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Environmental *Change* Institute

IN BRIEF

MEASURING PROGRESS TO A TEMPERATURE GOAL

Conventional "CO_2-equivalent" (CO_2-e) emissions calculated using 100-year "Global Warming Potentials" do not consistently reflect the impact of emissions on global temperature: they overstate the impact of constant emissions of any short-lived climate pollutant such as methane by a factor of about four, while understating the large impact of changes in methane emission rates. Myles Allen and Michelle Cain from the University of Oxford explain how CO_2-e emissions can be used to more accurately reflect their impact on global temperature, and provide a simple method of evaluating contributions towards achieving a global temperature goal. The use of these "warming-equivalent" aggregated emissions could help reduce long-standing confusion regarding what methane emissions are "worth", as it reflects the large impact of changing methane emission rates and the considerable opportunities afforded by methane emission reductions. Finally, estimating the impact of mitigation policies on global temperature is only possible if emissions of long- and short-lived climate pollutants are reported separately in national inventories, Nationally Determined Contributions, and in emissions trading.

To limit global warming, it is necessary to understand the impact of emissions of different greenhouse gases on global temperature. In 2018, it was agreed under the UN Framework Convention on Climate Change (UNFCCC) that emissions should be reported as "carbon dioxide-equivalent" (CO_2-e), calculated by multiplying tonnes emitted of each gas by its 100-year Global Warming Potential (GWP_{100}). However, using this measure alone does not accurately reflect the impact of different climate pollutants. This brief explains how a simple combination of cumulative and ongoing CO2-e emissions, denoted "CO_2-warming-equivalent" emissions, provides a much more accurate way of assessing the impact of methane and other short-lived climate pollutants (SLCPs) on global temperatures.

Why methane is different

The impacts of carbon dioxide (CO_2) emissions on global temperature are relatively simple. Every tonne of CO_2 emitted causes 0.45 (±0.23) trillionths of a degree Celsius of warming (a factor known as the TCRE).[1] This warming persists indefinitely until or unless another tonne of CO_2 is actively removed. So CO_2 emitted centuries ago continues to affect climate today; current CO_2 emissions of 42 billion tonnes per year are ratcheting up global temperatures by approximately 0.19°C per decade; and the only way of stopping CO_2 emissions from causing further warming is to reduce them to net zero, meaning all remaining anthropogenic CO_2 emissions (including indirect emissions such as CO_2 released by melting tundra) are balanced by active CO_2 removals. After CO_2 emissions reach net zero, atmospheric CO_2 concentrations decline gradually over centuries. This decline balances the slow uptake of heat by the deep ocean, resulting in no further warming or cooling of global average surface temperature.

Nitrous oxide (N_2O) behaves similarly. Like CO_2, it is very stable, with an atmospheric lifetime of over a century, so N_2O emissions also effectively accumulate in the climate system. It is also a very powerful greenhouse gas. Releasing one tonne of N_2O has approximately the same impact on global temperatures on decade to century timescales as releasing 265 tonnes of CO_2, 265 being the current[1] GWP_{100} value for N_2O. Hence emitting one tonne CO_2-e of N_2O actually does have a similar impact on global temperature as emitting one tonne of CO_2.

Methane (CH_4) behaves very differently. It is relatively short-lived: almost 10% of the methane in the atmosphere is destroyed by chemical reactions every year. Any permanent increase in the global methane emission rate drives up atmospheric methane concentrations, which then come into equilibrium with the new emission rate within a few decades, while any decrease in methane emission rate allows atmospheric methane concentrations to fall much faster than CO_2 concentrations would fall even if CO_2 emissions were reduced to zero. Conventionally, methane is assigned a GWP_{100} value of 28, equating one tonne of methane released with 28 tonnes of CO_2-e. But unlike N_2O, that tonne of methane would have a much greater impact on global temperatures over the decades immediately after it is emitted than 28 tonnes of CO_2, but a much smaller impact on longer

1 All values used here are from the IPCC Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

timescales. Hence the same CO_2-e emissions calculated with GWP_{100} can have very different impacts on global temperatures depending on whether they consist of methane, CO_2 or N_2O. This problem has been known for decades: GWP_{100} was introduced in the IPCC's First Assessment Report in 1990 "*to illustrate the difficulties inherent in the concept*".

