



# The relationship between net GHG emissions and radiative forcing with an application to Article 4.1 of the Paris Agreement

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## Abstract

This paper provides an assessment of Article 4.1 of the Paris Agreement on climate; the main goal of which is to provide guidance on how “to achieve the long-term temperature goal set out in Article 2”. Paraphrasing, Article 4.1 says that, to achieve this end, we should decrease greenhouse gas (GHG) emissions so that net anthropogenic GHG emissions fall to zero in the second half of this century. To aggregate net GHG emissions, 100-year global warming potentials (GWP-100) are commonly used to convert non-CO<sub>2</sub> emissions to equivalent CO<sub>2</sub> emissions. The GWP-scaling method is tested using methane as an example. The temperature projections using GWP-100 scaling are shown to be seriously in error. This throws doubt on the use of GWP-100 scaling to estimate net GHG emissions. An alternative method to determine the net-zero point for GHG emissions based on radiative forcing is derived, where the net-zero point is identified with the maximum of GHG forcing. This shows that, to meet the Article 2 warming goal, the net-zero point for GHG emissions needs to be reached as early as 2036, much sooner than in the Article 4.1 window. Other scientific problems in Article 4.1 that further undermine its purpose to guide efforts to achieve the Article 2 temperature targets are discussed.

**Keywords** Climate change · Climate policy · Paris Agreement · Greenhouse gases · Net-zero emissions · Global warming

## 1 Introduction

Article 4.1 tells us that, to achieve the Article 2 temperature goal, “Parties ... [should reduce the increase in greenhouse-gas (GHG) emissions] ... so that we reach a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century.”

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Article 2's goal can be broken down into two distinct components ... "Holding the increase in global average temperature to well below 2 °C above pre-industrial levels" (goal 1) and "pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (goal 2). These goals can and will be pursued in parallel. For the "well below 2 °C" target, it should be distinct from 1.5 °C: 1.7 °C or 1.8 °C would be in accord with the Article's wording.

To aggregate GHG sources across gases or across countries, the standard procedure is to convert the emissions of the individual non-CO<sub>2</sub> GHGs to CO<sub>2</sub> equivalent emissions (ECO<sub>2e</sub>) and then aggregate these values. For calculating CO<sub>2</sub> equivalence for individual gases, there is a UNFCCC convention to use 100-year global warming potentials (GWP-100) as a scaling factor. This blanket use of GWP-100 as a scaling factor for all non-CO<sub>2</sub> gases is a significant problem, discussed in the next section.

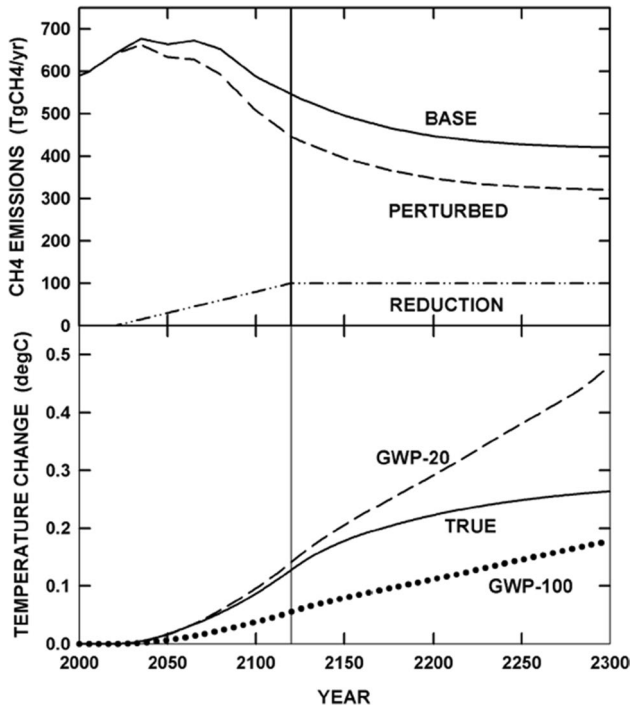
Section 3 points out areas of possible confusion in defining the words "net" and "anthropogenic." Section 4 suggests an alternative way to define and quantify net GHG emissions based on radiative forcing, so avoiding the (flawed) use of GWP-100 as a scaling factor to define equivalent CO<sub>2</sub> emissions. Section 5 concludes by summarizing the scientific flaws in Article 4.1 and makes some suggestions for how these could be corrected.

