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

Tom M. L. Wigley (tmlwigley@gmail.com)
University of Adelaide https://orcid.org/0000-0002-2882-5421

Research Article

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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_2 emissions to equivalent CO_2 emissions. As a test case using methane, 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. This shows that the net-zero point needs to be reached as early as 2036, much sooner than in the Article 4.1 window. Other scientific flaws in Article 4.1 that further undermine its purpose to guide efforts to achieve the Article 2 temperature targets are discussed.

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.”

Article 2’s goal can be broken down into two distinct goals … “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_2 GHGs to CO_2 equivalent emissions (ECO_{2e}) and then aggregate these values. For calculating CO_2 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_2 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_2 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 Emissions 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_2 gas emissions to equivalent CO_2 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_4) emissions changes to changes in equivalent CO_2 emissions.

This requires imposing some CH_4 reduction scenario on a baseline emissions 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 $TgCH_4$ over 2020 to 2120. Then the coupled gas-cycle/climate model MAGICC (Wigley et al., 2009) is used with a climate sensitivity of 3°C to calculate the corresponding temperature perturbation (labelled "TRUE" in Fig. 1). The equivalent CO_2 emissions perturbation is then calculated using, as scaling factors, the 20-year and 100-year GWP values for CH_4 from the IPCC AR5 report. The baseline CO_2 emissions are then reduced by these amounts. MAGICC is then used to determine the temperature perturbations for these CO_2 perturbations, keeping CH_4 emissions at the baseline level.

The results are shown in Fig. 1. It is clear that the use of GWP-100 grossly underestimates the magnitude of the temperature perturbation. This is a serious error. GWP-20, however, provides a much better match to the TRUE answer out to 2120 (the end of the CH_4 perturbation) and is superior to GWP-100 out to 2230. Quantitatively, these results are sensitive to the choice of baseline scenario and perturbation, but the general qualitative conclusion drawn here is independent of these choices.

The main significance of this GWP-100 error lies in its use in quantifying multi-gas Nationally Determined Contributions (NDCs) [emissions 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 is also an issue that should also be of concern to all countries where methane emissions reductions contribute significantly to their NDCs. Because of the GWP-100 error, these countries will not be given sufficient credit for their methane emissions 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 should be the starting point for such a guide.

For projecting 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 is given in the Summary for Policymakers of the IPCC SR15 report (Box SPM.1), which defines “Net-zero emissions” for CO_2 as occurring “ … when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals” (“Definition B”).

Since total sources (or sinks) are the sum of their anthropogenic and natural components, if there were a continuing balance between natural CO_2 sources and sinks these two definitions, A and B, would be equivalent. This is a debateable assumption; the above two definitions, in general, are not equivalent because natural GHG sources and sinks vary over time.

The UNFCCC definition for the anthropogenic component of the terrestrial CO_2 sink adds an additional complication. A major part of this sink is its amplification through the CO_2 fertilization effect, the changes in which result mainly from anthropogenic increases in atmospheric CO_2 concentration. While this affects all of the terrestrial biosphere, the UNFCCC rules state that only the part that arises in the managed terrestrial biosphere can be counted as anthropogenic. This is an important issue because Article 4.1 refers specifically to anthropogenic sources and sinks. If the UNFCCC definition for the terrestrial biospheric sink is used to define net anthropogenic emissions for CO_2 this leads to a third definition (“Definition C”). This complication is discussed further below.

It is clear from the above that any assessment of Article 4.1 is potentially a complex exercise. 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 goals 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_2 emissions to equivalent CO_2 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 aerosols, tropospheric ozone (which is not considered to be a GHG under the Kyoto Protocol) and land use changes.

The method derived here is to replace the net anthropogenic emissions concept by total radiative forcing, the sum of the forcings of all climatically active species and boundary changes, 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_2 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_2 emissions 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. How do we define and quantify this term? Using radiative forcing rather than concentration as a metric allows us to bypass this problem.For CO_2 maximizing concentration means that CO_2 radiative forcing is also maximized. In the GHG case, the net-zero GHG emissions point is therefore the point where total GHG radiative forcing is maximized. Radiative forcing is therefore a legitimate possible 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 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 emissions 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 at 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 credibilty 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 emissions 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 emissions point.

However, in terms of when these forcing maxima are reached, 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 2051 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.