Taking methane's true measure

The well-understood relationship between methane emission rates and atmospheric methane concentrations means that it is straightforward to compute "CO_2-warming-equivalent" emissions associated with any CO_2-e methane emission pathway. Suppose $E(t)$ represents CO_2-e emissions of methane in year t, calculated using GWP_{100} following UNFCCC guidelines, then CO_2-warming-equivalent emissions in that year are given by: $E^*(t) = 4 \times E(t) - 3.75 \times E(t-20)$, where $E(t-20)$ is methane CO_2-e emissions in the year 20 years previous to year t. More general versions of this expression can be found in further reading below and supporting publications.

Over a multi-decade period, releasing E^* tonnes of CO_2 calculated using this expression would have a very similar impact on global temperatures as the methane emissions themselves: hence the phrase "warming-equivalent". This is confirmed by simulating the actual warming response to methane and CO_2 emissions over a range of scenarios using climate models. It can also be understood in terms of basic properties of the climate system. In contrast, conventional CO_2-e emissions calculated with GWP_{100} overstate the warming impact of constant methane emissions by a factor of about four, and understate the large impact of changes in methane emission rates.

CO_2-warming-equivalent emissions of methane E^* can be positive or negative depending on whether methane emissions are rising or falling. If methane emissions fall faster than 0.3% per year, or halving over 200 years, then they would be equated with negative CO_2-warming-equivalent emissions ($E^*<0$). Rapid reductions in methane emissions have a net cooling effect on global average surface temperature, similar to active removal of CO_2. Conventional CO_2-e emissions are particularly misleading when methane emissions are falling. This net cooling effect will normally be only partially compensating for warming caused by past CO_2 emissions, past increases in methane emissions, or other climate pollutants. Even the most ambitious mitigation scenarios do not envisage reverting global temperature to or below its pre-industrial level.

This formula can also be applied to calculate CO_2-warming-equivalent emissions for any SLCP, while for N_2O or any long-lived climate pollutant (LLCP, or any gas with a lifetime longer than a century), CO_2-warming-equivalent emissions are equated with traditional CO_2-e emissions ($E^*=E$). Warming caused by greenhouse gas emissions over a multi-decade time period is given by total aggregate CO_2-warming-equivalent emissions over that time period multiplied by the TCRE:

$$\Delta T = \text{TCRE} \times \sum [E_{\text{LLCP}}(t) + 4 \times E_{\text{SLCP}}(t) - 3.75 \times E_{\text{SLCP}}(t-20)]$$

Hence, provided aggregate CO_2-e emissions for LLCPs and SLCPs are reported separately, their impact on global temperatures is straightforward to quantify. Despite its simplicity, this expression predicts the temperature response to individual gases and multi-gas emission pathways to within the uncertainty of more complex climate models.[2]

Policy implications

CO_2-warming-equivalent emissions multiplied by the TCRE indicate impact on global temperature. This allows emissions of methane to be combined with emissions of CO_2 and N_2O (as the three most important greenhouse gases) to indicate the contribution of a particular sector, non-state actor, country, or region to global temperature change over the coming decades. Applied to global emissions, this allows more accurate assessment of collective progress to a long-term temperature goal. At a national level, this allows countries' current, historical and projected contributions to global warming to be estimated without the use of complex climate models. At a sectoral level, this allows policies and measures to be compared directly in terms of their impact on global temperature.

How this information is used depends on additional considerations and perspectives, including the costs and co-benefits of different mitigation opportunities. The use of warming-equivalent emissions does not imply any specific policy outcome, but it could help reduce long-standing confusion regarding what methane emissions are "worth". Unlike aggregate CO_2-equivalent emissions, CO_2-warming-equivalent emissions do not overstate the impact of a constant source of methane, and they also accurately reflect the large impact of increasing methane emission rates and the considerable opportunities afforded by methane emission reductions. Finally, they show that estimating the impact of greenhouse gas emissions and mitigation policies on global temperature is only possible if aggregate CO_2-equivalent emissions of LLCPs and SLCPs are reported separately in both national inventories, Nationally Determined Contributions and in emissions trading.

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2 For more information, see Cain, M., Lynch, J., Allen, M.R., Fuglestvedt, J.S., Frame, D.J., & Macey, A.H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. npj Climate and Atmospheric Science. Volume 2, Article number: 29 (2019).