A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation

Article

Published Version

Open Access

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.
Published version at: http://dx.doi.org/10.1038/s41612-018-0026-8
To link to this article DOI: http://dx.doi.org/10.1038/s41612-018-0026-8

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

ARTICLE   OPEN

A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation

Myles R. Allen[1,2], Keith P. Shine [3], Jan S. Fuglestvedt[4], Richard J. Millar[1], Michelle Cain [1,5], David J. Frame[6] and Adrian H. Macey[7]

While cumulative carbon dioxide (CO_2) emissions dominate anthropogenic warming over centuries, temperatures over the coming decades are also strongly affected by short-lived climate pollutants (SLCPs), complicating the estimation of cumulative emission budgets for ambitious mitigation goals. Using conventional Global Warming Potentials (GWPs) to convert SLCPs to "CO_2-equivalent" emissions misrepresents their impact on global temperature. Here we show that peak warming under a range of mitigation scenarios is determined by a linear combination of cumulative CO_2 emissions to the time of peak warming and non-CO_2 radiative forcing immediately prior to that time. This may be understood by expressing aggregate non-CO_2 forcing as cumulative CO_2 forcing-equivalent (CO_2-fe) emissions. We show further that contributions to CO_2-fe emissions are well approximated by a new usage of GWP, denoted GWP*, which relates cumulative CO_2 emissions to date with the current rate of emission of SLCPs. GWP* accurately indicates the impact of emissions of both long-lived and short-lived pollutants on radiative forcing and temperatures over a wide range of timescales, including under ambitious mitigation when conventional GWPs fail. Measured by GWP*, implementing the Paris Agreement would reduce the expected rate of warming in 2030 by 28% relative to a No Policy scenario. Expressing mitigation efforts in terms of their impact on future cumulative emissions aggregated using GWP* would relate them directly to contributions to future warming, better informing both burden-sharing discussions and long-term policies and measures in pursuit of ambitious global temperature goals.

INTRODUCTION

The Paris Agreement introduced a regular (5-yearly) "stocktake" of collective progress towards achieving its long-term temperature goals, but the metrics of progress to be used in these stocktakes remain under discussion.[1–9] Relating emissions to future temperatures remains ambiguous as long as contributions are expressed, as in the majority of "Nationally Determined Contributions" (NDCs), in terms of CO_2-equivalent (CO_2-e) emission rates in a specific year defined using a metric such as the 100-year Global Warming Potential (GWP_{100}). Figure 1a shows peak warming in scenarios[10] considered by Working Group 3 of the IPCC 5th Assessment Report (AR5—colors represent scenarios categorized by 2100 CO_2-equivalent radiative forcing,[11] under the median climate response of the MAGICC simple climate model,[12] plotted against 2030 CO_2-e emissions conventionally calculated using AR5 GWP_{100} values. The two variables are positively correlated, but peak warming also depends on scenario-dependent assumptions about emissions after 2030. Most of these scenarios extrapolate the implications of short-term commitments using some notion of "sustained ambition", interpreted in a number of ways, including[13] an effective global carbon price increasing at a constant exponential rate over the 21st century. Despite having some

idealized economic justification, this may not coincide with many non-specialists' expectations of "sustained effort". Hence the conventional approach to assessing whether a medium-term emissions trajectory is consistent with a long-term temperature goal, simply by comparing it with a set of available scenarios, is opaque at best, and at worst misleading. Moreover, the correlation in Fig. 1a is weakest within the most ambitious (light blue) scenario family, reflecting the greater fractional contributions of non-CO_2 forcing agents to peak warming in scenarios with the lowest cumulative stock of CO_2 emissions.

The relationship between cumulative CO_2 emissions and CO_2-induced warming provides a simple, scenario-independent, approach to assessing the implications of future CO_2 emissions, but the concept of an "emissions budget" cannot be extended to CO_2-e emissions as conventionally calculated. Figure 1b shows trajectories of future warming plotted against cumulative CO_2-e emissions based on GWP_{100}. The correlation is stronger than in Fig. 1a, but breaks down as scenarios approach peak warming; the four most ambitious 430–480 ppm scenarios show almost 1000 $GtCO_2$-e emitted after temperatures have largely stabilised. These figures show that cumulative CO_2-e emissions calculated using GWP_{100} are a poor indicator of peak warming, and CO_2-e emission rates are a poor indicator of temperature stabilisation.

[1]Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK; [2]Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK; [3]Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK; [4]Center for International Climate and Environmental Research (CICERO), PO Box 1129 Blindern, 0318 Oslo, Norway; [5]Oxford Martin School, University of Oxford, 34 Broad Street, Oxford OX1 3BD, UK; [6]New Zealand Climate Change Research Institute, Victoria University of Wellington, PO Box 600, Wellington, New Zealand and [7]Institute for Governance and Policy Studies, Victoria University of Wellington, PO Box 600, Wellington, New Zealand
Correspondence: Myles R. Allen (myles.allen@ouce.ox.ac.uk)