## 2 Problems with using GWP-100 as an emission scaling factor

It was shown more than 20 years ago (Wigley 1998; see also Manning and Reisinger 2011) that using GWP-100 as a scaling factor to convert non-CO<sub>2</sub> gas emissions to equivalent CO<sub>2</sub> emissions, and then using these converted emissions to determine temperature changes, can lead to serious errors in the projected temperature changes. This problem is illustrated here in Fig. 1 using a simple example; the conversion of methane (CH<sub>4</sub>) emissions changes to changes in equivalent CO<sub>2</sub> emissions.

This requires imposing some CH<sub>4</sub> reduction scenario on a baseline emission scenario, for which the reference (no-new-climate-policies) scenario derived with the MiniCAM integrated assessment model and published in the CCSP 2.1a report (Clarke et al. 2007) is used. These emissions are perturbed with a linear reduction of emissions of 100 TgCH<sub>4</sub> over 2020 to 2120. The coupled gas cycle/climate model MAGICC (Wigley et al. 2009) is then used with a climate sensitivity of 3 °C to calculate the corresponding temperature perturbation (labelled "TRUE" in Fig. 1). The equivalent CO<sub>2</sub> emission perturbation is then calculated using, as scaling factors, the 20-year and 100-year GWP values for CH<sub>4</sub> from the IPCC AR5 report. The baseline CO<sub>2</sub> emissions are then reduced by these amounts. MAGICC is then used to determine the temperature perturbations for these CO<sub>2</sub> perturbations, keeping CH<sub>4</sub> emissions at the baseline level.

The results are shown in Fig. 1. Figure 1 shows that replacing the imposed CH<sub>4</sub> emission reduction by the equivalent reduction in CO<sub>2</sub> emissions, calculated using GWP-100 scaling, greatly underestimates the magnitude of the temperature perturbation. This is a serious error. Scaling with the larger GWP-20 value, however, provides a much better match to the TRUE answer out to 2120 (the end of the CH<sub>4</sub> perturbation) and beyond (to 2230). Quantitatively, these results are sensitive to the choice of baseline scenario, the non-CO<sub>2</sub> emission perturbation, and the chosen non-CO<sub>2</sub> gas, but the general qualitative conclusion that, in general, GWP-100 scaling leads to erroneous estimates of temperature perturbations is independent of these choices.



**Fig. 1** Testing  $\text{ECO}_{2c}$  based on GWP-100 for an idealized reduction in  $\text{CH}_4$  emissions. Temperature changes for the  $\text{ECO}_{2c}$  cases are compared with those based on the “TRUE” case derived using the original  $\text{CH}_4$  emission reduction. Both GWP-100 and GWP-20 results are shown for comparison.  $\text{CH}_4$  emissions are total emissions, anthropogenic plus natural. For clarity the temperature results, which are decreases, are multiplied by minus 1

The main significance of the error arising from the use of GWP-100 scaling lies in quantifying multi-gas Nationally Determined Contributions (NDCs) (emission reductions), where accurate quantification is crucial in assessing progress towards meeting the Article 2 temperature goal. The error in using GWP-100 as a scaling factor should also be of concern to all countries where methane emission reductions contribute significantly to their NDCs. Because of the GWP-100 error, these countries will not be given sufficient credit for their methane emission reduction contributions.

In the following sections, a different method for aggregating the emissions of different GHGs is derived.

### 3 Confusion in defining net anthropogenic emissions

The primary goal of Article 4.1 is to provide a guide to how the Article 2 temperature goal can be met. The pathway to projecting temperature changes is from emissions to concentration changes, to radiative forcing, to temperature ... so emissions are a justifiable starting point for such a guide.

For modeling future changes in concentrations, it is **total** sources and **total** sinks that determine these changes, and the term “net emissions” is commonly used as shorthand

for the difference between total sources and total sinks. This is “Definition A.” For the stated goal of Article 4.1, we therefore require information for total sources and total sinks. An alternative definition for net emissions is given in the Summary for Policymakers of the IPCC SR15 report (Box SPM.1), which defines “net-zero emissions” for CO<sub>2</sub> as occurring “... when anthropogenic CO<sub>2</sub> emissions are balanced globally by anthropogenic CO<sub>2</sub> removals” (“Definition B”).

Since total sources (or sinks) are the sum of their anthropogenic and natural components, if there was a continuing balance between natural CO<sub>2</sub> sources and sinks, these two definitions, A and B, would be equivalent. Today, however, natural sinks are much greater than natural sources (Friedlingstein et al. 2020), a situation that will prevail for many decades into the future, so the above two definitions are not equivalent.

