Assessing the Relative Climate Change Impacts of Methane and Nitrous Oxide by Using Climate Change Impact Potentials.

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Abstract

All greenhouse gases contribute to global warming, but they have different absorption properties of infrared radiation, and different longevities in the atmosphere. The comparison of different gases, or the importance of the release of the same gas emitted at different times, is currently quantified through their Greenhouse Warming Potentials. They are simply calculated as the cumulative radiative forcing attributable to each gas over a specified time horizon, most typically 100 years. However, those calculations are not explicitly linked to an assessment of the climate-change impacts that result from the emission of different gases.

A new metric is proposed here that explicitly starts from an assessment of climate change impacts to derive a quantitative assessment of the importance of each gas. This new metric would reduce the relative importance of methane emissions and increase the importance of nitrous oxide emissions.

1. Introduction

The importance of different greenhouse gases is generally quantified through their Greenhouse Warming Potentials (GWPs), which are calculated as the cumulative radiative forcing over a specified time frame (Lashof and Ahuja 1990; Rodhe 1990). The time frames typically used are 20, 100 and 500 years, with 100 years the most common. 100 years is also used for setting emissions targets under the Kyoto Protocol (UNFCCC 1997).

However, GWPs have been derived without an explicit notion of the ultimate climate change impacts that are to be avoided through greenhouse gas emission controls. Climate change mitigation is about ameliorating ultimate climate-change impacts, and it is only possible to assess the relative marginal contribution of different gases to ultimate climate-change impacts if impacts are explicitly defined and quantified. It is therefore important to begin with an explicit assessment and quantification of the key impacts, including a judgment of their relative importance. Relevant metrics for a comparison of different gases should then be derived as a subsequent step to guide appropriate mitigation efforts.

The present paper describes a new metric for comparing different greenhouse gases that could be used as an alternative to GWPs. This new metric, the climate change impact potential (CCIP), is based on an explicit and transparent consideration and quantification of climatic impacts. It aims to quantify the marginal impacts of extra units of CO_2, CH_4 and N_2O emitted in 2010 by calculating and summing impact damages over the next 100 years. The paper begins by listing the key elements included in deriving CCIPs, gives its mathematical implementation, and illustrates the impact patterns calculated for extra emissions of different gases, and how that is reflected in CCIPs. A more comprehensive description is provided by Kirschbaum (2013).

2. Requirements for Climate Change Impact Potentials

2.1 Kinds of Climate Change Impacts

There are at least three different kinds of climate change impacts (Kirschbaum 2003a, b, 2006) that can be categorised through their relationships to temperature increases. They are:

- the impact related to the direct effect of elevated temperature;
- the impact related to the rate of warming; and
- the impact related to cumulative warming.

The damage function used here sums impacts over 100 years, treating each of the three kinds of impacts as equally important.

2.1.1 Direct Temperature Impacts

The direct temperature increase is the relevant measure for impacts such as heat waves (e.g. Rey et al. 2007; Huang et al. 2011) and other extreme weather events (e.g. Webster et al. 2005; Hoyos et al. 2006). Coral bleaching, for example, has been observed in nearly all tropical coral-growing regions (e.g. Baker et al. 2008) and is clearly and unambiguously related to temperature anomalies (McWilliams et al. 2005; Baker et al. 2008). Similarly, crop failures caused by drought (e.g. Dai 2011), either due to below-average rainfall alone, or coupled with above-average temperatures (e.g. Nicholls 2004), can be linked to the climatic conditions in the year in which they occur.

2.1.2 Rate of Temperature Change Impacts

The rate of temperature increase is a concern because many aspects of a warmer world may not be inherently worse than the current conditions, but the change from current to future conditions will be difficult for both natural and socio-economic systems. If change is slow enough then systems can adapt or relocate with changing temperatures, but faster change may be too rapid for such adjustments.