npj

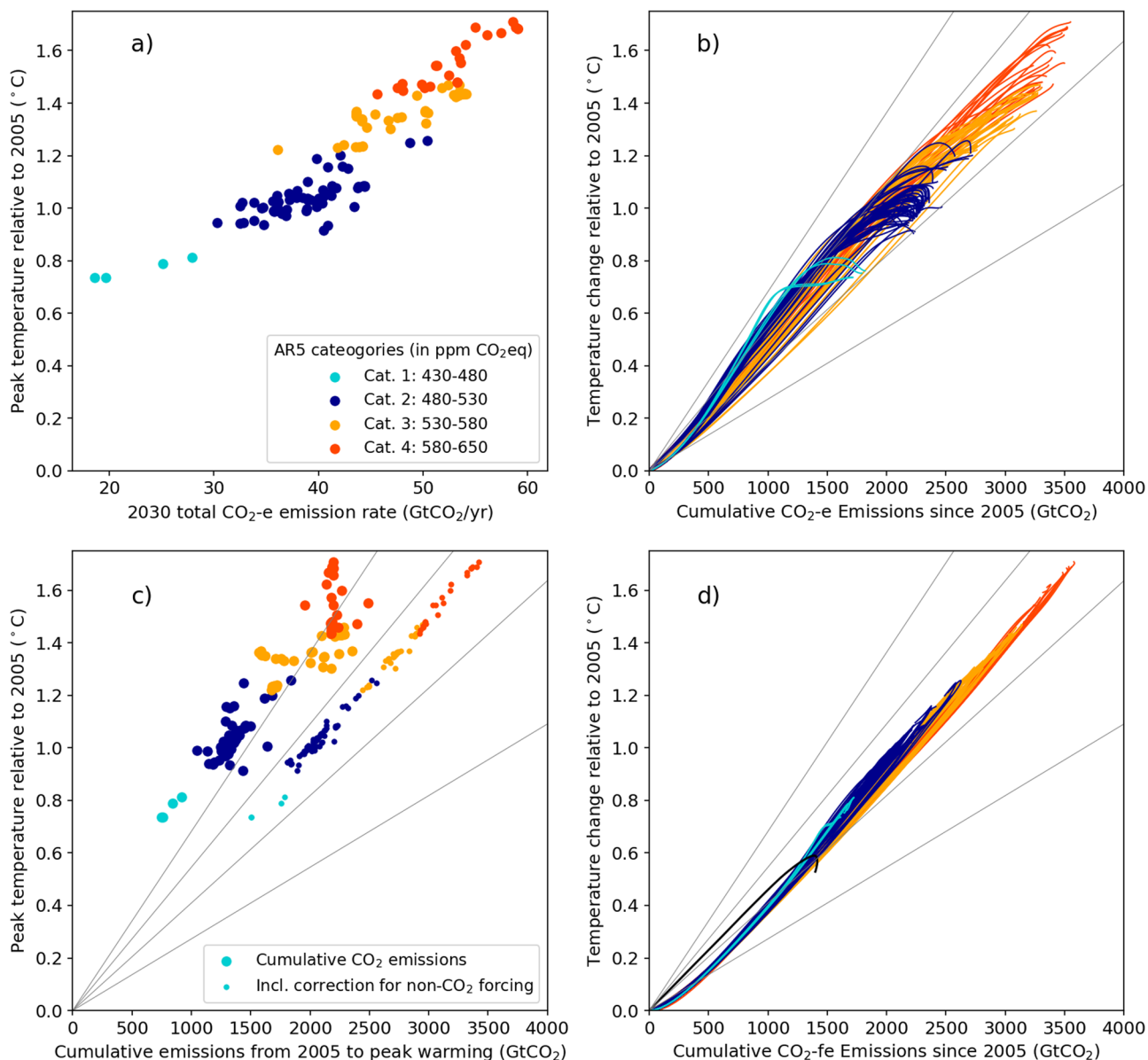A solution to the misrepresentations of CO₂-equivalent
MR Allen et al.

2

Fig. 1 Temperature change for the median climate response[12] to a subset of the IPCC AR5 scenario database plotted against **a** total CO_2-equivalent emissions in 2030 computed using GWP_{100}; **b** cumulative CO_2-e emissions; **c** cumulative CO_2 emissions to the time of peak warming excluding (large dots) and including (small dots) an empirical correction for non-CO_2 forcing and **d** cumulative CO_2-forcing-equivalent emissions. Gray lines in **b**–**d** show TCRE values of 1, 1.5, 2 and 2.5 °C/TtC. Black line in d shows warming as a function of cumulative CO_2 emissions in a simulation forced[11] with CO_2 emissions only from the RCP2.6 scenario. **a**, **c** show peak warming while **b** and **d** show temperature evolution, both relative to 2005, in each scenario

This paper explores an alternative approach to quantifying the contribution of non-CO_2 emissions to future temperatures, focussing on the kind of ambitious mitigation scenario that will be required if the goals of the Paris Agreement are to be met. It will also show how such an approach can be used to quantify the contribution of individual regions to future temperature change.

Context: alternatives to conventional CO_2-equivalent emissions

The concept of CO_2-e emissions is deeply embedded in climate policy[14] despite long-standing criticisms[15] of its application to SLCPs when constructed using GWP_{100}. Ambiguity arises because emissions of cumulative pollutants and SLCPs translate into impact on the planetary energy budget in fundamentally different ways: for cumulative pollutants like CO_2, radiative forcing largely

scales with the total stock (cumulative integral) of emissions to date, while for SLCPs like methane, it scales with the current flow (emission rate) multiplied by the SLCP lifetime.[4,5,16,17] The differing climate impacts of CO_2 and SLCP emissions become particularly problematic under ambitious mitigation. Falling SLCP emissions lead to falling global temperatures, while nominally "equivalent" CO_2 emissions, whether computed using GWP, global temperature-change potential (GTP),[4,14] or any other conventional metric, would incorrectly suggest that these falling emissions would cause further warming. As well as being misleading, using GWP to calculate CO_2-equivalent emissions has practical consequences: if "balance" is defined as net zero CO_2-e emissions, balanced emissions result not in temperature stabilisation, but an indefinite cooling trend, with the rate of cooling determined by on-going emissions of SLCPs.[18]

A solution to the misrepresentations of CO$_2$-equivalent
MR Allen et al.

npj

3

Figure 1c shows a more physically-based approach. Large dots show peak warming plotted against cumulative CO$_2$ emissions to the time of peak warming: there is a positive relationship, but with a large residual spread (0.13 °C standard deviation, or s.d., about the best-fit line). Small dots show that almost all of this spread can be accounted for by differences in non-CO$_2$ forcing between the different scenarios. They show peak warming plotted against a linear combination of cumulative CO$_2$ emissions to the time of peak warming and average non-CO$_2$ forcing over the 20 years prior to the time of peak warming (so assuming temperatures at the time of peak warming have adjusted to this forcing), with an empirically-estimated conversion factor of 1274 GtCO$_2$/(W/m^2). This leaves only a small unexplained residual (s.d. of 0.021 °C) across these scenarios. By contrast, if cumulative CO$_2$-e emissions computed using conventional GWPs are used to predict peak warming, as in Fig. 1b, the residual is significantly larger (s.d. of 0.052 °C). Hence cumulative emission budgets can be a useful and accurate tool for predicting peak warming under ambitious mitigation, but only if non-CO$_2$ forcings are accurately accounted for.

