end of Δt for SLCFs with lifetimes of the order of a decade, such as methane.

The quantity in square brackets in Equation 19 provides an estimate of aggregate CO_2-warming-equivalent (CO_2-we) emissions (20, 147–149), so called because it would have the same warming impact over this time interval as the emission of that amount of CO_2 (147). More precise methods of computing warming-equivalent emissions have been proposed, but as illustrated in **Figure 4**, the use of simple trailing 10- and 20-year averages to calculate ΔE_S in Equation 19 is already remarkably accurate at capturing the global temperature response to various forcing agents for both rising and falling emissions. In contrast, cumulative CO_2-e_{100} emissions reflect warming impact only for LLCFs.

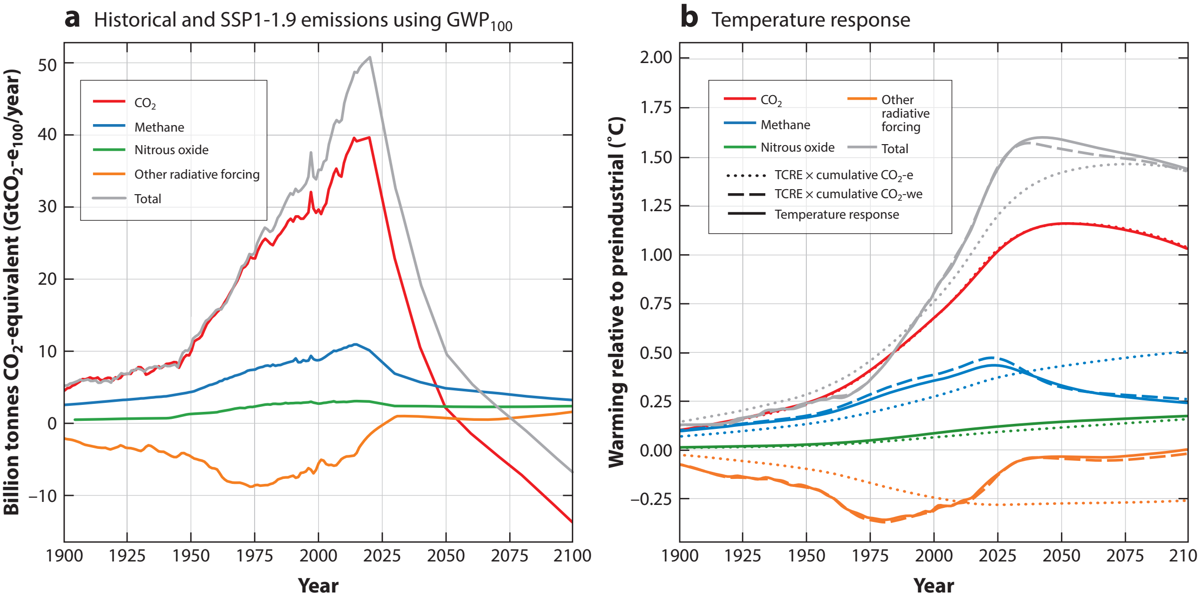

Figure 4

Historical and projected emissions and temperature response under the SSP1-1.9 mitigation scenario. (*a*) Emissions of CO$_2$, methane, nitrous oxide, and other RF (primarily aerosols, calculated by subtracting calculated forcing by these three gases from total anthropogenic forcing). CO$_2$-e$_{100}$ emissions calculated by multiplying GHG amounts by their respective GWP$_{100}$ values and by dividing other RF by A_{100}, the AGWP$_{100}$ of CO$_2$. (*b*) Solid lines show global temperature response to individual gases and to total anthropogenic forcing calculated with the FaIR 2.0 nonlinear climate model. Dotted lines show cumulative CO$_2$-e$_{100}$ emissions multiplied by the TCRE. These values provide a good approximation for the warming impact of LLCFs but fail to reflect the warming impact of SLCFs. Cumulative warming-equivalent emissions, represented as dashed lines for SLCFs and totals, identical to dotted lines for LLCFs, reflect temperature response much more accurately. Abbreviations: AGWP$_{100}$, 100-year absolute global warming potential; CO$_2$-e$_{100}$, CO$_2$-equivalent emissions using the GWP$_{100}$ metric; FaIR, Finite-amplitude Impulse Response; GHG, greenhouse gas; GWP$_{100}$, 100-year global warming potential; LLCF, long-lived climate forcer; RF, radiative forcing; SLCF, short-lived climate forcer; SSP, Shared Socioeconomic Pathway; TCRE, transient climate response to emissions. See the Python code used to generate Figure 4 in the **Supplemental Material**.

Supplemental Material >

Figure 4 also illustrates how the warming impact of immediate emission reductions depends strongly on the lifetime of the relevant forcing agent. Reducing aerosol emissions results in almost immediate warming, reducing methane emissions results in cooling with some delay, and reducing CO$_2$ and nitrous oxide emissions results only in a slowdown in the rate of warming until these emissions become net negative. One consequence of this is that an immediate cessation of all emissions could result in a temporary short-term warming due to rapid removal of aerosol forcing (150).

While there is consensus (21) on this physical understanding of how different climate forcing agents affect global temperature, the application of this understanding to climate policy and the definition of net zero remains contested. The IPCC defines net zero in terms of aggregate GHGs but is careful not to prescribe what metric is used for aggregation, recognizing this would be policy prescriptive.

Defining goals in terms of aggregate GHG emissions has advantages in identifying low-cost mitigation options across multiple gases, but using CO$_2$-e$_{100}$ for this purpose has the disadvantage (151) of disconnecting emissions from temperature outcomes: Whereas there is a straightforward relationship between CO$_2$ emissions and global temperature (each tonne of CO$_2$ emitted drives up global temperature by 0.45 ± 0.18 trillionths of a degree Celsius), **Figure 4** shows there is no such relationship between aggregate CO$_2$-e$_{100}$ emissions and global temperature. As stated in Reference 152 (p. 1016), "[E]xpressing methane emissions as CO$_2$-equivalent using GWP$_{100}$ [replacing $\kappa_F A_{100}(\Delta E_S + \rho \overline{E_S} \Delta t)$ with $\kappa_E \overline{E_S} \Delta t$ in Equation 19] overstates the effect of constant methane emissions on global temperature by a factor of 3 to 4 [the ratio $\kappa_E/(\kappa_F A_{100} \rho)$], while understating the effect of any new methane emission source by a factor of 4 to 5 over the 20 years following the introduction of the new source [4 to 5 includes the additional impact of the quantity $\kappa_F A_{100}/\kappa_E$ spread over 20 years]." Equation 19 shows that this problem applies to any SLCF.

Sustained net zero CO$_2$-e$_{100}$ emissions could therefore have a warming, zero, or cooling impact on global temperatures depending on the mix of gases involved (153). From Equation 19, if $\overline{E_L} = -\overline{E_S}$ (net zero CO$_2$-e$_{100}$ emissions), then $\Delta T \approx \kappa_E[85\Delta E_S - 0.72\overline{E_S}\Delta t]$. Hence, if net SLCF emissions are increasing by more than approximately 1% per year ($85\Delta E_S > 0.72\overline{E_S}\Delta t$), or are constant ($\Delta E_S = 0$) and negative ($\overline{E_S} < 0$), then net zero CO$_2$-e$_{100}$ emissions result in ongoing warming ($\Delta T > 0$). If net SLCF emissions are positive ($\overline{E_s} > 0$) and constant or declining ($\Delta E_s \leq 0$), then net zero CO$_2$-e$_{100}$ emissions result in a decline in global temperatures ($\Delta T < 0$). This disconnect between aggregate emissions and temperature outcomes means that many scenarios that meet the goal of Article 2 of the Paris Agreement (limiting warming to well below 2°C and close to 1.5°C) do not actually reach net zero CO$_2$-e$_{100}$ emissions in the second half of this century (153, 154).

At the global level, it has been argued that defining net zero emissions in terms of CO$_2$-e$_{100}$ emissions makes it a more ambitious goal than, for example, defining net zero and climate neutrality in terms of what it will take to halt global warming, because in all current scenarios net zero CO$_2$-e$_{100}$ emissions involve net negative CO$_2$ emissions balancing ongoing positive SLCF emissions (155). This assumes, of course, that net SLCF emissions do not increase after the date of net zero and that technologies for active removal of SLCFs are never deployed at scale, neither of which is guaranteed (156). Applied at the subglobal level, aiming for net zero CO$_2$-e$_{100}$ emissions allows offsetting of ongoing CO$_2$ emissions with avoided SLCF emissions, which results in long-term warming (157).

