Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets

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As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties’ Decision (4/CMA.1)10 to provide “information necessary for clarity, transparency and understanding” in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDs).

While differences remain between us regarding how best to set fair yet ambitious targets for individual emitters2–9, including how any additional information might be used, and the interpretation of the Paris Agreement, it is important to emphasise the high level of agreement on the underlying science of how different greenhouse gases affect global temperature. The 2018 IPCC Special Report on 1.5 °C (SR1.5)10 stated “Reaching and sustaining net-zero global anthropogenic CO2 emissions and declining net non-CO2 radiative forcing (Planetary energy imbalance resulting directly from human-induced changes) would halt anthropogenic global warming on multi-decadal timescales (high confidence). The maximum temperature reached is then determined by cumulative CO2 emissions, reaching at least net zero CO2 emissions, along with strong reductions in other greenhouse gas emissions”. Parties to the Paris Agreement agreed in Katowice in 2018 (Decision 18/CMA.1)11 to report past emissions of individual gases separately and use 100-year Global Warming Potentials (GWP100) when aggregating them to CO2-equivalent (we refer to these here as CO2-e100 emissions). The separate specification of individual gases minimises ambiguity in determining the climate impact of past emissions. NDCs and other future targets are, however, almost always expressed in terms of aggregate CO2-e100 emissions only, for which the implications for global temperature are ambiguous89. Separate specification of the contribution from CO2 helps, but ambiguity in global temperature outcomes remains if targets for non-CO2 gases comprise a mixture of long-lived climate forcers (LLCFs), such as nitrous oxide, with atmospheric lifetimes around 100 years or longer, and SLCFs, such as methane, most of which have lifetimes shorter than 20 years19.

Specifying the contributions of all gases individually in future targets as well as the reporting of past emissions would resolve the ambiguity in global temperature outcomes, and would also help quantify non-climate-benefits of emission reductions, especially for methane11. Governments and particularly corporations may, however, wish to retain some level of aggregation across gases to allow flexibility in how they achieve their targets. Fortunately, a much less restrictive approach delivers almost all the transparency benefits from a climate perspective. The climate system responds similarly over a broad range of timescales to equal emissions expressed in tonnes of CO2-e100 of all LLCFs, including CO212. Likewise, the net radiative forcing due to SLCFs on multi-decadal timescales is similar to the aggregated rate of SLCF emissions expressed in tonnes of CO2-e100 per year multiplied by the 100-year Absolute Global Warming Potential (AGWP100) of CO212. With this additional information, it is straightforward to express the SR1.5 statement quoted above in terms of CO2-e100 emissions: human-induced warming over any multi-decade time-interval is approximately the sum of (i) aggregate CO2-e100 emissions of LLCFs, including CO2, multiplied by a constant parameter, the Transient Climate Response to cumulative CO2 Emissions, or TCRE (the TCRE can alternatively be thought of as the Absolute Global Temperature-Change Potential for a sustained emission of CO2 divided by the time-horizon, AGTP/H13); (ii) any change in decadal-average radiative forcing due to SLCFs multiplied by another constant parameter, the Transient Climate Response to Forcing, or TCRF, another name for the “fast” component(s) of the climate response15; and (iii) a
gradual adjustment to average SLCF forcing\textsuperscript{16}, all evaluated over the same time-interval.

Hence a separate indication of the contributions of LLCFs and SLCFs in emission targets, or equivalently the LLCF contribution to total CO$_2$-e$_{100}$ emissions, is required to allow for the global temperature outcome to be calculated relatively unambiguously. It is important to note, however, that the evaluation of emission targets at the national or corporate level cannot be undertaken from a physical science perspective alone, but also depends on economic, social, equity and political considerations\textsuperscript{23–31}, including responsibility for past warming, capacity for and costs of abatement, and non-climate impacts. Separate specification would also facilitate the use of alternate or flexible emission metrics, which may be useful for achieving a cost-effective emission trajectory over time\textsuperscript{32} or addressing specific policy goals such as limiting near-term rates of warming\textsuperscript{19}. Indicative contributions from LLCF and SLCF abatement would not preclude trade-offs between them, but would clarify the need to monitor the temperature impacts of any such trade-offs over a range of timescales\textsuperscript{20}.