The definition used in UNFCCC CO<sub>2</sub> Inventories adds an additional complication. The background information for this issue is provided in Grassi et al. (2018) in their paper on anthropogenic, land-related CO<sub>2</sub> fluxes. These authors divide processes that drive land fluxes into anthropogenic effects (direct human-induced effects and indirect human-induced effects (e.g., climate change, CO<sub>2</sub> fertilization, nitrogen deposition)) and natural effects. They also consider managed and unmanaged land separately. (Globally, 22% of the land is unmanaged; see their Fig. 5b.) In UNFCCC CO<sub>2</sub> Inventories, fluxes into or out of managed land are considered to be anthropogenic, while fluxes into or out of unmanaged land are considered to be non-anthropogenic. Yet, for the CO<sub>2</sub> fertilization component of the unmanaged land sink, the driver for this sink is atmospheric CO<sub>2</sub> concentration increases, changes that are dominantly anthropogenic. There is a contradiction here.

This is an important issue because Article 4.1 refers specifically to anthropogenic GHG sources and sinks, so we need to be clear about what is anthropogenic and what is not. For the terrestrial CO<sub>2</sub> sink, with UNFCCC accounting, managed and unmanaged lands are treated differently, the former is considered to be anthropogenic, while the latter is not. In carbon cycle modeling, as in Definition A, and, more particularly, in Definition B, both are anthropogenic. Using the UNFCCC accounting procedure, therefore, a significant contribution to the anthropogenic terrestrial sink is ignored. This leads to a third definition for “net” (“Definition C”), which is similar to Definition B, but with a smaller anthropogenic terrestrial sink. This complication is discussed further below.

It is clear from the above that any assessment of Article 4.1 is potentially a complex exercise, with three different definitions for “net.” A guiding principle to weave a way through these definitional complications is the need to assess whether Article 4.1 succeeds in helping us to understand how the temperature goal of Article 2 can be met. First, to explain temperature changes that, in turn, are driven by concentration changes, it is essential to use Definition A. This is what will be used in the calculations below. Second, as already shown, the standard method for aggregating GHG emissions by converting non-CO<sub>2</sub> emissions to equivalent CO<sub>2</sub> emissions by scaling with GWP-100 fails to lead to accurate temperature projections, so this must be abandoned. A more accurate method is required. Third, concentrating on GHGs alone (or, even worse, only on anthropogenic emissions, as in Definitions B or C) is inadequate because it ignores the important climate effects of, e.g., aerosols and tropospheric ozone (which is not considered to be a GHG under the Kyoto Protocol).

The method derived here is to replace the net anthropogenic emission concept by total radiative forcing, the sum of the forcings of all climatically active species and processes, which are the true determinants of temperature change.

#### 4 Radiative forcing as a guide to net-zero GHG emissions

Because the standard (UNFCCC) method for aggregating net GHG emissions is flawed, and because the relationship between this variable and temperature is unclear, we need an alternative to net GHG emissions. Radiative forcing is an obvious possibility because it can be quantified accurately and is the most direct driver of temperature change. In the context of Article 4.1, the challenge then is to relate forcing to net GHG emissions ... or, more specifically, to the net-zero point for GHG emissions.

For CO<sub>2</sub> alone, a balance between sources and sinks means that both net emissions and the rate of change of concentration (dC/dt) drop to zero. The net-zero CO<sub>2</sub> emission point is therefore the point where C(t) maximizes. Similarly, for the GHG case, the net-zero point must be the point where “GHG concentration” maximizes. The term “GHG concentration,” however, as a composite term covering all GHGs has not been defined. Using radiative forcing rather than concentration as a metric allows us to bypass this problem. For CO<sub>2</sub>, maximizing concentration means that CO<sub>2</sub> radiative forcing is also maximized. In the GHG case, the net-zero GHG emission point is therefore the point where total GHG radiative forcing is maximized. Radiative forcing is therefore a legitimate replacement for net GHG emissions. This has the significant advantage that it is radiative forcing that directly determines temperature changes, while temperature changes cannot be determined solely from information about anthropogenic GHG sources and sinks.