An alternative approach is to define net zero emissions and climate neutrality in terms of CO$_2$-we emissions that have, by design, the same impact on global temperature as CO$_2$ emissions themselves (22, 23, 158). While this approach has advantages in establishing a transparent link between progress to net zero and progress toward a long-term temperature goal of halting global warming, it would represent a departure from the traditional approach of treating all gases expressed in CO$_2$-e$_{100}$ as interchangeable and could present challenges for conventional mitigation instruments such as emission trading systems. One option would be to adopt a dual reporting approach, defining emissions neutrality as net zero aggregate CO$_2$-e$_{100}$ emissions and climate neutrality or temperature neutrality as net zero CO$_2$-we emissions, and track progress to both (21, 151).

Whichever accounting definition of net zero is adopted, it is important to be clear about its implications for global temperature, for which Equations 1 and 19 provide a simple foundation. They make clear that to halt global warming we need net zero emissions of LLCFs and for SLCFs to decline at least at the rate indicated by the RACF. Hence, assessing progress toward achieving any long-term temperature goal requires separate specification (21) of aggregate LLCF and SLCF emissions in both emissions reporting and targets: The current practice of aggregating LLCF and SLCF emissions into a single CO$_2$-e$_{100}$ total obscures their impact on global temperature (152).

In summary, it is easy to overstate the importance of ongoing debates over metrics for aggregating GHGs. To be relevant to achieving the long-term temperature goal of the Paris Agreement, any net zero strategy must be sustainable over multiple decades and consistent with no further warming. This precludes large-scale offsetting of emissions between gases with different lifetimes, just as it precludes large-scale offsetting of continued fossil CO$_2$ emissions with biological carbon uptake as discussed in Section 3. The argument that adopting a net zero definition based on aggregate CO_2-e_{100} emissions automatically leads to greater mitigation ambition, because ongoing SLCF emissions must then be balanced by active CO_2 removal, is tendentious at best and could backfire if either SLCF emissions begin to increase in a net zero world or large-scale SLCF removal becomes a reality and is deployed to balance ongoing CO_2 emissions. It also has the confusing implication that higher ongoing emissions of SLCFs such as methane appear to result in faster reductions of global temperatures in the long term because they require higher rates of CO_2 removal to achieve net zero CO_2-e_{100}. If CO_2 removal is deployed to reduce global temperatures in the second half of this century, that will happen because of decisions made at the time, not because of any definition of net zero adopted today.

5. NET ZERO IN THE 2015 PARIS AGREEMENT AND THE 2021 GLASGOW CLIMATE PACT

Although the term net zero does not appear in the 2015 Paris Agreement, reading Articles 2 and 4, in light of the best available science, offers us an interpretative context for the concept and salience of net zero in the Paris Agreement. The 2021 Glasgow Climate Pact, a nonbinding decision of the Parties (meaning signatory States) to the Paris Agreement, references the term net zero in the context of operationalizing the Paris Agreement and helps provide concrete content to the concept of net zero within the architecture of the United Nations climate regime.

Article 2 of the Paris Agreement identifies the global temperature goal as holding the increase in global average temperature to "well below 2°C above preindustrial levels" and pursuing efforts toward a 1.5°C temperature limit (3). This temperature goal builds on the 1992 UNFCCC's (3, p. 4) objective of "prevent[ing] dangerous anthropogenic interference with the climate system" by setting out, in terms of avoided temperature rise, the limits of what should be understood as dangerous. The temperature goal allows scientists to quantify, within uncertainties, a global carbon budget and the global emissions reduction pathways necessary to remain within that budget (159).

The Paris Agreement's temperature goal is best interpreted as a single goal consisting of two textually inseparable elements: the 1.5°C aspirational goal and the "well below 2°C" goal. Within this single goal the "well below 2°C" goal is given prominence in its order and language. While Article 2.1(a) (3, p. 3) "aims to"…"hold" the temperature increase to "well below 2°C," it only "aims to"…"pursu[e] efforts to limit" the temperature increase to 1.5°C. At the time the Paris Agreement was negotiated, States were not on track to well below 2°C let alone 1.5°C, and they are not now either, but this provision provides a global direction of travel.

Interpreting the Paris Agreement's temperature goal as a single goal covering a range from well below 2°C to 1.5°C permits evolution in the science underpinning the goal to influence where in that range States should aim to be over time. Such evolution and influence are already discernible. The SR1.5 highlighted robust differences in impacts between 1.5°C and 2°C and catalyzed political momentum toward the lower end of this temperature range. This momentum is reflected in the 2021 Glasgow Climate Pact (para. 21, 22, and 34), which captures a resolve among States to pursue efforts to limit the temperature increase to 1.5°C (160). Such an interpretation of the temperature goal also permits the goal to be refined within that range based on improvements in observationally based estimates over time, as seen in the AR6.

There is much that is conspicuous by its absence in the Paris Agreement's temperature goal. For instance, Article 2 indicates neither a time frame to achieve the temperature goal nor whether an overshoot of well below 2°C and 1.5°C is permissible before the goal is reached. Most available scenarios temporarily exceed the 1.5°C limit before 2100 (161). Article 2 also does not indicate whether GHG emissions are to steadily decline over time or to stabilize once the goal is achieved.

These omissions have led to several interpretations in relation to the temperature goal. Some scholars argue that the Paris Agreement's temperature goal is a unitary one of 1.5°C with minimal overshoot (162). Yet others interpret 1.5°C as the limit within the long-term temperature goal, and that it "signals an increase in both the margin and likelihood by which warming is to be kept below 2°C" (161, p. 830).

Article 4.1 indicates how the temperature goal identified in Article 2 is to be achieved, that is, through global peaking of GHG emissions as soon as possible (with a recognition that peaking will take longer in developing countries), and rapid reductions thereafter, "so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century" (3, p. 4). The notion of a balance between GHG emissions and removals has been translated into net zero in the policy discourse.

The interpretation of Article 4.1, and indeed how the temperature goal is to be achieved, is evolving in line with the best available science. The SR1.5 indicates that for the world to be on a no/limited overshoot trajectory to 1.5°C, CO_2 emissions need to be 45% below 2010 levels by 2030 and to reach net zero around 2050 (10). This target has led to a shift from aiming to reach net zero in the second half of the century in the Paris Agreement to urging adoption of long-term strategies toward just transitions to net zero emissions by or around midcentury in the Glasgow Climate Pact (160). This shift is reflected in States' self-selected deadlines to reach net zero—ranging from 2030 to 2070. Vulnerable nations, including Bangladesh, Barbados, the Maldives, Uruguay, and South Sudan, chose 2030 deadlines. Bhutan and Suriname assert they are already carbon neutral. Most States have chosen 2050 as the target date for reaching carbon or climate neutrality, with China at 2060 and India at 2070 (163).

There is wide variation among these net zero targets in terms of their legal character (policy statement, executive order, or national legislation), scope (all GHGs or only CO_2), and coverage (sectors or economy-wide). This discordance has challenged the credibility, accountability, and fairness of net zero targets, in particular because current nationally determined contributions (NDCs) are not aligned with midcentury net zero targets. The latest update to the NDCs synthesis report indicates that the NDCs in place put us on track to GHG emissions of 13.7% above 2010 levels in 2030, far off track from the required reductions in CO_2 emissions of 45% below 2010 by 2030 (164). The Glasgow Climate Pact (160, para. 32) seeks to address this by integrating long-term net zero targets into the Paris Agreement architecture, urging States to communicate (and periodically update) long-term low greenhouse development strategies under Article 4 (21). It also stresses (para. 35) the importance of aligning NDCs with these long-term strategies. The extent to which successive cycles of NDCs will align with net zero targets remains to be seen, and it is on this that the achievement of the temperature goal depends.

Ensuring consistency with the best available science remains an ongoing challenge as new issues come to light. For example, as was pointed out in Section 4, assessing the alignment of NDCs with the achievement of the temperature goal depends on a separate indication of the contributions of SLCFs and LLCFs in NDCs (21, 151). Some countries already make this separation: Wider uptake of this practice and extending it, where possible, to sectoral targets and goals for nonstate actors would considerably enhance the robustness of the assessment that the UN global stocktake process undertakes. Another emerging issue is that States (and many nonstate actors, see Section 6) account for all CO_2 uptake on managed lands as anthropogenic removals in calculating net CO_2 emissions, whether it occurs as a direct consequence of current human actions (e.g., afforestation) or as an indirect consequence of past emissions (e.g., enhanced vegetation growth through CO_2 fertilization). This opens the risk of double-counting, because Earth system models consider all additional CO_2 uptake that occurs as an indirect consequence of past emissions as natural in the calculation of carbon budgets and in the definition of net zero anthropogenic emissions. Depending on the scenario and fraction of global land area classified as "managed," the difference can be several billion tonnes of CO_2 per year (165, 166).