Although Article 4.1 considers only the zero point of GHG forcing, the method used here to identify this point is of more general applicability. First, radiative forcing can easily be coverted to define the full time series of equivalent CO_2 concentrations in any future projection. Once the concentration trajectory has been established, this can then be converted to a projection of ECO_{2e} changes by using a carbon cycle model in inverse mode. Equally, historical ECO_{2e} variations can be quantified accurately in the same way using NDC information from Parties to the Paris Agreement, avoiding the use of flawed GWP-100 scaling. Further information on this approach is given in Wigley (1998), where inverse calculations are used to define the Forcing Equivalence Index (FEI) as an alternative to GWPs.

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 unconventional definition for the anthropogenic sink of CO_2 into the terrestrial biosphere used by the UNFCCC. The first thing to note is that this odd partitioning of the terrestrial sink 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 natural components.

However, there is an effect because of Article 4.1's restriction to employ only the anthropogenic 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_2 emissions will be less than that implied by Article 4.1. 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 UNFCCC sink rule were applied. In the context of providing a guide to how the Article 2 temperature goals might be reached, however, it is the results in Fig. 2 that are correct. The later net-zero results that would be derived by using the UNFCCC rule for the anthropogenic component of the terrestrial sink are merely a deceptive artefact of a sink term that misses a significant part of the total terrestrial biosphere 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 for NDCs, then the way anthropogenic emissions is defined is inconsistent with the conventional scientific definition. Fourth, although the method for calculating the net-zero window is not stated, if this 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, it has been shown that net-zero GHG emissions must 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 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 individual NDCs, 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 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..

Declarations

Competing interests:

The author declares no competing interests.

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Fact Sheet #1

For the paper by Tom Wigley, to be published in the journal *Climatic Change* entitled "The relationship between net GHG emissions and radiative forcing with an application to Article 4.1 of the Paris Agreement."

Introduction

The Paris Agreement on climate is the international agreement on how to respond to the threat of global warming. It was agreed to at a meeting of the United Nations Framework Convention on Climate Change (UNFCCC) held in Paris in November 2015. The Agreement entered into force on 4 November 2016.

From a climate science perspective, the most important Article in the Paris Agreement is Article 2, which specifies a global warming goal that Parties to the Agreement should strive to achieve in order to avoid dangerous interference with the climate system … i.e., a goal to keep the temperature of the planet within tolerable limits.

Article 2 quantifies this warming goal. It states that the increase in global average temperature since pre-industrial times (defined as the period 1850 to 1900) should be held "to well below 2°C", while "pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".

The scale of the challenge to keep warming within tolerable limits is evident when one realizes that we have already warmed the planet by about 1.2°C. The present warming rate is about 0.2°C per decade. No matter what we do, this rate will almost certainly continue for two or more decades into the future. It is clear, therefore, that we are virtually committed to passing the 1.5°C threshold some time in the mid to late 2030s.

Brief Summary

This paper presents a devastating critique of Article 4.1 of the Paris Agreement on climate change.

Article 4.1 suggests that to meet the temperature targets of Article 2 net anthropogenic GHG emissions must fall to zero some time in the window 2050 to 2099. Many countries have decided to aim for the low end of this range, but the present paper shows that even this is insufficient:"net-zero" needs to be reached even earlier than this, as early as 2036. The paper, furthermore, shows that the goal of reaching net zero GHG emissions *per se* is of minimal value because (1) it ignores the effects of non-GHG forcing agents, and (2) it fails to consider what might be required after the net-zero point is reached.

Manuscript Overview

This new paper is concerned with Article 4.1 of the Paris Agreement, the primary goal of which is to provide guidance on how "to achieve the long-term temperature goal set out in Article 2". To this end, Article 4.1 states that we need to decrease greenhouse-gas (GHG) emissions so that net anthropogenic GHG emissions fall to zero some time in the window 2050 to 2099. In other words, to meet the temperature goal of Article 2, net-zero anthropogenic GHG emissions must be reached some time in this window. Is the 2050 to 2099 window correct? … or, more importantrly, is it even relevant? My paper shows that the answer to these questions is, first, "no", and second, "only marginally".

The purpose of my paper is to provide a critical assessment of Article 4.1.

There are three aspects of the wording of Article 4.1 that are crucial here: (1) how to define "net emissions"; (2) the significance of the word "anthropogenic"; and (3) the focus on GHG emissions (i.e., not just the emissions of CO_2).