Genuinely equivalent emission pathways (in terms of their impact on global temperatures over the full range of timescales) can be derived by expressing a radiative forcing pathway as a CO$_2$-equivalent concentration pathway and then diagnosing the CO$_2$ forcing-equivalent (CO$_2$-fe) emissions[19] that would yield that concentration pathway using a carbon cycle model[20] (see Methods). By construction, these CO$_2$-fe emissions give the same radiative forcing pathway and hence temperature response[21] as the corresponding forcing agent(s) from which they are computed.[22] In Fig. 1d we observe the same linear, scenario-independent relationship between total human-induced warming and total cumulative CO$_2$-fe emissions (computed from all anthropogenic climate forcing agents, including aerosols) as is observed between CO$_2$-induced warming and cumulative CO$_2$ emissions in this version of the MAGICC model driven with the RCP2.6 scenario (black line). For reference, the gray lines in Fig. 1b–d show isolines of Transient Climate Response to Emissions, or TCRE: this model displays a TCRE of 1.69 °C/TtC for the 1000 GtCO$_2$ emitted after 2005, in approximate agreement with the slope of 1.83 °C/TtC for the small dots in Fig. 1c. Remaining discrepancies likely result from different temperature responses to different forcings in the MAGICC model (only total forcings, not effective radiative forcings,[14] are available for these scenarios, although a simple correction is applied to account for aerosol efficacy, see Methods) and the transition from concentrations-driven to emissions-driven integration after 2005.[23] Figure 1d shows that, in multi-gas scenarios, temperatures stabilise when and only when the annual net rate of total anthropogenic CO$_2$-fe emissions reaches zero, which is not the case for either CO$_2$ emissions alone or CO$_2$-e emissions computed using GWP.

CO$_2$-fe emissions depend on knowledge of the full scenario history and must be computed using a carbon cycle model, and so would be difficult to use directly as an emission metric. However, because they provide climatically equivalent emissions by construction, they represent a standard against which other emission metrics can be judged. Reference[3] showed that a new usage of the conventional GWP approximates the relative impact of both cumulative pollutants and SLCPs on global temperatures under some idealized scenarios. This usage, which we denote GWP*, considers a sustained one-tonne-per-year increase in the emission rate of an SLCP (as introduced by refs.[4,5]) to be equivalent (in terms of temperature impact) to a one-off pulse emission of GWP$_H$ × H tonnes of CO$_2$ (denoted CO$_2$-e*), where GWP$_H$ is the value of that SLCP's GWP for a time-horizon H. Here we add the additional refinement that the pulse emission is spread over 20 years following the increase in the SLCP emission rate: this reduces the volatility of CO$_2$-e* emissions in response to variations in SLCP emission rates, and better reflects the

temperature impact of SLCPs. For pollutants with lifetimes longer than H, like nitrous oxide (N$_2$O), GWP-based CO$_2$-e and CO$_2$-e* are identical.

CO$_2$-e* emissions can also be calculated directly from radiative forcing, which is useful for species such as aerosols for which trends in radiative forcing are better characterized than either emissions or lifetimes: a permanent unit increase in radiative forcing can be considered equivalent to an emission of H/AGWP$_{H-(CO_2)}$ tonnes of CO$_2$ distributed over the 20 years following the forcing increase, where AGWP$_{H(CO_2)}$ is the Absolute Global Warming Potential[4] of CO$_2$ over time-horizon H appropriate to these scenarios (see Methods). Hence we expect peak warming relative to the present to be given by

$$\Delta T_{\text{peak}} \approx \text{TCRE} \times \left(G_{\text{CO2}} + \Delta F_{\text{non-CO2}} \times \left(H/\text{AGWP}_{H(\text{CO}_2)} \right) \right) + \text{Constant},$$

where G_{CO2} is cumulative CO$_2$ emissions from now to the time of peak warming and $\Delta F_{\text{non-CO2}}$ the change in non-CO$_2$ forcing between 20 years prior to the present and 20 years prior to the time of peak warming. The small constant term (only -0.02 °C in this set of scenarios) reflects any systematic response to forcing outside this period. Thus, the empirical correction represented by the difference between the small and large dots in Fig. 1c is, in effect, an estimate of the factor $H/\text{AGWP}_{H(\text{CO}_2)}$, which is model-dependent and scenario-dependent.[24] Injection of CO$_2$ into this version of the MAGICC model (see Methods) indicates a value of 1216 GtCO$_2$/(W/m^2), in good agreement with the empirical estimate. AGWP$_{100}$ values from AR5 indicate[14] a central value of 1091 GtCO$_2$/(W/m^2), with a range of 866–1474 GtCO$_2$/(W/m^2) reflecting a variety of carbon cycle models, encompassing other recent estimates.[25]

RESULTS

Using GWP* in the analysis of ambitious mitigation scenarios

The advantages of GWP* over GWP under ambitious mitigation are even more apparent when we consider individual contributions to warming. Figure 2 shows historical emissions[9,14] and projected changes from 2015 following an ambitious mitigation scenario[23] (RCP2.6) expressed as CO$_2$-e (top) and CO$_2$-e* (bottom). Left panels show annual emission rates, and right panels show cumulative (integrated) emissions. CO$_2$-e and CO$_2$-e* emissions of CO$_2$ and N$_2$O are identical, but annual CO$_2$-e* methane emissions (Fig. 2c) track the rate of change of methane emissions, unlike CO$_2$-e (Fig. 2a), which track methane emissions themselves. Hence methane CO$_2$-e* emissions rose rapidly in the 1950s and fell over the 1990s as the rate of increase in methane emissions stalled. They have since recovered but are projected to soon become negative (falling actual methane emissions) under RCP2.6. CO$_2$-e* emissions of other SLCPs (primarily aerosols, but also including the impact of tropospheric ozone) follow an opposite path, but change sign earlier. Radiative forcing due to aerosols and ozone is estimated to have been almost constant over the past 20 years (giving near-zero current CO$_2$-e* emissions of SLCPs other than methane), while methane emissions have risen: hence the current decade is experiencing a uniquely high positive contribution to total CO$_2$-e* emissions (the difference between the orange and black lines in Fig. 2c from the combined effects of recent methane, aerosol and ozone trends.