6. NET ZERO CLAIMS BY CORPORATIONS AND OTHER NONSTATE ACTORS

The 2015 Paris Agreement provided a unifying global climate goal based explicitly on not-to-exceed temperature thresholds but implicitly on the need to achieve net zero emissions to stabilize temperatures at any level. At the subnational level, a host of nonstate actors, predominately corporations but also other private sector entities, academic institutions, philanthropic foundations, and nongovernmental organizations (NGOs), have been making voluntary climate commitments for decades, often preceding or in parallel with the official UNFCCC process. Current claims are usually based explicitly on delivering net zero by a given date, with the temperature target unstated and implicit as a function of the pace of global progress toward net zero. Here, we briefly review a history of the evolution of voluntary climate claims by nonstate actors, their makeup and typology, some of the attendant issues of ambiguity and divergence from scientific definitions, and the current state of play for voluntary climate claims.

For the past two decades, voluntary climate and net zero claims have been virtually ungoverned, evolving organically and idiosyncratically according to preferences and informal conventions. The use of terms such as carbon neutral and net zero has changed over time, and the terms have diverged from their IPCC origins, in which they were originally defined as the like-for-like balancing of anthropogenic CO_2 emissions with anthropogenic removal of CO_2 (11). In voluntary contexts, carbon neutrality is explicitly defined in the Publicly Available Specification (PAS) 2060 standard (167), which does not require that emissions be balanced with removals and instead allows carbon credits based on avoided emissions. Net zero is interpreted informally as an evolution or improvement on carbon neutrality, a fresh term denoting higher ambition. More recently, entirely new claims such as net negative and climate positive arose to fill lexical gaps and the ambitions of individual firms to stand out in a crowded field. Climate claims are made once corresponding targets have been reached. The key elements of a voluntary corporate net zero or carbon neutral target are (*a*) the boundaries within which emissions are measured and attributed, (*b*) the allowed means of fulfilling the target, and (*c*) the timeline over which the target is to be achieved. All three elements vary widely.

Setting emissions boundaries for corporate actors has long been a challenge due to the complex and essentially infinite depth of life cycle analysis if unconstrained (168). Emissions factors, emissions monitoring techniques, and life cycle analysis conventions varied among and within industries but began to coalesce in the early 2000s under the GHG Protocol, a private industry- and NGO-led initiative, and the Carbon Disclosure Project (CDP), a not-for-profit providing a global corporate disclosure function. The GHG Protocol sets guidelines and procedures for measuring and categorizing emissions, distinguishing between direct (Scopes 1 and 2) and extended value-chain (Scope 3) emissions. Most voluntary net zero commitments include Scope 3 emissions, which are the physically attributable Scope 1 or 2 emissions of other entities. In this narrow sense, corporate net zero targets that involve all three scopes are more ambitious than that which the physical science definition of net zero might be interpreted to require, because they necessitate the elimination or neutralization of other entities' emissions.

Regarding the allowed means of discharging a net zero commitment or obligation, every corporate net zero claim grapples with two key issues: (*a*) setting a reasonable pace for absolute reduction or elimination of emissions, which affects the final balance of gross residual emissions at the net zero date, and (*b*) setting the allowable means of neutralizing unabated residual emissions, either on the way to net zero or at the net zero date. There have been differing conventions for both, some diverging significantly from official IPCC definitions and pathways. For the first issue, attempts have been made to establish universal principles for what constitutes reasonable and practicable absolute emission reductions (169), to set clear definitions of which emissions are deemed hard-to-abate (170), and to set best practices for intermediate targets (171). Sector-specific guidance is under development by the Science Based Targets initiative (SBTi) but remains elusive due to its inherent subjectivity, as it requires disassembling the global net zero target into slices on a regional or industry basis. Such sectoral guidance is often informed by the global scenarios of the IPCC, although the IPCC itself notes, referring to the use of its scenarios (153, p. 20), "The most appropriate strategies will depend on national and regional circumstances, including enabling conditions and technology availability."

For the second issue, setting allowable means of addressing unabated emissions, voluntary approaches have differed. Participants in the voluntary carbon market (VCM) have long made claims of carbon neutrality and net zero on the basis of purchasing emission reduction or avoided emission carbon credits, which make up more than 96% of all VCM carbon credits issued to date (172). Setting aside critiques of the integrity of avoided emission and emission reduction carbon credits (173–175), attempting to use such credits to neutralize one's own physical emissions is, by definition, not sufficient to enable a net zero claim because no CO_2 has been physically removed from the atmosphere or upper oceans to compensate for the addition of CO_2 to the atmosphere. There is no universally agreed term to describe a state in which emissions are fully matched with avoided emission or emission reduction carbon credits. Whether due to the lack of availability of removals, limited understanding of the definition of net zero, lack of scientifically informed guidance (PAS 2060 allows the use of emission reduction and avoided emission carbon credits in delivering a carbon neutral claim; 167), or pressure to show faster climate progress than one's peers, corporate claims have consistently blurred the distinction between CO_2 removals and avoided emissions.

Finally, timelines for delivering on voluntary net zero claims vary. Of the approximately 820 companies with net zero targets that have clearly defined target dates in the Net Zero Tracker database as of 2021, 33% claim they will deliver by 2030 or sooner, 14% by 2040, and 53% by 2050 (4). Many organizations have attempted to claim to have already achieved net zero or carbon neutrality, in some cases receiving strong public criticism and pushback (176). No known large organizations have fully balanced all of their residual Scope 1, 2, and 3 emissions with high-durability removals, as required by the more stringent guidance on the use of carbon credits in net zero claims (139, 171), and therefore the focus has been on whether companies have net zero–aligned trajectories, as the delivery of net zero itself is years away for most.

Unprecedented growth in the global VCM, which tripled in 2021 to more than $1 billion (177), coupled with the lack of guidance on structuring credible corporate net zero targets and claims, spawned several efforts in 2020 and 2021 to resolve these ambiguities. These efforts included principles to define net zero–aligned offsetting that reaffirmed the need to balance residual emissions with removals, not avoidances, before a net zero claim could be made (139); a UNFCCC-endorsed lexicon of net zero–related terms (178); and several high-profile private sector– and philanthropic foundation–led efforts. The Taskforce on Scaling Voluntary Carbon Markets (and its successor, the Integrity Council for the Voluntary Carbon Market) focused on market mechanics for scale and guidelines for high-quality carbon project certification protocols and deliberately demurred to the question of what claims the purchase of these credits could enable. The Voluntary Carbon Markets Integrity Initiative took up this latter challenge. Finally, in late 2021, SBTi launched the first ever corporate net zero standard. Adherents must demonstrate a credible plan to halve emissions by 2030, eliminate gross emissions by 90–95% by 2050, and neutralize any remaining residual emissions with "permanent removal and storage from the atmosphere" (171, p. 9). The issue of potential double-counting of land-based removals highlighted at the end of Section 5 also applies here.

At the time of publication, official and public responses to SBTi's standard have been mixed, with some criticizing the high degree of absolute reductions required (more difficult for some industries than others, as well as potentially disincentivizing necessary investment in CO_2 removal technologies and practices) and others celebrating the emphasis on permanent removals and the exclusion of conventional avoided emission carbon credits.

On the cutting edge of voluntary climate targets, some entities have increased their climate ambition and targeted net negative emissions. The most ambitious are doing so on a cumulative basis, promising to remove from the atmosphere all the CO_2 they have emitted since inception (179) rather than simply targeting slightly negative emissions by midcentury. Still others are committing to be climate positive, which is either used as a synonym for net negative emissions or meant to imply further actions toward restoring and improving the environment to an even better state. Finally, there have been calls to step back from the focus on individual actors achieving net zero emissions within their operations and supply chains, shifting instead to a holistic approach where a company's contribution toward decarbonizing their sector, and the global economy, matters more than isolated efforts (180). This has renewed debate about the broader benefits of contribution claims (providing material support to climate action for its own sake) relative to compensation claims (funding reduction or removal activities to take direct credit for that mitigation) (181). For example, some actors are donating to or investing in nascent, high-cost carbon removal techniques to accelerate their deployment without claiming carbon credits. In other instances, contribution claims are used to fund projects with strong noncarbon environmental benefits but low-certainty carbon benefits, supporting desired outcomes while avoiding the risk of offsetting causing indirect carbon leakage.