1. The term "net emissions" is shorthand for the difference between sources and sinks. This is generally accepted. So the question is … what emissions?
2. Article 4.1 restricts emissions to anthropogenic emissions only (i.e., those arising from human activities). Is this enough? Again, the answer is "no". In modelling the growth of CO_2 and other GHG concentrations, it is essential to consider **all** sources and sinks, not just anthropogenic sources and sinks.

3. The focus on GHGs alone in Article 4.1 is an even more limiting restriction. Temperature changes depend on the effects of all factors that affect the climate, not just GHGs. The most important missing factors are aerosols, particularly sulfate aerosols, and tropospheric ozone.

Article 4.1, with its restriction to anthropogenic GHGs, falls at the first jump, because information on anthropogenic GHGs alone is insufficient to fully understand how to meet the Article 2 temperature goals.

There is a more fundamental problem with Article 4.1, and this is the issue of how to combine, or aggregate, the emissions of different GHGs. To do so we need to make the emissions of different GHGs directly comparable. The UNFCCC recommends that we do this by applying appropriate scaling factors to the emissions of different GHGs; and they further tell us to use 100-year Global Warming Potentials (100-year GWPs) as the scaling factors. Applying these scaling factors converts the emissions of non-CO_2 gases to “equivalent CO_2 emissions”… after which we can calculate the aggregated effect of all GHGs simply by adding their equivalent CO_2 emissions.

In the first part of my paper I test this GWP-100 scaling method using a reduction in methane emissions as an example of an emissions perturbation for a non-CO_2 gas. I calculate temperature changes for this scenario in two ways. Firstly, I use a climate model to calculate the effects of the reduction in methane emissions directly. Secondly, I use the GWP-100 scaling method to convert the methane emissions reduction to the equivalent CO_2 emissions reduction, and then use the climate model again to calculate the implied change in temperature. The results of these two methods differ markedly. **The UNFCCC scaling method fails.**

We therefore need a more accurate method for aggregating GHG emissions. I derive a method that uses radiative forcing as the aggregation metric. This allows me to define the required net-zero GHG point accurately: the net-zero point corresponds to the point at which total GHG radiative forcing maximizes.

Using emissions scenarios that meet the 1.5°C warming target specified in Article 2, I find that the net-zero GHG point must be reached as early as 2036. In other words, if the claim implied by Article 4.1 that the net-zero GHG emissions point is what controls whether we meet the Article 2 warming targets is correct, then we need to reach this point much earlier than the window stated in Article 4.1. But this claim is manifestly incorrect. Whether or not we reach an Article 2 warming goal depends as much on what we do after reaching the target net-zero date, as it does on the target date *per se*.

The term “net-zero” has become a buzz-word for many politicians and environmental groups, but I suspect that few of these people understand what the term “net-zero emissions” means, or just how relevant the net-zero emissions point is to meeting the warming goal of Article 2.

My work shows, first, that the target for reaching net-zero GHG emissions given in Article 4.1 is much too lenient. This is important because it means that **we must reduce GHG emissions much more rapidly than is implied by Article 4.1**. However, in terms of meeting the ultimate warming goal set in Article 2, the net-zero emissions point is of only marginal relevance at best. This is because GHG emissions are only part of the reason for future warming. To understand and project future warming we must consider all climate-forcing agents … and Article 4.1 fails to do this. Furthermore, it is likely that many of those who advocate for “net-zero” fail to realize that this is not the end. **Even when the net-zero point is reached, net emissions and both GHG and total radiative forcing will have to continue to be reduced for at least a further century if we are to successfully meet the Article 2 target.**

In my paper I consider, as well as GHGs alone, the effects of the full suite of climate forcing agents. Scientifically, it is true that GHG forcing results are interesting. However, in the context of the issue of knowing “how to get there from here” (with “there” being the Article 2 warming targets) GHG-only target dates are, as already noted, of only marginal value. Yes, it is important to realize that the 2050 to 2099 window is far too weak a target … we must reduce GHG emissions much more rapidly than implied by this target if we are ever to meet the Article 2 warming goal. But we already have far more relevant and useful information for this purpose, to wit, the many detailed, multi-gas emissions scenarios that have been constructed for the IPCC SR-15 report, the focus of which is to assess the implications of the 1.5°C warming target. It is these data that provide scientifically credible insights into how to meet the Article 2 targets.