The greater "environmental integrity" of the GWP* metric (meaning, in the UNFCCC context,[26] its fitness-for-purpose as a metric of progress towards a global-temperature-related climate goal) is evident comparing cumulative CO$_2$-e and CO$_2$-e* emissions in Fig. 2b, d with global temperature responses (dashed lines and right axes) and CO$_2$-fe emissions (thin lines in 2d), both diagnosed from the associated radiative forcing timeseries.[23] Cumulative CO$_2$-e* emissions closely track both cumulative CO$_2$-fe emissions and resulting temperature changes (Fig. 2d), while
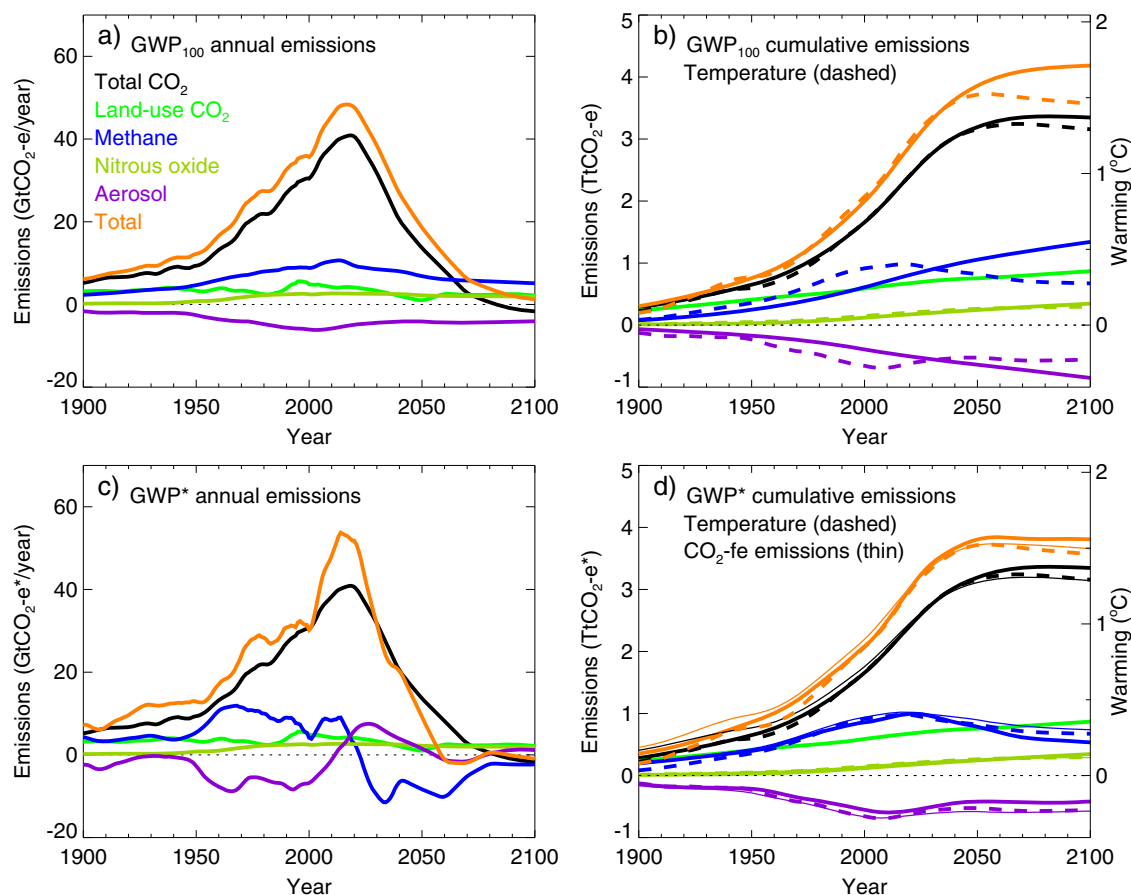
npj

A solution to the misrepresentations of CO2-equivalent
MR Allen et al.

4

Fig. 2 Annual **a**, **c** and cumulative **b**, **d** CO₂-e and CO₂-e* emissions under the GWP₁₀₀ **a**, **b** and GWP* **c**, **d** metrics using historical emissions to 2015 extended with the RCP2.6 scenario. Dashed lines show global mean surface temperature (GMST) response to radiative forcings associated with these emissions (not available separately for land-use CO₂). Colors indicate gases following the legend in **a**, with "Aerosol" also including ozone and other minor constituents. Thin solid lines in **d** show cumulative CO₂-forcing-equivalent emissions closely tracking GMST response

GWP₁₀₀-based CO₂-e performs poorly for SLCPs, particularly when emissions are falling (Fig. 2b—see especially the divergence between the orange dashed and solid lines after 2050, and between blue and purple dashed and solid lines from 2000 onwards). Adopting another conventional time-invariant metric such as GWP₂₀ or a GTP would simply scale up or scale down the methane and aerosol CO₂-e emissions in Fig. 2b, making no difference to their poor temporal correspondence with CO₂-fe emissions or temperature responses. Even a time-dependent GTP[17] would still equate a falling rate of emission of an SLCP with a continued positive emission of CO₂.

It is important to note that, despite corresponding to zero CO₂-e*, a constant on-going high level of SLCP emissions may still represent an important contribution to warming to date and/or a mitigation opportunity. Negative CO₂-e* emissions become possible through reducing SLCP emission rates: a policy intervention that permanently reduces an SLCP emission rate corresponds, in terms of its impact on future temperatures, to active removal of a given amount of CO₂. Active CO₂ removal may become increasingly important under ambitious mitigation, making it all the more important for metrics to relate it realistically to other measures.

Since cumulative CO₂-e* emissions based on GWP* provide a relatively unambiguous indication of future warming, CO₂-e* emission rates indicate future warming rates. This makes it clear what the commitments made in the Paris Agreement actually promise: they directly determine the rate of human-induced warming in 2030 due to gases covered by the agreement.

Assuming nationally determined contribution (NDC) goals are met, and using the breakdown of emissions provided by ref.[8] (many countries do not specify this in their NDCs), combined CO₂, methane and nitrous oxide emissions in 2030 are 28% lower than in a "Reference-No Policy" scenario if measured by GWP*. Because of the unambiguous relationship between CO₂-e* emissions and future temperatures, this equates to a 28% reduction in the rate of warming caused by these gases in 2030; the same NDCs correspond to an 18% reduction in CO₂-e emission based on GWP₁₀₀, but there is no unambiguous way of relating this to future temperatures.