In summary, voluntary climate targets and the associated claims are diverse and sometimes inconsistent with scientific guidance, but new initiatives are working to bridge that gap. The critical challenge is to ensure that genuine climate ambition is driving real progress toward sustainably limiting global warming, consistent with the goals of the Paris Agreement.

7. CONCLUSIONS: RECLAIMING NET ZERO

Our understanding of net zero has morphed over the past 15 years from a scientific fact to a pragmatic solution to an estimation problem to an accounting target to an article of faith. The scientific fact, understood at least since the 1970s, is that fossil fuel emissions have a near-permanent impact on atmospheric CO_2 concentrations through their impact on ocean chemistry, such that cumulative CO_2 emissions since preindustrial times cause an effectively permanent warming that can be reversed only by active CO_2 removal (182). This equilibrium net zero, or long-term warming associated with this millennial-timescale CO_2 AF, emerges only over many centuries, limiting its immediate policy relevance.

The persistent challenge of placing a useful upper bound on the ECS, or the long-term warming associated with any specific atmospheric CO_2 concentration, led to the pragmatic observation that a more robust constraint could be placed on peak warming under scenarios in which CO_2 emissions reach net zero and atmospheric CO_2 concentrations consequently peak and decline. This led to the concept of a dynamic net zero under which ongoing oceanic thermal adjustment balances declining CO_2 radiative forcing, leading to approximately constant surface temperatures. We have shown that there is no fundamental reason why this balance should be exact. On the basis of current evidence, any increase or decrease of CO_2-induced warming accompanying net zero CO_2 emissions would be indistinguishable from natural climate variability for many decades, but not necessarily identically zero.

That said, stopping CO_2 emissions from causing global warming within the next few decades, as required to meet the goals of the Paris Agreement, will as likely as not require net zero CO_2 emissions by the middle of this century or shortly thereafter. Even if not exactly zero, any residual imbalance would be, in absolute terms, at least a factor of 10 smaller than current emissions and likely less than uncertainty in ongoing emissions and removals, so whether it eventually turns out to be positive or negative has little immediate policy impact. Recalling the fruitless debate over the value of the ECS and safe stabilization concentrations, it is important to avoid uncertainties in the long-term behavior of the climate system distracting from immediate policy decisions to which they are irrelevant. We cannot afford to spend the next quarter century arguing over the exact level of ongoing CO_2 emissions or removals that is consistent with no further warming.

Recognizing the need for near–net zero CO_2 emissions at the global level, some countries and many nonstate actors, such as cities, regions, and companies, are setting goals to reach net zero emissions well in advance of the date of global net zero. Translating these goals into specific targets has required a reframing of net zero as an accounting target involving a specific balance of emissions and removals of CO_2 and other GHGs. The problem with this framing is that accounting targets tend to apply to a particular year, such as 2030 or 2050. To be relevant to the long-term temperature goal of the Paris Agreement, net zero must be sustained over many decades. A net zero balance that depends on large-scale compensation between emissions and removals of GHGs with different lifetimes, or sources and sinks of CO_2 associated with different timescales, is ultimately unsustainable. Hence, any entity relying on such a balance to achieve net zero emissions (e.g., offsetting ongoing fossil CO_2 emissions by paying for methane emission reductions or nature-based CO_2 uptake) must also have a strategy to ensure a transition within a few decades to like-for-like balancing of emissions and removals (including the requirement that any continued generation of fossil CO_2, whether or not it is emitted to the atmosphere, must be balanced by geological CO_2 sequestration or equally permanent disposal).

It has become almost an article of faith that achieving net zero CO_2 emissions, or net zero CO_2-e_{100} emissions, is necessary to meet our climate goals. Although this may be a helpful simplification for motivating climate policies today, it is not entirely rigorous: The RAZE is small, but not necessarily zero, and could take either sign. The only thing that can be said with rigor is that ongoing CO_2 emissions consistent with no detectable further CO_2-induced warming are close to zero, could be negative or positive, and are at least an order of magnitude smaller than CO_2 emissions today. Net zero CO_2-e_{100} emissions in the second half of this century may or may not be required to meet the goals of the Paris Agreement depending on the mix of LLCFs and SLCFs in the emissions scenario.

Whatever definition of net zero is adopted, it is vital that the implications for global temperature and carbon stocks are clear. Separate specification of aggregate SLCFs and LLCFs in all reported emissions and emissions targets would be a straightforward innovation and immediately improve the transparency of any global stocktake of progress toward a long-term global temperature goal (21). Specification of CO_2 origin and storage type would also increase the transparency of any emissions-management strategy, given the need to transition away from using land-based removals to compensate for fossil emissions and to avoid the risk of double-counting of CO_2 uptake on managed lands.

Constructive ambiguity plays a vital role in negotiation, and net zero is not the first example of everyone agreeing that something is a good idea before agreeing exactly what it means. The advantage of net zero as a term is that is it just a number and therefore has to refer to something: net zero what? If the goal is net zero emissions, which gases, how are they aggregated, and which (biological and geological, natural and anthropogenic) sources and sinks are included? If the goal is net zero additional warming, on what timescale? Imposing a restrictive definition on net zero itself may simply be divisive, and energy might be better spent on understanding the implications of applying the term to different target quantities, which we hope will be supported by the quantitative framework provided in this review.

SUMMARY POINTS

1. The term net zero emissions means a balance between ongoing anthropogenic release of greenhouse gases (GHGs) into the atmosphere and active GHG removal either through direct capture and disposal or anthropogenically enhanced natural removal processes: The term may be applied to an individual gas, such as CO_2, or a basket of gases combined using a GHG metric.
2. CO_2 emissions from fossil fuels have been understood for decades to have a substantial and effectively permanent impact on global climate through well-understood ocean chemistry: Hence, sustained net zero CO_2 emissions are needed to restore climate equilibrium on multimillennial timescales.
3. On multidecadal timescales, approximately net zero CO_2 emissions are also required to halt global warming through a dynamic balance between CO_2 uptake by the oceans and biosphere and the ongoing thermal adjustment of the deep oceans and evolving atmospheric feedbacks.
4. The ongoing rate of CO_2 emissions consistent with no further increase in global average surface temperature is given by cumulative emissions prior to the date of net zero multiplied by the rate of adjustment to zero emissions (RAZE). It is more than one order of magnitude smaller than present-day emissions, is indistinguishable from zero on multidecadal timescales, and may be either positive or negative, so equating it with zero is a justifiable simplification for policy.
5. Nature-based solutions (NbS) provide immediate cost-effective opportunities for reducing net CO_2 emissions with substantial co-benefits, but they will likely be needed in the future to compensate for essential emissions from food production and the release of carbon from the biosphere due to global warming itself. NbS are unlikely to be scaled sufficiently to compensate for ongoing fossil fuel emissions past midcentury.
6. Unlike net zero CO_2, net zero GHG emissions may cause ongoing warming or cooling depending on the mix of emissions and removals of long-lived climate forcers (LLCFs) and short-lived climate forcers (SLCFs) and the metric used to combine them: Halting global warming requires net zero emissions of LLCFs such as CO_2 and nitrous oxide and declining (but not necessarily zero) net emissions of SLCFs such as methane, with the rate of decline being at least the rate of adjustment to constant forcing (RACF), or approximately 3% per decade.

FUTURE ISSUES

1. Research is required to better constrain the RACF, or the fractional rate of change of global average surface temperature following a stabilization of radiative forcing after a multidecadal period of increasing forcing. The RACF also represents the fractional rate at which total effective radiative forcing needs to decline to halt global warming.

2. Research is also required to constrain the RAZE, or the fractional rate of change of CO_2-induced global warming after CO_2 emissions reach net zero following a multidecadal period of positive CO_2 emissions. The RAZE is related to, but less scenario dependent than, the zero emissions commitment, which also depends on the level of warming at the time of net zero emissions.
3. Wider appreciation is required of the need for a durable net zero, involving like-for-like balancing of emissions by sources with removals by sinks of similar or greater permanence. Under durable net zero, any remaining CO_2 generation from fossil fuel use would be balanced by active CO_2 removal to geological-timescale storage.
4. Separate specification of aggregate emissions of LLCFs (or GHGs with lifetimes longer than approximately 100 years, such as CO_2 and nitrous oxide) and SLCFs (with lifetimes shorter than 20 years, such as methane) in emissions targets would greatly facilitate any stocktake of progress toward halting global warming.
5. National and corporate strategies for achieving net zero should account for the warming impact of their GHG emissions during the transition. To facilitate this, we note that additional warming ΔT caused by GHG emissions over multidecadal time interval Δt may be estimated by

$$\Delta T \approx \kappa_E [\overline{E_L} \Delta t + 85 \Delta E_S + 0.28 \overline{E_S} \Delta t],$$

where $\overline{E_L}$ and $\overline{E_S}$ are average rates of aggregate LLCF and SLCF emissions, respectively, over that time interval, and ΔE_S is the change in SLCF emission rates between the beginning and the end of that time interval, where all emissions are expressed as CO_2-equivalent using 100-year global warming potentials. The transient climate response to emissions $\kappa_E = 0.45 \pm 0.18$°C per $TtCO_2$.