The important bottom line from my paper is that **one cannot provide useful guidance for achieving the Article 2 (or any) temperature goal using information about GHGs alone (or, more crucially, net anthropogenic GHG emissions alone).** Essentially, with the present wording, **Article 4.1 is conceptually flawed, incomplete and mathematically incorrect.**

As a final aside, it is my view that the above-mentioned SR-15 scenarios do not cover the full spectrum of possibilities for meeting the Article 2 targets, but that is a discussion for another day.

Tom M.L. Wigley, 14 Oct, 2021

School of Biological Sciences,

University of Adelaide,

South Australia, 5005.

Tel. +61 (0) 438 662 399

tmlwigley@gmail.com

Fact Sheet #2

For the paper by Tom Wigley, to be published in the journal *Climatic Change* entitled “The relationship between net GHG emissions and radiative forcing with an application to Article 4.1 of the Paris Agreement.”

The problem in a nutshell

My paper is primarily a critique of Article 4.1 of the Paris Agreement on climate.

The main goal of Article 4.1 is to provide guidance on “how to achieve the long-term temperature goal set out in Article 2”. The Article 2 goal is “Holding the increase in global average temperature to well below 2°C above pre-industrial levels”, while, at the same time, “pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”.

The guidance provided by Article 4.1 is that “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.”

Paraphrasing, this means we need to reach net-zero emissions of anthropogenic GHGs some time in the 2050 to 2099 window.

My paper shows that we must reach this net-zero point as early as 2036.

The new science in my paper

Why is my result so different from the Article 4.1 window? I answer this question below.

The underlying scientific issue is … how to determine the net-zero point? I introduce a new method for determining the net-zero point. I show that the net-zero point for GHG emissions corresponds to the point at which GHG radiative forcing maximizes. This is a new result. It defines the net-zero point accurately, whereas the method used by the UNFCCC in determining this point is not accurate.

To provide the guidance required to fulfill the primary goal of Article 4.1 we must ask the right question.

The question

If we have an emissions scenario that satisfies either the “1.5°C” or “well below 2°C” goal of Article 2, at what point does this scenario reach the net-zero point for GHG emissions?

This is the question that my paper addresses and answers.

Just why my result is so different from the Article 4.1 window is difficult to answer, because the question that Article 4.1 addresses is never articulated. However, part of the answer lies in the fact that the method used by the UNFCCC to determine the net-zero point is based on flawed science. The early part of my paper explains and illustrates this flaw. It relates to the use of Global Warming Potentials (GWPs) to aggregate the emissions of different GHGs.

Article 4.1 is further flawed because it considers only GHG emissions. Temperature changes are determined by the full suite of climate forcing agents, which, apart from GHGs, include a range of aerosols and the effects of tropospheric ozone changes. This combination is referred to as “total forcing”. My paper considers total forcing as well as just GHG forcing.

Alternative questions

The question posed above is not the correct question to ask if we want to provide useful guidance on how to achieve the goal of Article 2 … even if we go beyond a consideration of just anthropogenic GHGs and consider the full suite of climate forcing agents..

What we need to know is, what is the net-zero point that will guarantee that we achieve the warming goal of Article 2. There is no single answer to this question. We can see this by thinking more about the original question and its answer.

What happens if we are successful in reaching a specific net-zero point … such as the 2036 point that corresponds, according to my analysis, to an eventual warming of 1.5°C after a small warming oveshoot.

There is no guarantee that, after this, we will limit eventual warming to 1.5°C. The problem is that Article 4.1 says nothing about what happens, or needs to happen, after we reach the net-zero point; and here there is an infinite range of post net-zero possibilities. My paper shows that, to achieve the 1.5°C goal, we must continue to reduce GHG emissions for a century or more after reaching the net-zero point. If we fail to meet this long-term emissions reduction challenge, the eventual warming will be greater than 1.5°C, and could be significantly greater than 2°C.

Furthermore, my paper shows that, if it appears that we will not reach, for example, the 2036 net-zero point until some time after this date, all is not lost. We could still achieve the 1.5°C eventual warming target by reducung emissions more rapidly after 2036.

Flexibility after reaching (or failing to reach) some net-zero point still allows us to "catch up" if we appear to be failing to achieve an Article 2 goal. Specifying a particular net-zero target date may be useful to "concentrate the mind", but it is of little value by itself in determining policy. Policies need to look beyond the point at which some net-zero GHG emissions point is reached … and what we do "beyond net-zero" is at least as important as what happens up to this point. Article 4.1 fails to consider this.