It has long been accepted\textsuperscript{21} that stringent mitigation of both LLCFs and SLCFs is needed to meet any ambitious temperature goal, but making progress on two fronts necessitates monitoring progress on two fronts. Some countries (but very few companies) already specify the contribution of LLCFs and/or SLCFs to total CO$_2$-e$_{100}$ emissions in NDCs, LT-LEDSs and science-based targets (https://sciencebasedtargets.org/) communicated under the Greenhouse Gas Protocol. Quantifying the aggregated implications of these targets for future global temperature simply requires a much wider uptake of this practice, representing a simple and achievable innovation that would enhance the transparency of any stocktake of progress towards any global temperature outcome. Separate indication of LLCF and/or SLCF contributions could be communicated by countries as additional information consistent with Decision 4/CMA.1. This does not have to affect any existing or planned NDCs or long-term net zero strategies\textsuperscript{22} communicated using aggregate CO$_2$-e$_{100}$.

\section*{WHY SEPARATE SPECIFICATION IS SO USEFUL}

To quantify the SR1.5 and AR6 statements quoted above, human-induced global temperature change over a multi-decade time-interval $\Delta t$, relative to the level of human-induced warming at the beginning of that interval (e.g. the present day or pre-industrial), can be decomposed using the framework articulated above as follows:

\begin{equation}
\Delta T = \kappa_{E} F_{E} \Delta t + \kappa_{F} (\Delta F_{N} + \rho F_{N} \Delta t),
\end{equation}

where $F_E$ and $F_N$ are globally aggregated average CO$_2$ emission-rates and non-CO$_2$ radiative forcing, respectively (so $F_E$ is the sum of cumulative CO$_2$ emissions), and $\Delta F_{N}$ is the change in decadal-average non-CO$_2$ forcing, all evaluated over that interval (the geophysical “Zero Emissions Commitment” is expected to be relatively small over a multi-decade time-interval\textsuperscript{23}, but this may not be the case on longer timescales). The coefficients $\kappa_E$ (the TCRE) and $\kappa_F$ (the TCFR, or “fast” component of the climate response to any forcing change, denoted $c_1$ in ref. 12, or sum of fast components\textsuperscript{33}; see supplementary material), are both scenario-independent in the absence of strongly non-linear carbon cycle feedbacks or climate response. The only scenario-dependent coefficient is $\rho$, the fractional Rate of Adjustment to Constant Forcing (RACF), or the relatively small fractional rate at which forcing needs to decline to maintain stable temperatures. It depends on how fast and how recently $F_N$ has increased (this term represents the delayed adjustment to past forcing increases, so is larger for more recent and rapid increases). If $F_N$ varies only on multi-decadal timescales, $\rho = c_2/(\kappa_{F} s_2)$, where $c_2$ is the “slow” (multi-century) component of the climate sensitivity, and $s_2$ the

deep ocean thermal adjustment timescale. For representative\textsuperscript{12} coefficient values, $\rho \approx 0.3\%$ per year, making this third term usually small.

Aggregate CO$_2$-e$_{100}$ emissions cannot be used to calculate $F_N$ if these comprise a mixture of LLCFs and SLCFs. Aggregate CO$_2$-e$_{100}$ emissions of LLCFs, $E_L$, can, however, be combined unambiguously and have the same impact on global temperature on decade to century timescales as the corresponding quantity of CO$_2$. Likewise, aggregate CO$_2$-e$_{100}$ emissions of SLCFs, $E_S$, multiplied by the AGWP$_{100}$ of CO$_2$, $A_{100}$, give SLCF radiative forcing, $F_S$. $A_{100}$ normally includes a first-order estimate of the impact of carbon cycle feedbacks\textsuperscript{25} so, for consistency, this should also be included in the GWP$_{100}$ values used to compute $E_S$.

For emissions reported as CO$_2$-e$_{100}$ the above expression can therefore be re-written (now grouping all LLCFs with CO$_2$):

\begin{equation}
\Delta T = \kappa_{E} F_{E} \Delta t + \kappa_{F} (\Delta F_{S} + \rho F_{S} \Delta t),
\end{equation}

or equivalently, using $F_S = A_{100} F_{S}$ on multi-decadal timescales,

\begin{equation}
\Delta T = \kappa_{E} F_{E} \Delta t + \kappa_{A} A_{100} (\Delta E_{S} + \rho E_{S} \Delta t).
\end{equation}

Hence $\Delta T$ can be estimated directly using well-known (albeit uncertain) climate system properties if, and only if, total CO$_2$-e$_{100}$ emissions of long-lived climate forcers, $E_t$, are specified in emission targets together with total CO$_2$-e$_{100}$ emissions, $E_L + E_S$; or, equivalently, $E_L$ and $E_S$ are specified separately. $\Delta T$ cannot be calculated from the sum of $E_L + E_S$ alone.