DISCLOSURE STATEMENT

M.R.A. is a member of the Advisory Board of Puro.Earth. E.M.-L. is the launch director of CarbonGap. C.A.J.G. is a director of Nature-based Insetting. The other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This review was supported by the Oxford Net Zero initiative funded by the Strategic Research Fund of the University of Oxford. M.R.A., P.F., S.J., G.P.P., and E.M.-L. were supported by the 4C, FORCeS, NEGEM, and Paris Reinforce projects funded by the European Union's Horizon 2020 research and innovation program under grant agreements 821003, 821205, 869192, and 820846. S.J. was also supported by UK NERC grant NE/L002612/1. Y.M. was supported by the Frank Jackson Foundation and the Leverhulme Trust. C.A.J.G., E.M.-L., and L.R. were supported by the Biodiversity Network, Clarendon Fund, and Strategic Research Fund, respectively, of the University of Oxford, and M.R.A. received additional support from the Oxford Martin School. The authors would like to thank Heather Waller for help with compiling references; Ray Pierrehumbert, Keith Shine, and an anonymous reviewer for helpful suggestions; Savitha Viswanathan for assistance with figures; and Marie-Thérèse Wright for support throughout the production process.

LITERATURE CITED

1. IPCC (Intergov. Panel Clim. Change). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, et al. Cambridge, UK: Cambridge Univ. Press. 1535 pp.
2. UNFCCC (U. N. Framew. Conv. Clim. Change). 2015. *Report on the structured expert dialogue on the 2013–2015 review. Note by the co-facilitators of the structured expert dialogue*. Rep. UNFCCC, Bonn, Ger. **https://unfccc.int/documents/8707**
3. UNFCCC (U. N. Framew. Conv. Clim. Change). 2015. *Paris Agreement, 21st Conference of the Parties, Paris*. Bonn, Ger. UNFCCC. **https://unfccc.int/sites/default/files/english_paris_agreement.pdf**
4. Hale T, Kuramochi T, Lang J, Yeo ZY, Smith S, et al. 2022. *Net Zero Tracker*. Cologne, Ger.: NewClimate Institute. **https://zerotracker.net/methodology**
5. Matthews HD, Caldeira K. 2008. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* 35:L04705
6. Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, et al. 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458:1163–66
7. Meinshausen M, Meinshausen N, Hare W, Raper SC, Frieler K, et al. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458:1158–62
8. Matthews HD, Gillett NP, Stott PA, Zickfeld K. 2009. The proportionality of global warming to cumulative carbon emissions. *Nature* 459:829–32
9. Zickfeld K, Eby M, Matthews HD, Weaver AJ. 2009. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *PNAS* 106:16129–34
10. IPCC (Intergov. Panel Clim. Change). 2018. Summary for policymakers. In *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, ed. V Masson-Delmotte, O Zhai, H-O Pörtner, D Roberts, J Skea, et al., pp. 3–24. Cambridge, UK/New York: Cambridge Univ. Press. **https://doi.org/10.1017/9781009157940**
11. IPCC (Intergov. Panel Clim. Change). 2018. Annex I: glossary. In *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, ed. V Masson-Delmotte, O Zhai, H-O Pörtner, D Roberts, J Skea, et al., pp. 541–62. Cambridge, UK/New York: Cambridge Univ. Press. **https://doi.org/10.1017/9781009157940**
12. IPCC (Intergov. Panel Clim. Change). 2021. Summary for policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. V Masson-Delmotte, P Zhai, A Pirani, SL Connors, C Péan, pp. 3–32. Cambridge, UK: Cambridge Univ. Press
13. Solomon S, Plattner G-K, Knutti R, Friedlingstein P. 2009. Irreversible climate change due to carbon dioxide emissions. *PNAS* 106:1704–9
14. MacDougall AH, Frölicher TL, Jones CD. 2020. Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from CO_2. *Biogeosciences* 17:2987–3016
15. Frölicher TL, Winton M, Sarmiento JL. 2014. Continued global warming after CO_2 emissions stoppage. *Nat. Clim. Change* 4:40–44
16. Gregory JM, Jones CD, Cadule P, Friedlingstein P. 2009. Quantifying carbon cycle feedbacks. *J. Clim.* 22:5232–50
17. Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, et al. 2013. Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, et al., pp. 1031–106. Cambridge, UK: Cambridge Univ. Press
18. Held IM, Winton M, Takahashi K, Delworth T, Zeng F, Vallis GK. 2010. Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. *J. Clim.* 23:2418–27

19. Tsutsui J. 2017. Quantification of temperature response to CO_2 forcing in atmosphere-ocean general circulation models. *Clim. Change* 140:287–305
20. Jenkins S, Cain M, Friedlingstein P, Gillett N, Walsh T, Allen MR. 2021. Quantifying non-CO_2 contributions to remaining carbon budgets. *NPJ Clim. Atmos. Sci.* 4:47
21. Allen MR, Peters GP, Shine KP, Azar C, Balcombe P, et al. 2022. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. *NPJ Clim. Atmos. Sci.* 5:5
22. Cain M, Lynch J, Allen MR, Fuglestvedt JS, Frame DJ, Macey AH. 2019. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *NPJ Clim. Atmos. Sci.* 2(1):29
23. Smith MA, Cain M, Allen MR. 2021. Further improvement of warming-equivalent emissions calculation. *NPJ Clim. Atmos. Sci.* 4:19
24. UNFCCC (U. N. Framew. Conv. Clim. Change). 1992. *United Nations Framework Convention on Climate Change*. Bonn, Ger.: UNFCCC. **https://unfccc.int/resource/docs/convkp/conveng.pdf**
25. Leggett J, Pepper WJ, Swart RJ. 1992. Emissions scenarios for IPCC: an update. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, ed. JT Houghton, BA Callandar, SK Varney, pp. 73–95. Cambridge, UK: Cambridge Univ. Press
26. Wigley TML, Richels R, Edmonds JA. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* 379:240–43
27. Nakicenovic N, Swart RJ, eds. 2000. *IPCC Special Report on Emissions Scenarios*. Cambridge, UK: Cambridge Univ. Press
28. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, et al. 2011. The representative concentration pathways: an overview. *Clim. Change* 109:5
29. Friedlingstein P, Fung I, Holland E, John J, Brasseur G, et al. 1995. On the contribution of CO_2 fertilization to the missing biospheric sink. *Glob. Biogeochem. Cycles* 9:541–56
30. Joos F, Bruno M, Fink R, Siegenthaler U, Stocker TF, et al. 1996. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus B Chem. Phys. Meteorol.* 48:394–417
31. Enting IG, Wigley TML, Heimann M. 1994. *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses*. Canberra, Aust. CSIRO Div. Atmos. Res.
32. Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heimann M, et al. 2001. The carbon cycle and atmospheric carbon dioxide. In *Climate Change 2001: The Scientific Basis*, ed. JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, et al., pp. 185–237. Cambridge, UK: Cambridge Univ. Press
33. Charney J, Arakawa A, Baker J, Bolin B, Dickinson RE, et al. 1979. *Carbon Dioxide and Climate: A Scientific Assessment*. Washington, DC: Natl. Acad. Press
34. Houghton JT, Jenkins GJ, Ephraums JJ. 1990. *Climate Change: The IPCC Scientific Assessment*. Cambridge, UK: Cambridge Univ. Press
35. Joos F, Bruno M. 1996. Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO_2 and global warming. *Phys. Chem. Earth* 21:471–76
36. Andronova NG, Schlesinger ME. 2001. Objective estimation of the probability density function for climate sensitivity. *J. Geophys. Res. Atmos.* 106:22605–11
37. Forest CE, Stone PH, Sokolov AP, Allen MR, Webster MD. 2002. Quantifying uncertainties in climate system properties with the use of recent climate observations. *Science* 295:113–17
38. Murphy JM, Sexton DM, Barnett DN, Jones GS, Webb MJ, et al. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* 430:768–72
39. Stainforth DA, Aina T, Christensen C, Collins M, Faull N, et al. 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature* 433:403–6
40. IPCC (Intergov. Panel Clim. Change). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, et al. Cambridge, UK: Cambridge Univ. Press. 881 pp.
41. IPCC (Intergov. Panel Clim. Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S Solomon, D Qin, M manning, Z Chen, M Marquis, et al. Cambridge, UK: Cambridge Univ. Press. 996 pp.