Using GWP* to quantify regional contributions to global temperature change

In addition to assessing the implications of future policies, emission metrics can also be used to assess countries' or regions' contributions to changes in global average temperature. Figure 3 shows emissions from different regions (defined in the ref.[9]) either in 2010–2014 (left panels), or from 1870 to 2012 (right panels), computed using the metrics from the corresponding panels of Fig. 2, all plotted against the model-estimated contribution to warming to date relative to pre-industrial (or, in Fig. 3c, current warming rate), which we simulate (see Methods) using emissions from that region alone, setting emissions in all other regions to zero. The solid diagonal line in each panel shows the ratio of global temperature rise (or warming rate in Fig. 3c) to aggregate global emissions under each metric: in the absence of
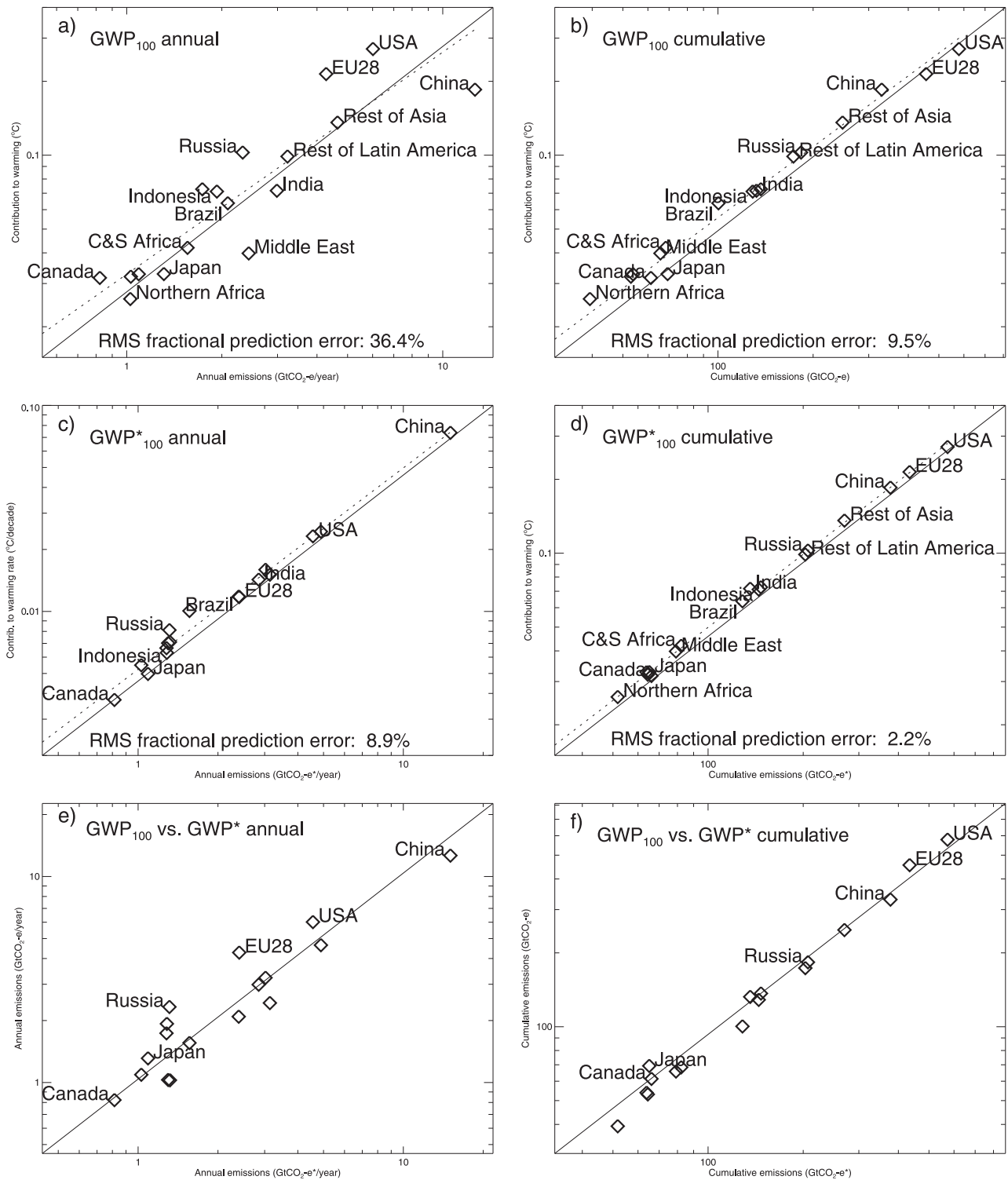
A solution to the misrepresentations of CO_2-equivalent
MR Allen et al.

np|

5

Fig. 3 Annual (left: 2010-2014 average) and cumulative (right: from 1751 to 2012) CO_2-equivalent emissions under the GWP and GWP* metrics for selected regions, compared with the contributions of emissions from these regions to global temperature rise to 2012 (**a**, **b**, and **d**) and the rate of global temperature rise 2010–2014 (**c**) estimated using a simple climate model; see Methods. Solid diagonal lines show ratio of total global temperature rise (or rate of rise in **c**) to total global emissions under the metric shown. Dotted lines show best-fit regression lines under a logarithmic fit, with residuals about these lines given as root-mean-square fractional prediction errors. **e**, **f** Compare annual rates of emissions and cumulative emissions, respectively, under the two different metrics

non-linearity, with a single greenhouse gas and identical time-histories of emissions in all regions, all points would lie on this line. How close points are to a straight line is an indication of the accuracy of different greenhouse gas metrics as indicators of

warming given diverse regional emissions time-histories and the mix of CO_2 and SLCPs emitted.

Annual GWP$_{100}$-based emissions (Fig. 3a) are a relatively poor indicator of regional contributions to warming, although often

npj

A solution to the misrepresentations of CO_2-equivalent
MR Allen et al.

6

used in discussions of burden sharing: the root-mean-square fractional prediction error (FPE—see Methods) is over 36%. Cumulative GWP_{100}-based emissions (Fig. 3b) perform better, largely because many regions' historical emissions are dominated by CO_2, but the FPE is still over 9%. Cumulative emissions based on GWP* Fig. 3d) provide a very accurate indication of relative contributions to warming, with an FPE of only 2%. While Fig. 3b, d provide a like-for-like comparison, Figure 3c shows, for comparison, that annual emission rates computed using GWP* also provide a reasonably accurate prediction of contributions to current warming rates (FPE of 9%, but of a much noisier quantity): if computed using GWP (not shown, but visually similar to Fig. 3a) the FPE in warming rates increases to over 30%. GWP could even predict contributions to warming rates of the wrong sign under falling SLCP emissions: hence problems with the use of GWP to compare regions' contributions will intensify as more regions undertake ambitious SLCP mitigation. Figure 3e, f show regions' annual and cumulative emissions calculated with GWP_{100} and GWP* plotted against each other, with diagonal lines showing corresponding ratios of global emissions. Regions above the line in 3e would show a nominal fall in their annual emissions (relative to the global total) if recalculated using GWP* rather than GWP_{100}. These are typically regions with high but falling SLCP emissions over the 20 years preceding 2012. Agreement between cumulative emissions under the two metrics is much better, reflecting the fact that these are dominated by CO_2 in many regions.

Parties to the UNFCCC have considerable latitude in how they arrive at their NDCs, but given that the long-term goals of the Paris Agreement are expressed in terms of global temperature, a more consistent alignment of NDCs with the long-term temperature goal might clarify their implications in any stocktake mechanism. A region's contribution to total future warming by any given date is simply its total cumulative CO_2-e* emissions, computed with GWP*, between now and that time, multiplied by the TCRE.[27,28] Hence GWP* provides a way of applying the TCRE, a useful summary metric of climate response and the uncertainties therein, also to gases other than CO_2.