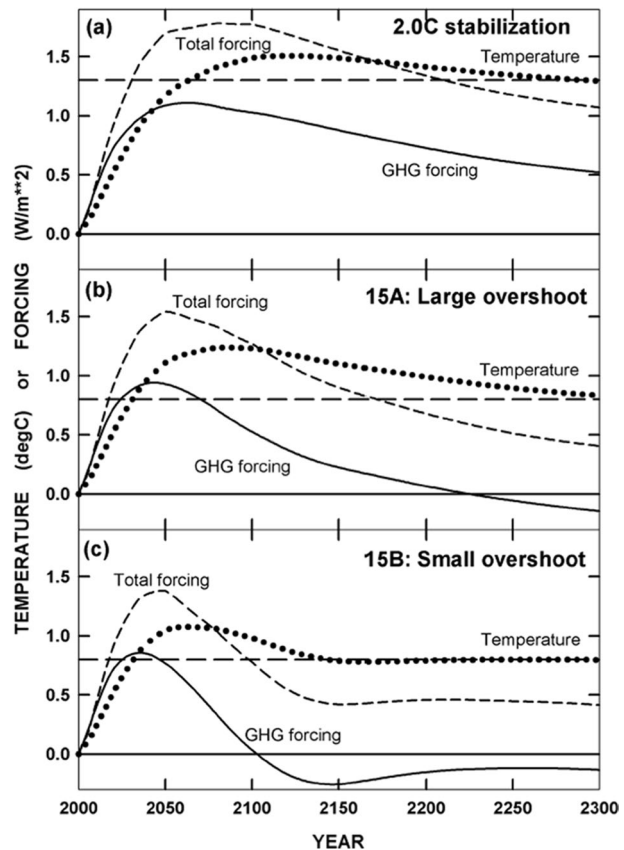
To show how radiative forcing varies for scenarios that meet the Article 2 temperature targets of 1.5 °C or “well below 2 °C,” the emission scenarios from Wigley (2018) may be used. There are many other scenarios in the literature that meet these warming targets, but few that do so without first overshooting the targets. (Some of these will be considered below.) The results are given in Fig. 2, which shows, for three scenarios, temperature changes, total radiative forcing, and GHG radiative forcing. There are two cases that approach 1.5 °C asymptotically but with different amounts and durations of warming overshoot, and a third case that tends to 2 °C asymptotically. Although this is not a “well below 2 °C” example, it provides what can be considered the extreme example of this target.

For the Article 4.1/Article 2 link, the key results are the points of maximization of **total** radiative forcing, where the maxima are reached in 2050 (15A, large overshoot), 2049 (15B, small overshoot), and 2080 (2 °C stabilization). Note that it is total radiative forcing, not GHG forcing, that is the key to linking Articles 4.1 and 2. Maximum GHG forcing, however, must also be considered to assess the credibility of Article 4.1, recalling that maximum GHG forcing corresponds to the point of net-zero GHG emissions. These maxima occur in 2044 for 15A, 2036 for 15B, and 2062 for 2 °C stabilization. By interpolation, the net-zero point for stabilization at 1.8 °C (i.e., “well-below 2 °C”) may be estimated to occur in the range 2052 to 2055. For both of the 1.5 °C cases, net-zero GHG emissions occur well before the earliest date in the Article 4.1 2050 to 2099 window. For the 1.8 °C case, the net-zero point occurs near the minimum of the Article 4.1 window.

Figure 2 shows another important result that has been noted on a number of occasions in the literature (albeit not mentioned specifically in the Paris Agreement) that, even after the net-zero GHG emission point is reached, the climate challenge continues and both GHG and total radiative forcings must continue to be reduced for at least a century after the net-zero point is reached.

These results are new in that this is the first time that the correspondence between radiative forcing maxima and net-zero GHG emissions has been used to identify the net-zero GHG emission point. However, in terms of when these forcing maxima are reached,

**Fig. 2** Temperature and radiative forcing changes for two scenarios that tend asymptotically to 1.5 °C above the pre-industrial level (b and c) and a third case (a) where the asymptotic value is 2 °C. Results are shown for both GHG-only and total forcing. Peak GHG forcing corresponds to the point of net-zero GHG emissions. The dashed horizontal lines correspond to warmings of 2 °C (panel a) and 1.5 °C (panels b and c) above the pre-industrial level



the results here are similar to those in other “Paris” scenarios. The results in Tanaka and O’Neill (2018, Fig. 2(n); corrected data from Katsumasa Tanaka) are representative. These authors consider ten scenarios. For the four that correspond, at least approximately, to the 1.5 °C Paris target, maximum total forcing occurs in 2026 (for an unrealistic case with no warming overshoot ... all other scenarios have substantial warming overshoots), 2045, 2048, and 2048 (cf. my 2049 and 2050 results). For the five cases that correspond roughly to 2 °C stabilization, their total forcing maxima occur in 2048, 2049, 2050, 2061, and 2072 (my result is 2080). The differences here in the timing of total radiative forcing maxima largely reflect the considerable uncertainties in aerosol forcing.