42. Allen MR, Stott PA, Mitchell JFB, Schnur R, Delworth TL. 2000. Quantifying the uncertainty in forecasts of anthropogenic climate change. *Nature* 407:617–20
43. Frame DJ, Booth BBB, Kettleborough JA, Stainforth DA, Gregory JM, et al. 2005. Constraining climate forecasts: the role of prior assumptions. *Geophys. Res. Lett.* 32:L09702
44. Roe GH, Baker MB. 2007. Why is climate sensitivity so unpredictable? *Science* 318:629–32
45. Raper SCB, Gregory JM, Stouffer RJ. 2002. The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response. *J. Clim.* 15:124–30
46. Knutti R, Tomassini L. 2008. Constraints on the transient climate response from observed global temperature and ocean heat uptake. *Geophys. Res. Lett.* 35:L09701
47. Gregory JM, Forster PM. 2008. Transient climate response estimated from radiative forcing and observed temperature change. *J. Geophys. Res. Atmos.* 113:D23105
48. Gregory JM, Mitchell JFB. 1997. The climate response to CO_2 of the Hadley Centre coupled AOGCM with and without flux adjustment. *Geophys. Res. Lett.* 24:1943–46
49. Siegenthaler U, Oeschger H. 1978. Predicting future atmospheric carbon dioxide levels. *Science* 199:388–95
50. Maier-Reimer E, Hasselmann K. 1987. Transport and storage of CO_2 in the ocean—an inorganic ocean-circulation carbon cycle model. *Clim. Dyn.* 2:63–90
51. Hansen J, Sato M, Ruedy R, Nazarenko L, Lacis A, et al. 2005. Efficacy of climate forcings. *J. Geophys. Res. Atmos.* 110:D18104
52. Winton M, Takahashi K, Held IM. 2010. Importance of ocean heat uptake efficacy to transient climate change. *J. Clim.* 23:2333–44
53. Gregory JM. 2000. Vertical heat transports in the ocean and their effect on time-dependent climate change. *Clim. Dyn.* 16:501–15
54. Hansen J, Russell G, Lacis A, Fung I, Rind D, Stone P. 1985. Climate response times: dependence on climate sensitivity and ocean mixing. *Science* 229:857–59
55. Arrhenius S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *Philos. Mag. J. Sci.* 41:237–76
56. Manabe S, Wetherald RT. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.* 24:241–59
57. Zhou C, Zelinka MD, Dessler AE, Wang M. 2021. Greater committed warming after accounting for the pattern effect. *Nat. Clim. Change* 11:132–36
58. Matthews HD, Solomon S. 2013. Irreversible does not mean unavoidable. *Science* 340:438–39
59. Cockburn H. 2021. Climate crisis: greenhouse gases already emitted will warm Earth beyond limits in Paris Agreement, research suggests. *The Independent*, Jan. 5. **https://www.independent.co.uk/climate-change/news/greenhouse-gases-committed-warming-climate-change-b1782571.html**
60. Gregory JM, Stouffer RJ, Raper SCB, Stott PA, Rayner NA. 2002. An observationally based estimate of the climate sensitivity. *J. Clim.* 15:3117–21
61. Levitus S, Antonov JI, Boyer TP, Stephens C. 2000. Warming of the world ocean. *Science* 287:2225–29
62. Armour KC, Bitz CM, Roe GH. 2013. Time-varying climate sensitivity from regional feedbacks. *J. Clim.* 26:4518–34
63. Allen MR, Frame DJ. 2007. Atmosphere: Call off the quest. *Science* 318:582–83
64. Andrews T, Gregory JM, Webb MJ, Taylor KE. 2012. Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. *Geophys. Res. Lett.* 39:L09712
65. Frame DJ, Stone DA, Stott PA, Allen MR. 2006. Alternatives to stabilization scenarios. *Geophys. Res. Lett.* 33:L14707
66. Cummins DP, Stephenson DB, Stott PA. 2020. Optimal estimation of stochastic energy balance model parameters. *J. Clim.* 33:7909–26
67. Seshadri AK. 2017. Fast-slow climate dynamics and peak global warming. *Clim. Dyn.* 48:2235–53
68. Geoffroy O, Saint-Martin D, Olivié DJL, Voldoire A, Bellon G, Tytéca S. 2013. Transient climate response in a two-layer energy-balance model. Part I: analytical solution and parameter calibration using CMIP5 AOGCM experiments. *J. Clim.* 26:1841–57
69. Peters GP, Aamaas B, Berntsen T, Fuglestvedt JS. 2011. The integrated global temperature change potential (iGTP) and relationships between emission metrics. *Environ. Res. Lett.* 6:044021

70. Li S, Jarvis A. 2009. Long run surface temperature dynamics of an A-OGCM: the HadCM3 4×CO_2 forcing experiment revisited. *Clim. Dyn.* 33:817–25
71. Cubasch U, Meehl GA. 2001. Projections of future climate change. In *Climate Change 2001: A Scientific Basis*, ed. JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, et al., pp. 526–82. Cambridge, UK: Cambridge Univ. Press
72. Millar RJ, Otto A, Forster PM, Lowe JA, Ingram WJ, Allen MR. 2015. Model structure in observational constraints on transient climate response. *Clim. Change* 131:199–211
73. Pfister PL, Stocker TF. 2018. The realized warming fraction: a multi-model sensitivity study. *Environ. Res. Lett.* 13:124024
74. Joos F, Gerber S, Prentice IC, Otto-Bliesner BL, Valdes PJ. 2004. Transient simulations of Holocene atmospheric carbon dioxide and terrestrial carbon since the Last Glacial Maximum. *Glob. Biogeochem. Cycles* 18:GB2002
75. Archer D, Eby E, Brovkin V, Ridgwell A, Cao L, et al. 2009. Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* 37:117–34
76. Revelle R, Suess HE. 1957. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades. *Tellus* 9:18–27
77. Pierrehumbert RT. 2014. Short-lived climate pollution. *Annu. Rev. Earth Planet. Sci.* 42:341–79
78. Lenton TM. 2006. Climate change to the end of the millennium. *Clim. Change* 76:7–29
79. Millar JR, Nicholls ZR, Friedlingstein P, Allen MR. 2017. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* 17:7213–28
80. Caldeira K, Kasting JF. 1992. The life span of the biosphere revisited. *Nature* 360:721–23
81. Friedlingstein P, Solomon S. 2005. Contributions of past and present human generations to committed warming caused by carbon dioxide. *PNAS* 102:10832–36
82. Shine KP, Fuglestvedt JS, Hailemariam K, Stuber N. 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Change* 68:281–302
83. Raper SCB, Gregory JM, Osborn TJ. 2001. Use of an upwelling-diffusion energy balance climate model to simulate and diagnose A/OGCM results. *Clim. Dyn.* 17:601–13
84. Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408:184–87
85. Friedlingstein P, Dufresne J-L, Cox PM, Rayner P. 2003. How positive is the feedback between climate change and the carbon cycle? *Tellus B Chem. Phys. Meteorol.* 55:692–700
86. Fung IY, Doney SC, Lindsay K, John J. 2005. Evolution of carbon sinks in a changing climate. *PNAS* 102:11201–6
87. Zeng N, Qian H, Munoz E, Iacono R. 2004. How strong is carbon cycle-climate feedback under global warming? *Geophys. Res. Lett.* 31:L20203
88. Matthews HD. 2006. Emissions targets for CO_2 stabilization as modified by carbon cycle feedbacks. *Tellus B Chem. Phys. Meteorol.* 58:591–602
89. Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, et al. 2006. Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison. *J. Clim.* 19:3337–53
90. Koven CD, Ringeval B, Friedlingstein P, Ciais P, Cadule P, et al. 2011. Permafrost carbon-climate feedbacks accelerate global warming. *PNAS* 108:14769–74
91. Arora VK, Katavouta A, Williams RG, Jones CD, Brovkin V, et al. 2020. Carbon-concentration and carbon-climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences* 17:4173–22
92. Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, et al. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579:80–87
93. Gloor M, Sarmiento JL, Gruber N. 2010. What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction? *Atmos. Chem. Phys.* 10:7739–51
94. Bennedsen M, Hillebrand E, Koopman SJ. 2019. Trend analysis of the airborne fraction and sink rate of anthropogenically released CO_2. *Biogeosciences* 16:3651–63
95. Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, et al. 2020. Global carbon budget 2020. *Earth Syst. Sci. Data* 12:3269–40