Tom M.L. Wigley, 14 Oct, 2021

School of Biological Sciences,

University of Adelaide,

South Australia, 5005.

Tel. +61 (0) 438 662 399

tmlwigley@gmail.com

Figures

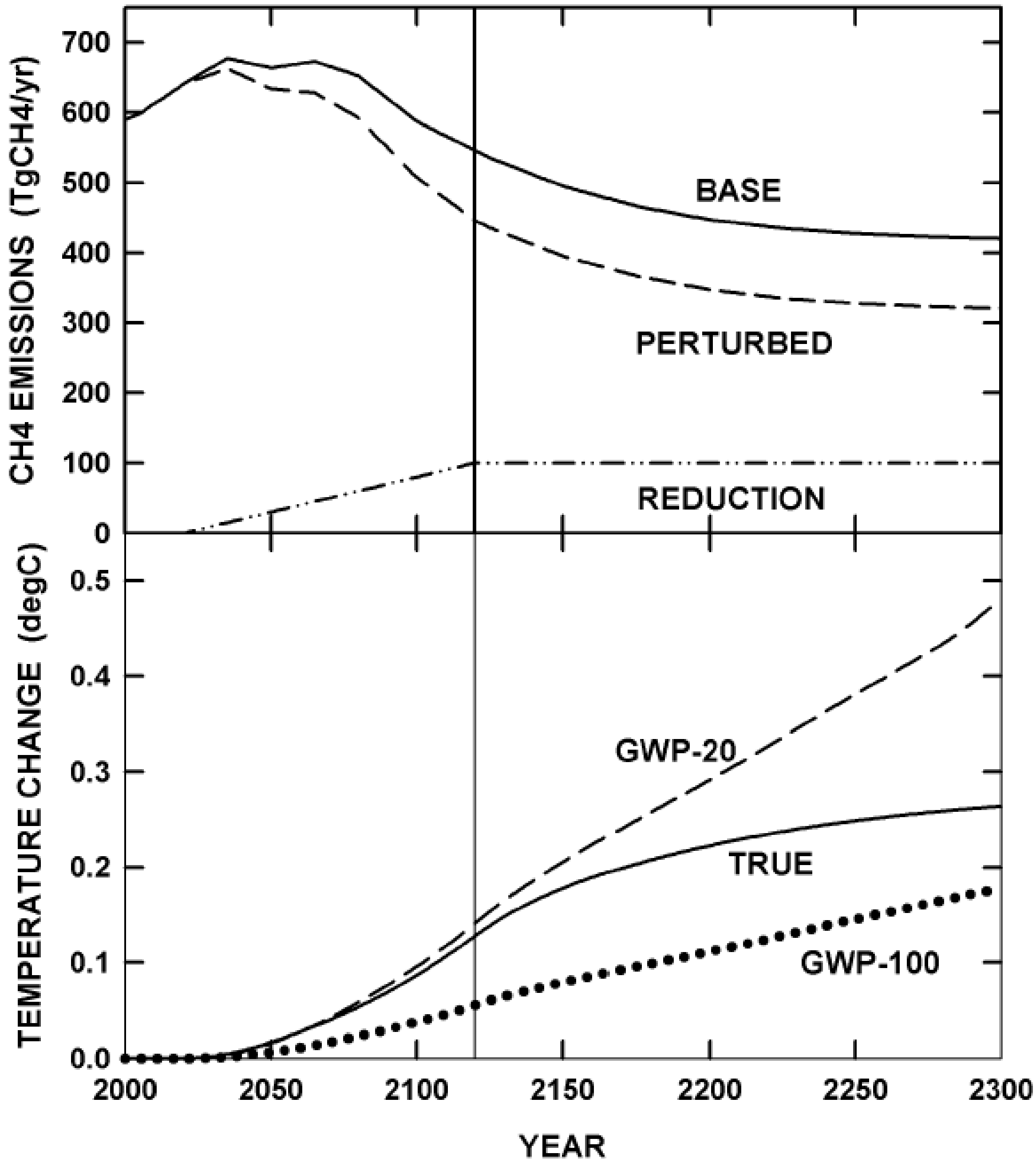

Figure 1

Testing ECO2e based on GWP-100 for an idealized reduction in CH4 emissions. Temperature changes for the ECO2e cases are compared with those based on the "TRUE" case derived using the original CH4 emissions reduction. Both GWP-100 and GWP-20 results are shown for comparison. CH4 emissions are total emissions, anthropogenic plus natural. For clarity the temperature results, which are decreases, are multiplied by minus 1.