This is illustrated by Fig. 1, which shows the impact of LLCF and SLCF emissions, expressed as CO$_2$-e$_{100}$ on global temperature change over a multi-decade period, relative to the level of warming at the beginning of that period, calculated with a simple climate model\textsuperscript{12}. Stylised cases of constant (darker shades) and step-change (+10%, lighter shades, and −50%, dotted lines) emissions are shown in panels a and c. Warming due to LLCF emissions (the term $\kappa_{E} E_{L} \Delta t$ in Eq. (3)) increases linearly with cumulative emissions in all three cases (panel b). Warming due to an ongoing constant increase in CO$_2$ emissions of an LLCF that started decades before the beginning of this period (the $\kappa_{E} A_{100} F_{E} \Delta t$ term) also increases linearly (panel d, darker blue) but at a slower rate per tCO$_2$-e$_{100}$ emitted (by a factor of about 4, because $k_{E} = 4 \times k_{F}$, global temperatures have already partially equilibrated with this constant emission (by how much depends on how long ago these SLCF emissions began, which is why $\rho$ is the only scenario-dependent coefficient in these expressions). Finally, warming due to an increase in SLCF emissions (the $k_{F} A_{100} \Delta E_{S}$ term, panel d, lighter blue) is 4–5 times greater than would be expected from the same increase in tCO$_2$-e$_{100}$ emissions of an LLCF (panel b, lighter red) over the 20 years following the increase ($\kappa_{A} A_{100} = 4.5 \times \kappa_{E} \times 20$ years). Hence the AR6 statement “expressing methane emissions as CO$_2$ equivalent emissions using GWP$_{100}$ overstates the effect of constant methane emissions on global surface temperature by a factor of 3–4 … while understating the effect of any new methane emission source by a factor of 4–5 over the 20 years following the introduction of the new source”\textsuperscript{26} applies to the impact of global emissions of any SLCF. Any decrease in SLCF emissions also has a much greater impact on temperatures over a multi-decade period per tCO$_2$-e$_{100}$ avoided than a corresponding decrease in LLCF emissions (red and blue dotted lines) (Fig. 1).

Temperature changes in the figure are calculated using a particular model, LLCF, SLCF and scenario. The figure would, however, appear similar if another model, combination of gases or scenario of prior emissions were used, provided emissions do not change rapidly immediately before the beginning or end of the period shown, because the relationship between emissions and warming expressed in Eq. (3) is generic. Individual terms in Eq. (3), assuming constant coefficients, are shown by the arrows on the right of panels.
b and d. These match the warming calculated by the explicit simple climate model within modelling uncertainties. The figure shows temperature change relative to the start of the period rather than absolute warming because the latter is not determined by Eq. (3) but depends on the prior LLCF and SLCF emissions history (the specific scenario used to generate this figure is shown in full in the Supplementary Information).

Temperature change $\Delta T$ over a multi-decade period depends, to first order, on cumulative emissions of LLCFs $E_L \Delta t$, cumulative emissions of SLCFs $E_S \Delta t$, and net change in total SLCF emission rates $\Delta E_S$ over that period alone. As the SRT1.5 and AR6 emphasised, future warming depends on future emissions. Making use of this information, however, requires both $E_L$ and $E_S$ to be specified: only specifying the sum $E_L + E_S$ introduces an ambiguity in temperature outcome.

Separate specification also facilitates assessing the implications of different metrics. For example, aggregate CO$_2$-equivalent emissions using the 20-year Global Warming Potential (GWP$_{20}$) can be approximated by $E_L + 3E_S$ if both $E_L$ and $E_S$ are reported as CO$_2$-e100, with a slightly higher multiplicative factor (up to 4) if $E_S$ is dominated by forcers with lifetimes of order one year (Table 8.A.1 of ref. 12 shows that GWP$_{20}$ values are similar to GWP$_{100}$ values for LLCFs and 3 or 4 times GWP$_{100}$ values for gases with lifetimes of order a decade or a year, respectively). Finally, we re-emphasise that these expressions capture our physical understanding of how global emissions of LLCFs and SLCFs collectively determine global
temperature change, and illustrate the utility of separate specification of $E_L$ and $E_R$. How this understanding is used to inform the assessment of the adequacy of individual emission targets depends on other considerations listed above and cannot be argued from a physical science perspective alone. There will be several other advantages to the additional communication such as being able to estimate air quality co-benefits of mitigation.