DISCUSSION

The importance of cumulative CO_2 emissions has long been recognised,[15,17,19,25,29] but climate policy has continued to focus on CO_2-e emission rates because cumulative budgets have been thought to apply only to CO_2. Relating emissions using GWP* allows all emissions to be considered in a common cumulative framework. CO_2-e* emissions closely approximate CO_2-fe emissions, which behave (by construction) exactly like CO_2. Formulating NDCs and, perhaps even more important, "mid-century, long-term low greenhouse gas emission development strategies",[25] in terms of cumulative CO_2-e* emissions would provide a more accurate indication of progress towards climate stabilisation.[30] While shorter-term goals for emission rates of individual gases and broader metrics encompassing emissions' co-impacts[2,6,31] remain potentially useful in defining how cumulative contributions will be achieved, summarising commitments using a metric that accurately reflects their contributions to future warming would provide greater transparency in the implications of global climate agreements as well as enabling fairer and more effective design of domestic policies and measures. Policies drawing on GWP* could thus be a useful step towards reducing ambiguity in outcomes and ultimately implementing mitigation strategies for meeting the global goals of the Paris Agreement.

METHODS

Methods and sources used in constructing Figs. 1, 2 and 3

Emissions and temperature responses in Fig. 1 are drawn directly from the IPCC AR5 scenarios provided on the IIASA database.[10,13,32] The calculations

for CO_2-e and CO_2-e* emissions use GWP_{100} values of 28 (39% uncertainty) for CH_4, 265 (29% uncertainty) for N_2O, and 9.17×10^{-14} W m^{-2} year kg^{-1} (26% uncertainty) for $AGWP_{100}(CO_2)$, taken from ref.[14] Small dots in Fig. 1c show peak warming plotted against cumulative CO_2 emissions empirically adjusted using the term in parenthesis in the model

$$\Delta T \approx a_1 \times (G_{CO2} + a_2 \times \Delta F_{non-CO2} + a_0)$$

with the parameters a_i estimated using an ordinary least-squares fit. The change in non-CO_2 radiative forcing ($\Delta F_{non-CO2}$) was calculated using radiative forcings from the IIASA database, with 1986–2005 forcing from the RCP8.5 historical forcing. Since only total forcings are available in the IIASA database, non-Kyoto-gas anthropogenic forcing is multiplied by a time-invariant scaling factor of 1.4 such that ensemble average scenario forcing reproduces observed[14] aerosol ERF in the first year of the scenarios, 2005.

Emissions in Fig. 2 use historical data[9] to 2015, extended with diagnosed emissions[23] for the RCP2.6 scenario scaled to match the historical series in 2015. Aerosol and other forcing uses the RCP2.6 series scaled to reproduce the estimate of total anthropogenic forcing in 2011 given in ref.[14] Annual emissions and forcing are smoothed with a 5-year running mean before computing CO_2-e, CO_2-e* and CO_2-fe emissions. Temperatures in Fig. 2 are computed directly from radiative forcing using a 2-time-constant climate response[33] with an equilibrium climate sensitivity of 3 °C and transient climate response of 1.8 °C, matching the median behavior of the CMIP5 ensemble.

The agreement between cumulative CO_2-equivalent methane emissions under GWP* and methane-induced warming in Fig. 1d might be further improved by including a small contribution that scales with time-integrated methane emissions. This could be justified by carbon cycle feedbacks[34,35] and the oxidation of methane (from fossil sources) to CO_2, but a composite metric would require more parameters, and precise agreement would depend on uncertain details of the climate response.

Temperatures in Fig. 3 are computed from regional emissions using a simple carbon cycle climate model that allows for changing airborne fraction in response to cumulative emissions and warming,[24] and single lifetime models and standard formulae[14] for radiative forcing for methane and N_2O. Lifetimes of methane and N_2O in this calculation only are adjusted to ensure global emissions result in observed concentration increase to 2011 (8.3 and 100 years, respectively). For these small warming levels, the impact of non-linearity in the response to CO_2 is small but appreciable: the warming response to global emissions is 8% lower than the total of the warming responses to individual regions' emissions, but the impact on relative contributions is negligible.[9] Best-fit lines (dotted) in Fig. 3 are computed by a linear regression between the logarithms of the quantities plotted, with RMS fractional prediction errors expressed as $100 \times \left(\exp\left(\sqrt{\chi^2/(n-1)}\right) - 1\right)\%$, where χ^2 is the sum of the squared residuals of the logarithmic fit and n is the number of scenarios or regions.

Further details on the derivation of CO_2 equivalent emissions using different metrics

GWP is defined as the Absolute GWP (AGWP) for a given climate forcing agent (the radiative forcing due to a pulse emission of that agent integrated over a time-horizon H) divided by the AGWP of CO_2. Conventional CO_2-e emissions for an SLCP are defined simply as emissions multiplied by the GWP: $E_{CO_2e} = E_{SLCP} \times GWP_H$

Under GWP*, the time-integral of the rate of change of SLCP emissions over any given time period, or equivalently the change in SLCP emission rates between the beginning and end of that period, multiplied by $GWP_H \times H$, gives total CO_2-e* emissions over that period. This contrasts with the conventional use of GWP, under which CO_2-e emissions are given by the time integral of the SLCP emissions themselves, multiplied by GWP_H. Hence the rate of CO_2-e* emissions under GWP* is defined for SLCP emissions by

$$E_{CO_2e*} = \frac{\Delta E_{SLCP}}{\Delta t} \times GWP_H \times H,$$

and for radiative forcing by

$$E_{CO_2e*} = \frac{\Delta F}{\Delta t} \times \frac{H}{AGWP_{H(CO_2)}},$$

where ΔE_{SLCP} and ΔF are the change in SLCP emission rate or forcing over the preceding time-interval Δt (20 years in the examples here), GWP_H is the SLCP GWP and $AGWP_{H(CO_2)}$ is the Absolute GWP (AGWP) for CO_2, both for

A solution to the misrepresentations of CO_2-equivalent
MR Allen et al.

npj

7

time-horizon H. For example, the annual rate of CO_2-e* emissions for an SLCP in 2030 is the difference between the SLCP emission rate in 2030 and that in 2010 multiplied by $GWP_H \times H/20$, while cumulative CO_2-e* emissions to date for a particular SLCP are simply the average SLCP emission rate over the past 20 years multiplied by $GWP_H \times H$. Conversely, a permanent 1 tonne-per-year change in emission rate of an SLCP in 2010 is equated to the emission of $1/(GWP_H \times H)$ tonnes of CO_2-e* spread over the years 2010–2030.