For example, the distribution of most naturally occurring species is restricted to a narrow range of temperatures (e.g. Hughes et al. 1996), and climate change will make climatic conditions in their current habitats unsuitable for many species. Modelling studies have thus pointed to serious and massive extinction risks from climate change (e.g. Thomas et al. 2004). Parmesan and Yohe (1993) documented that many species are already impacted by climate change and that their distributions are moving to higher latitudes or altitudes. However, recorded migration rates are substantially slower than the current rate of movement of zones with equivalent climatic conditions, pointing to an increasing mismatch between the habitats where species thrive and the conditions in which they actually find themselves.

Some modelling studies have also shown that other concerning climate phenomena, such as the over-turning of deep-ocean water, may be related to the rate of change of climatic conditions (Stocker and Schmittner 1997).

2.1.3 Cumulative Warming Impacts

The third kind of impact relates to cumulative warming, which is the relevant metric for impacts such as sea-level rise (Vermeer and Rahmstorf 2009). The extent of sea-level rise is related to both the magnitude of warming and the length of time over which oceans and glaciers are exposed to increased surface temperatures. Sea level rise will therefore not be halted even if further temperature increases could be curtailed (e.g. Meehl et al. 2012). Sea levels will continue to rise for many centuries if global temperatures remain above pre-industrial levels.

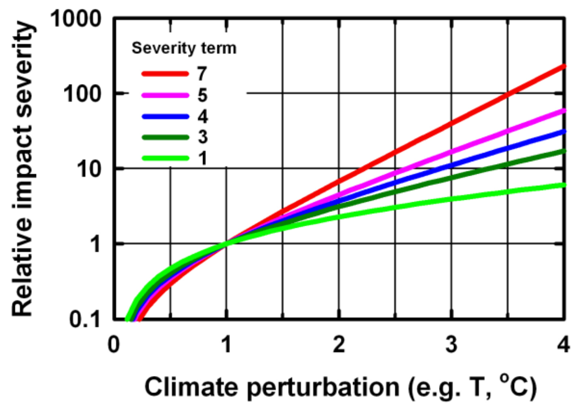
Lenton et al. (2008) further listed a range of possible tipping points in the global climate system. If the world passes these thresholds, the world's climate could shift into a different climate mode, with potentially serious and possibly irreversible consequences. These tipping points include factors such as dieback of the Amazon rainforest, shut-off of the Atlantic thermohaline circulation, or Arctic sea-ice melting. Their likely occurrence is mainly linked to cumulative warming.

2.2 Impact Severity

Climate change impacts clearly increase with the extent of the underlying climate perturbation – but how strongly? By 2012, global temperatures had increased by about 1°C above pre-industrial temperatures (Jones et al. 2012), equivalent to a rate of change of about 0.01°C yr^{-1}, with sea-level rise by about 20 cm (Church and White 2011; Spada and Galassi 2012), and there are increasing numbers of unusual current-day weather-related events that have been attributed to climate change (e.g. Schneider et al. 2007; Trenberth and Fasullo 2012). By the time temperature increase reaches 2°, or sea level rise reaches 40 cm, would we expect their impacts to be twice as bad, or increase more sharply?

Schneider et al. (2007) comprehensively reviewed and discussed the quantification of climate change impacts and its relationship to underlying climate perturbations, but concluded that a formal quantification of impacts is not yet possible. This is due to a combination of the considerable scientific uncertainty that still remains and the intertwining of the scientifically quantifiable probability of the occurrence of certain events and a value judgement as to their importance and significance.

Figure 1. Quantification of the severity of impacts for different climate perturbations, such as temperature changes, using different severity parameters.



Schneider et al. (2007) therefore provided only a partial quantification of climate change impacts. While a damage response function cannot be obtained rigorously and objectively, such a function is nonetheless used implicitly whenever society makes any assessment of the importance of climate change. The process followed formally in this paper is akin to the process that has been followed implicitly in discussions of the importance of climate change and that has led to the current level of concern and the partial willingness to pursue mitigative measures.