**DATA AND CODE AVAILABILITY**

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study. A self-contained Python notebook to reproduce the figure is provided on https://gitlab.ouce.ox.ac.uk/OMP_climate_pollutants/separate-contributions.

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**REFERENCES**

1. UNFCCC, https://unfccc.int/sites/default/files/resource/cma2018_3_add2_new_advance.pdf (2018).
2. Rogelj, J. & Schleussner, C.-F. Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. Environ. Res. Lett. 14, 114039 (2019).
3. Cain, M. et al. Comment on 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'. Environ. Res. Lett. 16, 068001 (2021).
4. Rogelj, J. & Schleussner, C.-F. Reply to Comment on 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'. Environ. Res. Lett. 16, 068002 (2021).
5. Schleussner, C.-F., Naufel, A., Schaeffer, M., Hare, W. & Rogelj, J. Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement. Environ. Res. Lett. 14, 124055 (2019).
6. IPCC, 2018. In Global Warming of 1.5 °C (eds Masson-Del享受到). World Meteorological Organization, 2018.
7. IPCC, 2021. In Climate Change 2021, the Physical Science Basis (eds. Masson-Delﻡ, V. et al) (Cambridge University Press, 2021).
8. Tanaka, K. & Ohashi, M. The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. Nat. Clim. Change 8, 319–324 (2018).
9. Denison, S., Forster, P. & Smith, C. J. Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. Environ. Res. Lett. 14, 124002 (2019).
10. Smith, S. et al. Equivalence of greenhouse-gas emissions for peak temperature limits. Nat. Clim. Change 2, 535–538 (2012).
11. Schindell, D. et al. A climate policy pathway for near- and long-term benefits. Science 356, 493–494 (2017).
12. Myhre, G. et al. Anthropogenic and Natural Radiative Forcing. 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 (eds. Stocker, T. F. et al.) Ch. 8 (2013).
13. Shine, K. et al. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Clim. Change 68, 281–302 (2005).
14. Gregory, J. M. et al. Quantifying carbon cycle feedbacks. J. Clim. 22, 5232–5250 (2009).
15. Held, I. M. et al. Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. J. Clim. 23, 2418–2427 (2010).
16. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants, npj Clim. Atmos. Sci. 2, 29 (2019).
17. Rajamani, L. et al. National ‘fair shares’ in reducing greenhouse gas emissions within the principled framework of international environmental law. Clim. Policy, https://doi.org/10.1080/14693062.2021.1970504 (2021).
18. Tanaka, K. et al. Cost-effective implementation of the Paris Agreement using flexible greenhouse gas metrics. Sci. Adv. 7, eaba9002 (2021).
19. Ocko, I. et al. Unmask temporal trade-offs in climate policy debates. Science 356, 492–493 (2017).
20. Allen, M. R. et al. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. Environ. Res. Lett. 16, 074009 (2021).
21. Shindell, D. et al. Simultaneously mitigating near-term climate change and improving human health and food security. Science 335, 183–189 (2012).
22. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Net-zero emissions targets are vague: three ways to fix. Nature 591, 365–368 (2021).
23. MacDougall, A. H. et al. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2. Biogeosciences 17, 2987–3016 (2020).
24. Tsutsumi, J. Quantification of temperature response to CO2 forcing in atmosphere-ocean general circulation models. Climatic Change 140, 287–305 (2017).
25. Gasser, T. et al. Accounting for the climate-carbon feedback in emission metrics. Earth Syst. Dynam. 8, 235–253 (2017).
26. Forster, P. et al. In Climate Change 2021, the Physical Science Basis (eds. Masson-Del摩擦, V. et al) Ch. 7 (Cambridge University Press, 2021).

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**COMPETING INTERESTS**

The authors declare no competing interests.

**ADDITIONAL INFORMATION**

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