A linear forcing increase of 1 W/m² between the periods 1990-2010 and 2050-2070 equates to a total emission of $H/AGWP_{H(CO_2)}$ tonnes of CO_2-e* following a trapezoidal emission profile, increasing linearly from 2010 to 2030, then constant to 2050 and declining linearly to 2070.[36] Injection of additional CO_2 following this profile into this version of the MAGICC model gives a directly-estimated value for $H/AGWP_{H(CO_2)}$ of 1216 GtCO₂/(W/m²) for the total amount of CO_2 required to increase average radiative forcing over the period 2050–2070 relative to 1990–2010. Modeling discontinuous changes in radiative forcing using CO_2-e* would require infinite emission rates (just as it would require an infinite rate of emission of CO_2 to give a discontinuous change in CO_2-induced forcing).

Hence, under GWP*, a steadily declining rate of emission of an SLCP becomes equivalent to a negative sustained rate of emission of CO_2-e*; likewise, a constant rate of SLCP emission equates to zero CO_2-e*. This mimics the behavior of corresponding temperature responses: declining SLCP emissions reduce temperatures, while constant SLCP emissions cause no further warming. GWP or any other conventional metric treats these SLCP emissions as equivalent to continued positive emissions of CO_2.

In defining CO_2-e and CO_2-e* emissions, we use $H = 100$ years following established practice. Results under GWP* are insensitive to this provided H is much greater than the lifetime of the SLCP because the absolute GWP of an SLCP becomes a constant at these timescales, while the $AGWP_H$ of the reference gas, CO_2, increases linearly with H—see ref. [3] and Fig. 8.29 of ref. [14] Hence the H-dependence cancels out in the calculation of CO_2-e* for both SLCP emissions and radiative forcing. In contrast, GWP-based CO_2-e values for SLCPs scale approximately with $1/H$, making the nominal relative importance of SLCPs and cumulative pollutants acutely sensitive to this choice of time-horizon. For completeness, aerosols and tropospheric ozone are shown as CO_2-e emissions in Fig. 2a by dividing combined aerosol and ozone forcing by the $AGWP_{100}$ of CO_2, although as Fig. 2b demonstrates, this does not correspond to a geophysical quantity.

We use a simple 20-year difference (Δt in the above equations) to define rates of change of SLCP emissions, corresponding to the longest timescale over which emission policies are typically set: using a shorter Δt affects the variance of annual CO_2-e* emission rates, but has no impact on cumulative CO_2-e*. This introduces an average 10-year lag between changes in SLCP emission rates and their associated CO_2-e* emissions, consistent with Fig. 2b of ref. [3] which shows that global temperatures take at least a decade longer to respond to a step-change in SLCP emission rates than to a pulse injection of CO_2[37] because of the short-term response of the carbon cycle.[32]

A further consequence of the linear relationship between $AGWP_{H(CO_2)}$ and H, combined with that between warming ΔT and forcing increase ΔF over a multi-decade time-period,[38] is that the TCRE, or ratio[26,27] of CO_2-induced warming to cumulative CO_2 emissions E, is given by

$$\text{TCRE} = \frac{\Delta T}{E} = \frac{\Delta T}{\Delta F} \times \frac{\Delta F}{E} = \frac{\text{TCR}}{F_{2x}} \times \frac{AGWP_{H(CO_2)}}{H},$$

where TCR is the Transient Climate Response, or the (non-equilibrium) warming at the time forcing reaches F_{2x}, the equivalent of doubling CO_2 concentrations. The $AGWP_{H(CO_2)}$ and F_{2x} values given in ref. [14] corresponding to early 21st-century conditions, imply $\text{TCRE} = 0.9\text{TCR}$ per PgC, consistent with the overall IPCC assessment of TCRE and TCR.[39] Climate models indicate[40] the TCR is expected to increase under high forcing, while $AGWP_{H(CO_2)}$ may decrease[24] due to the logarithmic relationship between forcing and CO_2 concentration, partially compensated for by increasing CO_2 airborne fraction.[41] In the model used here, the $AGWP_{H(CO_2)}$ decline dominates, such that CO_2 emissions rise somewhat faster than CO_2-induced warming after 2050 under a high (RCP8.5) emissions scenario. This decline in the TCRE under high emissions is not reflected in all models[42] and is not relevant to the issue of GHG equivalence under ambitious mitigation.

CO_2-fe emissions are diagnosed from radiative forcing timeseries by converting radiative forcing into CO_2-equivalent concentrations, and then diagnosing the emissions required to give that concentration pathway using a carbon cycle model, in exactly the same way the CO_2 emissions are

routinely diagnosed from CO_2 concentrations.[23] The carbon cycle model used (FAIR)[32] was parameterized using the following values to calculate the 100-year integrated impulse response function, $iRF_{100} = r_0 + r_c C_{acc} + r_T T$; where $r_0 = 33.6$ years; $r_c = 0.0206$ years GtC⁻¹; $r_T = 4.635$ years K^{-1}, C_{acc} is the accumulated perturbation carbon stock in the land and ocean and T is the global mean temperature anomaly relative to the preindustrial period. Parameters were chosen to maximize the agreement between cumulative CO_2 emissions in MAGICC for the AR5 scenarios and those derived by inverting radiative forcing from MAGICC using the FAIR model. Full details of the FAIR model can be found in ref. [32]

Differential radiative forcing efficacies and responses[43] could be taken into account in this definition, although we use AR5 values throughout because only total radiative forcing is available for the MAGICC scenarios. The absolute magnitudes of CO_2-fe emissions are affected by climate and carbon cycle uncertainties, but not their relative magnitudes or evolution over time.[44]

Data availability statement

All emission scenario and forcing datasets are downloaded from their respective websites. The FAIR model used in Figs. 2 and 3 is are available on https://github.com/OMS-NetZero/FAIR. The code and data used to produce Fig. 1 is available on https://gitlab.ouce.ox.ac.uk/OMP_climate_pollutants/gwpstar.git.

AUTHOR CONTRIBUTIONS

M.R.A. conceived and led the study. M.C. and R.J.M. performed the calculations behind Fig. 1; all authors contributed to extensive discussions, analysis, interpretation and writing of the paper.