96. Leach NJ, Jenkins S, Nicholls Z, Smith CJ, Lynch J, et al. 2021. FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. *Geosci. Model Dev.* 14:3007–36
97. Raupach MR. 2013. The exponential eigenmodes of the carbon-climate system, and their implications for ratios of responses to forcings. *Earth Syst. Dyn.* 4:31–49
98. Raupach MR, Gloor M, Sarmiento JL, Canadell JG, Frölicher TL, et al. 2014. The declining uptake rate of atmospheric CO_2 by land and ocean sinks. *Biogeosciences* 11:3453–75
99. Herrington T, Zickfeld K. 2014. Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth Syst. Dyn.* 5:409–22
100. Leduc M, Matthews HD, de Elia R. 2015. Quantifying the limits of a linear temperature response to cumulative CO_2 emissions. *J. Clim.* 28:9955–68
101. MacDougall AH. 2016. The transient response to cumulative CO_2 emissions: a review. *Curr. Clim. Change Rep.* 2:39–47
102. Millar R, Allen M, Rogelj J, Friedlingstein P. 2016. The cumulative carbon budget and its implications. *Oxf. Rev. Econ. Policy* 32:323–42
103. MacDougall AH, Friedlingstein P. 2015. The origin and limits of the near proportionality between climate warming and cumulative CO_2 emissions. *J. Clim.* 28:4217–30
104. Goodwin P, Williams RG, Ridgwell A. 2015. Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake. *Nat. Geosci.* 8:29–34
105. Williams RG, Goodwin P, Roussenov VM, Bopp L. 2016. A framework to understand the transient climate response to emissions. *Environ. Res. Lett.* 11:015003
106. Gillett NP, Arora VK, Matthews D, Allen MR. 2013. Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. *J. Clim.* 26:6844–58
107. Millar RJ, Friedlingstein P. 2018. The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philos. Trans. R. Soc. A* 376:20160449
108. Seshadri AK. 2017. Origin of path independence between cumulative CO_2 emissions and global warming. *Clim. Dyn.* 49:3383–401
109. Zickfeld K, Herrington T. 2015. The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environ. Res. Lett.* 10:031001
110. Zickfeld K, Azevedo D, Mathesius S, Matthews HD. 2021. Asymmetry in the climate-carbon cycle response to positive and negative CO_2 emissions. *Nat. Clim. Change* 11:613–17
111. Rogelj J, Schaeffer M, Friedlingstein P, Gillett NP, van Vuuren DP, et al. 2016. Differences between carbon budget estimates unravelled. *Nat. Clim. Change* 6:245–52
112. Ricke KL, Caldeira K. 2014. Maximum warming occurs about one decade after a carbon dioxide emission. *Environ. Res. Lett.* 9:124002
113. Plattner G-K, Knutti R, Joos F, Stocker TF, von Bloh W, et al. 2008. Long-term climate commitments projected with climate-carbon cycle models. *J. Clim.* 21:2721–51
114. Gasser T, Kechiar M, Ciais P, Burke EJ, Kleinen T, et al. 2018. Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release. *Nat. Geosci.* 11:830–35
115. Mahowald NM, Randerson JT, Lindsay K, Munoz E, Doney SC, et al. 2017. Interactions between land use change and carbon cycle feedbacks. *Glob. Biogeochem. Cycles* 31:96–113
116. Matthews HD, Solomon S, Pierrehumbert R. 2012. Cumulative carbon as a policy framework for achieving climate stabilization. *Philos. Trans. R. Soc. A* 370:4365–79
117. Millar RJ, Fuglestvedt JS, Friedlingstein P, Rogelj J, Grubb MJ, et al. 2017. Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nat. Geosci.* 10:741–47
118. Zickfeld K, Arora VK, Gillett NP. 2012. Is the climate response to CO_2 emissions path dependent? *Geophys. Res. Lett.* 39:L05703
119. Allen MR, Ingram WJ. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature* 419:224–32
120. Mengel M, Nauels A, Rogelj J, Schleussner C-F. 2018. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nat. Commun.* 9:601
121. Girardin CAJ, Jenkins S, Seddon N, Allen M, Lewis SL, et al. 2021. Nature-based solutions can help cool the planet—if we act now. *Nature* 593:191–94

122. IUCN (Int. Union Conserv. Nat.). 2020. *Guidance for using the IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of Nature-based Solutions*. Gland, Switz.: IUCN. **https://portals.iucn.org/library/sites/library/files/documents/2020-021-En.pdf**
123. Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, et al. 2017. Natural climate solutions. *PNAS* 114:11645–50
124. Seddon N, Smith A, Smith P, Key I, Chausson A, et al. 2021. Getting the message right on nature-based solutions to climate change. *Glob. Change Biol.* 27:1518–46
125. Anderson CM, DeFries RS, Litterman R, Matson PA, Nepstad DC, et al. 2019. Natural climate solutions are not enough. *Science* 363:933–34
126. Friedlingstein P, Allen M, Canadell JG, Peters GP, Seneviratne SI. 2019. Comment on "The global tree restoration potential." *Science* 366:eaay8060
127. Lewis SL, Wheeler CE, Mitchard ETA, Koch A. 2019. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* 568:25–28
128. Roe S, Streck C, Obersteiner M, Frank S, Griscom B, et al. 2019. Contribution of the land sector to a 1.5°C world. *Nat. Clim. Change* 9:817–28
129. Requena Suarez D, Rozendaal DMA, De Sy V, Phillips OL, Alvarez-Dávila E, et al. 2019. Estimating aboveground net biomass change for tropical and subtropical forests: refinement of IPCC default rates using forest plot data. *Glob. Change Biol.* 25:3609–24
130. Cook-Patton SC, Leavitt SM, Gibbs D, Harris NL, Lister K, et al. 2020. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585:545–50
131. Holl KD, Brancalion PHS. 2020. Tree planting is not a simple solution. *Science* 368:580–81
132. Busch J, Engelmann J, Cook-Patton SC, Griscom BW, Kroeger T, et al. 2019. Potential for low-cost carbon dioxide removal through tropical reforestation. *Nat. Clim. Change* 9:463–66
133. Luyssaert S, Schulze ED, Börner A, Knohl A, Hessenmöller D, et al. 2008. Old-growth forests as global carbon sinks. *Nature* 455:213–15
134. Zeng J, Matsunaga T, Tan ZH, Saigusa N, Shirai T, et al. 2020. Global terrestrial carbon fluxes of 1999–2019 estimated by upscaling eddy covariance data with a random forest. *Sci. Data* 7:313
135. Howard J, Sutton-Grier A, Herr D, Kleypas J, Landis E, et al. 2017. Clarifying the role of coastal and marine systems in climate mitigation. *Front. Ecol. Environ.* 15:42–50
136. Solan M, Archambault P, Renaud PE, März C. 2020. The changing Arctic Ocean: consequences for biological communities, biogeochemical processes and ecosystem functioning. *Philos. Trans. R. Soc. A* 378:20200266
137. Rifai SW, Li S, Malhi Y. 2019. Coupling of El Niño events and long-term warming leads to pervasive climate extremes in the terrestrial tropics. *Environ. Res. Lett.* 14:105002
138. Fankhauser S, Smith SM, Allen M, Axelsson K, Hale T, et al. 2022. The meaning of net zero and how to get it right. *Nat. Clim. Change* 12:15–21
139. Allen MR, Axelsson K, Caldecott B, Hale T, Hepburn C, et al. 2020. *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Rep., Univ. Oxford, UK. **https://www.smithschool.ox.ac.uk/sites/default/files/2022-01/Oxford-Offsetting-Principles-2020.pdf**
140. Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, et al. 2019. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. *Annu. Rev. Environ. Resour.* 44:255–86
141. IPBES (Intergov. Sci.-Policy Platform Biodivers. Ecosyst. Serv.). 2019. *The Global Assessment Report on Biodiversity and Ecosystem Services: Summary for Policymakers*. Bonn, Ger.: IPBES. **https://ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf**
142. Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, et al. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B* 375:20190120
143. Maes J, Zulian G, Guenther S, Thijssen M, Raynal J. 2019. *Enhancing Resilience of Urban Ecosystems through Green Infrastructure (EnRoute): final report*. Tech. Rep., EUR 29630 EN, Publ. Off. Eur. Union, Luxembourg
144. Chausson A, Turner B, Seddon D, Chabaneix N, Girardin CAJ, et al. 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. *Glob. Change Biol.* 26:6134–55