The one point not yet discussed is the implication of the use of net anthropogenic emissions in the wording of Article 4.1, especially given the fact that current CO<sub>2</sub> inventory calculations assume that CO<sub>2</sub> sinks into unmanaged land are considered to be non-anthropogenic. The first thing to note is that this unusual partitioning of the terrestrial sink into managed (where the sinks are considered to be anthropogenic) and unmanaged (non-anthropogenic) components has no effect on the model results presented in Fig. 2. These calculations use total sources and sinks, and these totals are unchanged by the method used to apportion the anthropogenic and non-anthropogenic (i.e., natural) components.

However, there is an effect on how we interpret Article 4.1, which arises because of Article 4.1’s restriction to employ only anthropogenic emission components, coupled with

a definition of the anthropogenic component of the terrestrial sink that differs from common scientific usage. The use of total sources and sinks here means that net CO<sub>2</sub> emissions will be less than that implied by Article 4.1's restriction. Because net emissions are decreasing as we move towards (and beyond) the net-zero point, this point will be reached earlier in the present calculations than it would if the unmanaged land sink rules were applied. In the context of providing a guide to how the Article 2 temperature goals might be reached, however, it is the total forcing results in Fig. 2 that are most appropriate. The later net-zero results that would be derived by using the UNFCCC GHG Inventory definition for the anthropogenic component of the terrestrial sink are an artefact of a sink term that misses a significant part of the total terrestrial sink.

## 5 Conclusions

Article 4.1 of the Paris Agreement is an attempt, by specifying a window when net-zero anthropogenic GHG emissions must be reached, to provide a guide to the emissions required to achieve the warming targets defined in Article 2. This window is, *a priori*, incorrect, for four reasons. First, to relate emissions to temperature changes, one must use the total emissions of all climate forcing agents. Second, apart from failing to consider the full suite of forcing agents, Article 4.1 fails to consider changes over time of natural forcing agents. Third, even then, if Article 4.1 terminology echoes terminology defined in GHG inventories, then the way anthropogenic emissions is defined is inconsistent with the conventional scientific definition. Fourth, if the net-zero windows stated in Article 4.1 were derived through the use of GWP-100 values to aggregate emissions over GHG gases, then this will lead, through this alone, to incorrect results ... as demonstrated in Section 2.

As a positive note in regard to the fourth item, the UNFCCC allows some flexibility in how emissions should be aggregated (see paragraphs 37 and 38 of the Annex to UNFCCC Decision 18/CMA.1, agreed at COP24 in December 2018). Thus, even under existing legislation, it would be legitimate to use radiative forcing as the aggregation metric ... with the clear advantage that it provides a direct link to temperature changes.

A primary result of this paper is to provide a way to accurately determine the net-zero point for GHG emissions, by showing that this point corresponds to the point at which GHG radiative forcing is maximized. For the 1.5 °C Article 2 target, net-zero GHG emissions have been found to occur well before 2050 (in 2036 and 2044 in the two 1.5 °C examples). For the alternative target of "well-below 2 °C," net-zero GHG emissions must be reached early in the 2050s decade. The implication for future emissions is that the mitigation task is much more difficult than might be inferred from Article 4.1. Even correcting the Article 4.1 window, however, is not enough to satisfy the goal of linking Article 4.1 to Article 2 because giving information on net anthropogenic GHG emissions alone is insufficient: it is total radiative forcing that determines future warming.

Monitoring progress towards net-zero GHG emissions using the conventional GWP-100 scaling method, even if this could be done accurately, is of little value. Instead, what is required is to monitor changes in GHG forcing based on observed concentrations, together with other forcing agents that affect the climate system, and aggregating these quantities. This would provide more accurate and more useful information than is currently available.

To account for these results would require a fairly radical change to the UNFCCC inventory accounting procedure, eliminating the use of the GWP-100 scaling procedure and prioritizing the use of radiative forcing as an aggregation metric. Whether this requires adding



an Annex to the Paris Agreement (as allowed under Article 23 of the Agreement) is an issue that could be discussed at the first scheduled global stocktake meeting in 2023 (see Article 14 of the Agreement, which also notes the need for policies to be based on the “best available science”). Although stocktake meetings are primarily to assess “progress towards achieving the purpose of (the) Agreement,” it is clear that improvements in the science underlying the Agreement should be incorporated in UNFCCC documents, because such improvements are central to assessing progress towards meeting the temperature targets defined in Article 2.

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**Data availability** Data for all figures and the emission scenarios employed are available through Figshare via ... <https://doi.org/10.4225/55/5a164b9179a9a>.

**Code availability** An open source version of the MAGICC code is in the process of being made available. A user-friendly version of the software can be downloaded from the NCAR web site.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The author declares no competing interests.

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