ADDITIONAL INFORMATION

Competing interests: The authors declare no competing interests.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

1. Rogelj, J. et al. Paris agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534**, 631–639 (2016).
2. Ocko, I. B. et al. Unmask temporal trade-offs in climate policy debates. *Science* **356**, 492–493 (2017).
3. Allen, M. R. et al. A new use of Global Warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Change* **6**, 773–776 (2016).
4. Shine, K., Fuglestvedt, J., Hailemariam, K. & Stuber, N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Change* **68**, 281–302 (2005).
5. Lauder, A. R. et al. Offsetting methane emissions—an alternative to emission equivalence metrics. *Int. J. Greenh. Gas Control* **12**, 419–429 (2013).
6. Shindell, D. et al. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183–189 (2012).
7. Shine, K. P., Berntsen, T. K., Fuglestvedt, J. S., Skeie, R. B. & Stuber, N. Comparing the climatic effects of emissions of short- and long-lived climate agents. *Philos. Trans. R. Soc. A* **365**, 1903–1914 (2007).
8. Fawcett, A. A. et al. Can Paris pledges avert severe climate change? *Science* **350**, 1168–1169 (2015).
9. Skeie, R. B. et al. Perspective has a strong effect on the calculation of historical contributions to global warming. *Environ. Res. Lett.* **12**, 024022 (2017).
10. Clark, L. et al. Assessing transformation pathways. in Edenhofer, O. et al (eds.) *Climate Change 2014: Mitigation of Climate Change, Contribution of IPCC Working Group III to AR5* (eds, Edenhofer, O. et al) (Cambridge University Press, Cambridge, 2014).

np

A solution to the misrepresentations of CO₂-equivalent
MR Allen et al.

8

11. Krey, V. et al. Annex 2—metrics and methodology. in *Climate Change 2014: Mitigation of Climate Change. Contribution of IPCC Working Group III to AR5* (eds, Edenhofer, O. et al) (Cambridge University Press, Cambridge, 2014).

12. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 1: model description and calibration. *Atmos. Chem. Phys.* **11**, 1417–1456 (2011).

13. Kriegler, E. et al. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Social Change* **90A**, 24–44 (2015).

14. Myhre, G. et al. Anthropogenic and natural radiative forcing. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. & Qin, D. et al.) Ch. 8 (Cambridge University Press, Cambridge, 2013).

15. Pierrehumbert, R. T. Short-lived climate pollution. *Ann. Rev. Earth Planet. Sci.* **42**, 341–379 (2014).

16. Smith, S. M. et al. Equivalence of greenhouse-gas emissions for peak temperature limits. *Nat. Clim. Change* **2**, 535–538 (2012).

17. Reisinger, A., Havlik, P., Riahi, K. & Herrero, M. Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Clim. Change* **117**, 677–690 (2013).

18. Fuglestvedt, J. S. et al. Implications of possible interpretations of "greenhouse gas balance" in the Paris agreement. *Philos. Trans. R. Soc. A.* https://doi.org/10.1098/rsta.2016.0445 (2018).

19. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci.* **106**, 16129–16134 (2009).

20. Wigley, T. M. L. The Kyoto protocol: CO₂, CH₄ and climate implications. *Geophys. Res. Lett.* **25**, 2285–2288 (1998).

21. Tanaka, K. et al. Evaluating Global Warming potentials with historical temperature. *Clim. Change* **96**, 443–466 (2009).

22. Manning, M. & Reisinger, A. Broader perspectives for comparing different greenhouse gases. *Philos. Trans. R. Soc. A* **369**, 1891–1905 (2011).

23. Meinshausen, M. et al. The RCP greenhouse gas concentrations and their extension from 1765 to 2300. *Clim. Change* **109**, 213 (2011).

24. Reisinger, A. M., Meinshausen, M. & Manning, M. Future changes in Global Warming potentials under representative concentration pathways. *Environ. Res. Lett.* **6**, 024020 (2011).

25. Sterner, A. O. & Johansson, D. J. A. Effects of climate-carbon feedbacks on emission metrics. *Environ. Res. Lett.* **12**, 034019 (2017).

26. UNFCCC, Adoption of the Paris Agreement, FCCC/CP/2015/10/Add.1, Article 4.13: https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf (2015).

27. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).

28. Gillett, N. P., Arora, V. K., Matthews, D. & Allen, M. R. Constraining the ratio of global warming to cumulative CO2 emissions using CMIP5 simulations. *J. Clim.* **26**, 6844–6858 (2013).

29. Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).

30. Bowerman, N. H. A. et al. The role of short-lived climate pollutants in meeting temperature goals. *Nat. Clim. Change* **3**, 1021–1024 (2013).

31. Shindell, D. et al. A climate policy pathway for near- and long-term benefits. *Science* **356**, 493–494 (2017).

32. IAMC AR5 Scenario Database: https://secure.iiasa.ac.at/web-apps/ene/AR5DB (2014).

33. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* **17**, 7213–7228 (2017).

34. Gillett, N. P. & Matthews, H. D. Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. *Environ. Res. Lett.* **5**, 034011 (2010).

35. Gasser, T. et al. Accounting for the climate-carbon feedback in emission metrics. *Earth Syst. Dynam.* **8**, 235–253 (2017).

36. Berntsen, T. K. et al. Response of climate to regional emissions of ozone precursors: sensitivities and warming potentials. *Tellus B* **57**, 283–304 (2005).

37. Ricke, K. L. & Caldeira, K. Maximum warming occurs about one decade after a carbon dioxide emission. *Environ. Res. Lett.* **9**, 124002 (2014).

38. Gregory, J. M. & Forster, P. M. Transient climate response estimated from radiative forcing and observedclimate change. *J. Geophys. Res.* **113**, D23105 (2008).

39. Collins, M. et al. Long-termclimate change: projections, commitment and irreversibility. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. & Qin, D. et al.) Ch. 8 (Cambridge University Press, Cambridge, 2013).

40. Gregory, J. M., Andrews, T. & Good, P. The inconstancy of the transient climate response parameter under increasing CO₂. *Philos. Trans. R. Soc. A* **373**, 20140417 (2015).

41. Millar, R., Allen, M. R., Rogelj, J. & Friedlingstein, P. The cumulative carbon budget and its implications. *Oxf. Rev. Econ. Policy* **32**, 323–342 (2016).

42. Tokarska, K. B., Gillett, N. P., Weaver, A. J., Arora, V. K. & Eby, M. The climate response to 5 trillion tonnes of carbon. *Nat. Clim. Change* **5**, 851–855 (2016).

43. Shindell, D. Inhomogeneous forcing and transient climate sensitivity. *Nat. Clim. Change* **4**, 274–277 (2014).

44. Jenkins, S., Millar, R. J., Leach, N., Allen, M. R. (2018): Framing climate goals in terms of cumulative CO₂-forcing-equivalent emissions, *Geophys. Res. Lett.* https://doi.org/10.1002/2017GL076173 (2018).