145. Fuglestvedt J, Rogelj J, Millar RJ, Allen M, Boucher O, et al. 2018. Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philos. Trans. R. Soc. A* 376:20160445

146. Etminan M, Myhre G, Highwood EJ, Shine KP. 2016. Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. *Geophys. Res. Lett.* 43:12614–23

147. Jenkins S, Millar RJ, Leach N, Allen MR. 2018. Framing climate goals in terms of cumulative CO_2-forcing-equivalent emissions. *Geophys. Res. Lett.* 45:2795–804

148. Allen MR, Shine KP, Fuglestvedt JS, Millar RJ, Cain M, et al. 2018. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Clim. Atmos. Sci.* 1:16

149. Collins WJ, Frame DJ, Fuglestvedt JS, Shine KP. 2020. Stable climate metrics for emissions of short and long-lived species—combining steps and pulses. *Environ. Res. Lett.* 15:024018

150. Matthews HD, Zickfeld K. 2012. Climate response to zeroed emissions of greenhouse gases and aerosols. *Nat. Clim. Change* 2:338–341

151. Daniel JS, Solomon S, Sanford TJ, McFarland M, Fuglestvedt JS, Friedlingstein P. 2012. Limitations of single-basket trading: lessons from the Montreal Protocol for climate policy. *Clim. Change* 111:241–48

152. Forster PM, Storelvmo T, Armour K, Collins W, Dufresne JL, et al. 2021. The Earth's energy budget, climate feedbacks, and climate sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. V Masson-Delmotte, P Zhai, A Pirani, SL Connors, C Péan, et al., pp. 923–1054. Cambridge, UK: Cambridge Univ. Press

153. IPCC (Intergov. Panel Clim. Change). 2022. Summary for policymakers. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J Skea, PR Shukla, A Reisinger, R Slade, M Pathak, et al. Cambridge, UK: Cambridge Univ. Press

154. Tanaka K, O'Neill BC. 2018. The Paris Agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. *Nat. Clim. Change* 8:319–24

155. Schleussner C-F, Nauels A, Schaeffer M, Hare W, Rogelj J. 2019. Inconsistencies when applying novel metrics for emissions accounting to the Paris Agreement. *Environ. Res. Lett.* 14:124055

156. Jackson RB, Solomon EI, Canadell JG, Cargnello M, Field CB. 2019. Methane removal and atmospheric restoration. *Nat. Sustain.* 2:436–38

157. Allen M, Tanaka K, Macey A, Cain M, Jenkins S, et al. 2021. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. *Environ. Res. Lett.* 16:074009

158. Allen MR, Fuglestvedt JS, Shine KP, Reisinger A, Pierrehumbert RT, Forster PM. 2016. New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Change* 6:773–76

159. Rajamani L, Werksman J. 2018. The legal character and operational relevance of the Paris Agreement's temperature goal. *Philos. Trans. R. Soc. A* 376:20160458

160. UNFCCC (U. N. Framew. Conv. Clim. Change). 2021. Decision/CMA.3 Glasgow Climate Pact, Nov. 13. **https://unfccc.int/sites/default/files/resource/cma3_auv_2_cover%20decision.pdf**

161. Schleussner CF, Rogelj J, Schaeffer M, Lissner T, Licker R, et al. 2016. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change* 6:827–35

162. Mace MJ. 2016. Mitigation commitments under the Paris Agreement and the way forward. *Clim. Law* 6:21–39

163. Lang J. 2021. Net zero: the scorecard - ECIU. *Energy & Climate Intelligence Unit*. **https://eciu.net/analysis/briefings/net-zero/net-zero-the-scorecard**

164. UNFCCC (U. N. Framew. Conv. Clim. Change). 2021. *Nationally determined contributions under the Paris Agreement*. Rep. Bonn, Ger. UNFCCC. **https://unfccc.int/sites/default/files/resource/cma2021_08r01_E.pdf**

165. Grassi G, House J, Kurz WA, Cescatti A, Houghton RA, et al. 2018. Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nat. Clim. Change* 8:914–20

166. Grassi G, Stehfest E, Rogelj J, van Vuuren D, Cescatti A, et al. 2021. Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nat. Clim. Change* 11:425–34

167. Higgins G. 2021. PAS 2060:2014 – specification for the demonstration of carbon neutrality. *Antaris Blog*, Aug. 3. **https://antarisconsulting.com/pas-20602014-specification-for-the-demonstration-of-carbon-neutrality/**

168. Matthews HS, Hendrickson CT, Weber CL. 2008. The importance of carbon footprint estimation boundaries. *Environ. Sci. Technol.* 42:5839–42

169. Pike H, Khan F, Amyotte P. 2020. Precautionary principle (PP) versus as low as reasonably practicable (ALARP): which one to use and when. *Process Saf. Environ. Prot.* 137:158–68

170. Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, et al. 2018. Net-zero emissions energy systems. *Science* 360:eaas9793

171. SBTi (Science Based Targets initiative). 2021. *SBTi Corporate Net-Zero Standard*. **https://sciencebasedtargets.org/resources/files/Net-Zero-Standard.pdf**

172. Mitchell-Larson E, Bushman T. 2021. *Carbon Direct Commentary: Release of the Voluntary Registry Offsets Database*. **https://carbon-direct.com/wp-content/uploads/2021/04/CD-Commentary-on-Voluntary-Registry-Offsets-Database_April-2021.pdf**

173. Warnecke C, Schneider L, Day T, La Hoz Theuer S, Fearnehough H. 2019. Robust eligibility criteria essential for new global scheme to offset aviation emissions. *Nat. Clim. Change* 9:218–21

174. Haya B, Cullenward D, Strong AL, Grubert E, Heilmayr R, et al. 2020. Managing uncertainty in carbon offsets: insights from California's standardized approach. *Clim. Policy* 20:1112–26

175. Cames M, Harthan RO, Füssler J, Lazarus M, Lee CM, et al. 2016. *How additional is the Clean Development Mechanism?* Rep., Oeko-Institut e.V., Freiburg, Ger. 173 pp. **https://ec.europa.eu/clima/system/files/2017-04/clean_dev_mechanism_en.pdf**

176. Shankleman J, Rathi A. 2021. Mark Carney walks back Brookfield net-zero claim after criticism. *Bloomberg.com*, Feb. 25. **https://www.bloomberg.com/news/articles/2021-02-25/mark-carney-s-brookfield-net-zero-claim-confounds-climate-experts**

177. Donofrio S, Maguire P, Myers K, Daley C, Lin K. 2021. *State of the Voluntary Carbon Markets 2021. Installment 1: Market in Motion*. Forests Trends Association, Washington, DC, Sep. 15. **https://www.forest-trends.org/publications/state-of-the-voluntary-carbon-markets-2021/**

178. UNFCCC (U. N. Framew. Conv. Clim. Change). 2021. *Race to Zero Lexicon*. Bonn, Ger., UNFCCC. **https://racetozero.unfccc.int/wp-content/uploads/2021/04/Race-to-Zero-Lexicon.pdf**

179. Joppa L. 2020. Progress on our goal to be carbon negative by 2030. *Microsoft on the Issues Blog*, Jul 21. **https://blogs.microsoft.com/on-the-issues/2020/07/21/carbon-negative-transform-to-net-zero/**

180. Broekhoff D. 2021. For corporate net-zero targets, focus on the big picture. *SEI*, Nov. 5. **https://www.sei.org/perspectives/corporate-net-zero-targets/**

181. VCMII (Volunt. Carbon Mark. Integr. Initiat.). 2021. *VCM related claims categorization, utilization, & transparency criteria*. Work. Pap., VCMII. **https://vcmintegrity.org/wp-content/uploads/2021/07/Criteria-for-Voluntary-Carbon-Markets-Related-Claims.pdf**

182. Raupach MR, Canadell JG, Ciais P, Friedlingstein P, Rayner PJ, Trudinger CM. 2011. The relationship between peak warming and cumulative CO_2 emissions, and its use to quantify vulnerabilities in the carbon–climate–human system. *Tellus B Chem. Phys. Meteorol.* 63:145–64

Annual Review of Environment and Resources

Volume 47, 2022

Contents

I. Integrative Themes and Emerging Concerns

II. Earth's Life Support Systems

III. Human Use of the Environment and Resources

IV. Management and Governance of Resources and Environment

V. Methods and Indicators

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://www.annualreviews.org/errata/environ