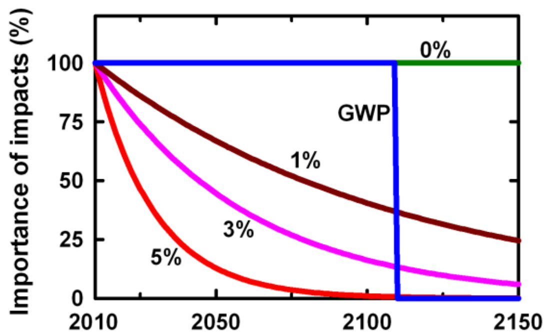
Figure 1 shows possible responses curves between an underlying climate perturbation and the resultant impact severity, with the central curve the one used in the present work. This is quantified as the relative impact, normalised to the impact for a perturbation of 1, such as a 1° increase in temperature, which approximates the current climate perturbation. The curve used below gives an approximately exponential increase in impacts with increasing perturbations. The function with impact severity ‘4’, for example, means that a 3°C temperature rise would have 10 times the impact of a 1°C temperature increase (Fig. 1). This choice of response functions, with both its shape a severity value of 4 thus includes both value judgement and a scientific assessment of key impacts and vulnerabilities.

2.3 Discount Factors

The next question is whether future impacts should be discounted in some way. Should near-term impacts be treated as more important than impacts in the more distant future? Economists typically apply fairly large discount rates (of at least several percent), which mathematically render impacts more than a few decades into the future as essentially irrelevant (Fig. 2). The choice of discount rates is hence one of the most critical components of any impacts analysis. The influential Stern report (Stern 2006), for example, derived a fairly bleak outlook on the seriousness of climate change, which was to a large extent due to the use of an unusually low discount rate of only 1.4%.

While the use of large discount rates is sensible in purely economic analyses, it is questionable in environmental assessments as it essentially treats the lives and livelihood of our children and grandchildren as less important than our own, which is hard to justify on ethical grounds (e.g. Schelling 1995; Sterner and Persson 2008). On the other hand, using a 0 discount rate would treat impacts in perpetuity as equally important as short-term impacts, which raises at least practical problems as the ability to predict events and their significance for future populations must surely decline over time.

Figure 2. The relative importance of impacts encountered in different years with the use of different discount rates. The Figure also shows the approach used in the calculation of Greenhouse Warming Potentials (GWP).



The calculation of GWPs essentially uses a 0 discount rate over a chosen assessment horizon (usually 100 years), but truncates the assessment at the end of the assessment period. This avoids a preferential emphasis on the impacts of one generation over another, yet avoids the unmanageable situation of having to assess impacts in perpetuity. That approach is also used for the present work.

3. Calculation Methods

3.1 Quantifying Climate Change Impact Potentials

To quantify the three different kinds of impacts, it is necessary to first calculate the perturbation that underlies each kind of impact. The perturbations $P_{y,T}$ in year y underlying direct temperature impacts are simply calculated as:

$$P_{y,T} = T_y - T_p \tag{1}$$

where T_y is the temperature in year y and T_p the pre-industrial temperature.

The rate of temperature change perturbation, $P_{y,\Delta}$, is calculated as the rate of temperature change over 100 years:

$$P_{y,\Delta} = (T_y - T_{y-100}) / 100. \tag{2}$$

The cumulative temperature perturbation, $P_{y,\Sigma}$, is calculated as the sum of temperatures above pre-industrial temperatures:

$$P_{y,\Sigma} = \sum_{i=p}^{y} (T_i - T_p) \tag{3}$$

where T_i is the temperature in every year from pre-industrial times to the year of interest, y. For practical reasons, the year 1900 was taken as the pre-industrial year.