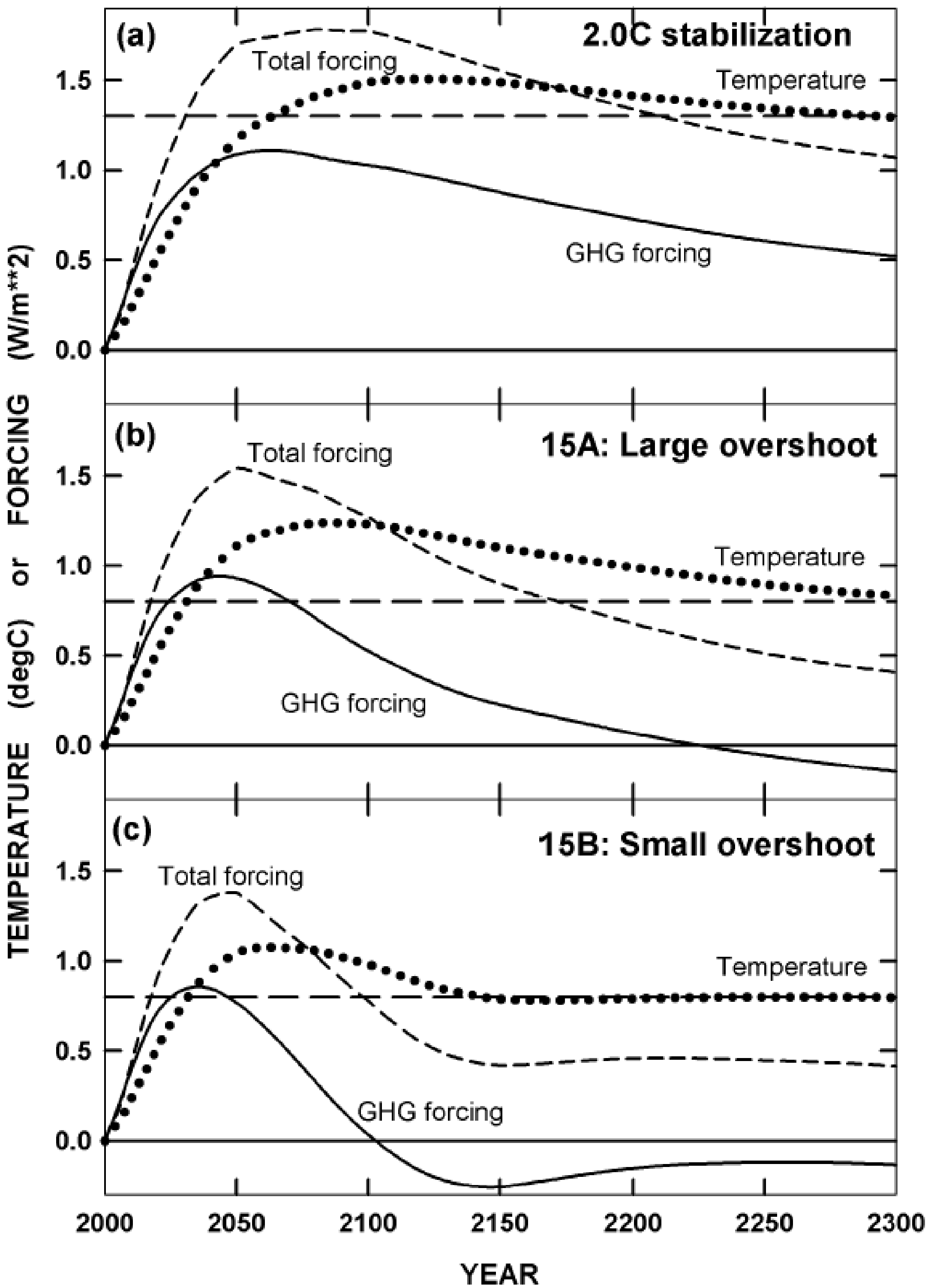

Figure 2

Temperature and radiative forcing changes for two scenarios that tend asymptotically to 1.5°C above the pre-industrial level (panels 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.