All three perturbations are then normalised to generate relative perturbations, Q, in a range up to 1 by dividing by the most extreme perturbation over the next 100 years, calculated under the RCP6 concentration pathway (see below):

$$Q_{y,T} = P_{y,T} / max(P_{T,RCP6}) \tag{4a}$$

$$Q_{y,\Delta} = P_{y,\Delta} / max(P_{\Delta,RCP6}) \tag{4b}$$

$$Q_{y,\Sigma} = P_{y,\Sigma} / max(P_{\Sigma,RCP6}) \tag{4c}$$

where the P-terms are the perturbations calculated under the three kinds of impacts, the Q-terms are the normalised forms of the perturbations, and the *max*-terms are the maximum perturbations calculated over the next 100 years.

Impacts, I, are then derived from their respective relative perturbations as:

$$I_{y,T} = [(e^s)^{Q_{y,T}}] - 1 \tag{5a}$$

$$I_{y,\Delta} = [(e^s)^{Q_{y,\Delta}}] - 1 \tag{5b}$$

$$I_{y,\Sigma} = [(e^s)^{Q_{y,\Sigma}}] - 1 \tag{5c}$$

where the Q-terms are the normalised perturbations and s is a severity term that describes the steepness of impact increases with increasing relative perturbation. This equation is graphically illustrated with different severity terms in Figure 1.

The work here is based on the IPCC emission pathways prepared for the Fifth Assessment Report (van Vuuren et al. 2011). Four "representative concentration pathways" (RCPs) were developed to cover the range of likely future concentrations based on a range of socio-economic and technological assumptions and mitigative responses. The key simulations shown here are based on RCP6 (with radiative forcing of 6 W m^{-2} after 2100).

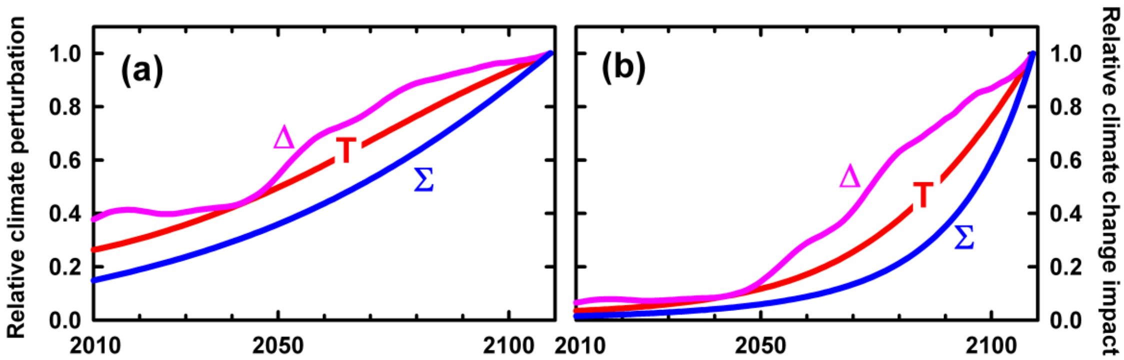
The calculations of radiative forcing and temperature follow the approach of Kirschbaum et al. (2013) as adapted for the calculation of CCIPs by Kirschbaum (2013). Readers are referred to those publications for further details of the underlying calculations.

4. Results

4.1 Impacts under Business-As-Usual Concentrations

Underlying any assessment of the marginal effect of an additional unit of a specific gas must be an assessment of the impacts that already occur without the additional emission units. This is shown here for both the underlying perturbations related to the three kinds of impacts (Fig. 3a) and the resultant impacts after applying the severity term to each (Fig. 3b). This is expressed relative to the most severe perturbations and resultant impacts expected over the next 100 years.

Figure 3. Calculated relative climate perturbations (a) and resultant impacts (b) under the three kinds of impacts. T refers to direct temperature impacts, Δ to impacts related to the rate of warming, and Σ to impacts related to cumulative warming. Maximum perturbations to 2109 were 3.4 °C, 0.025 °C yr^{-1} and 241 °C yr for the three kinds of impacts, respectively.

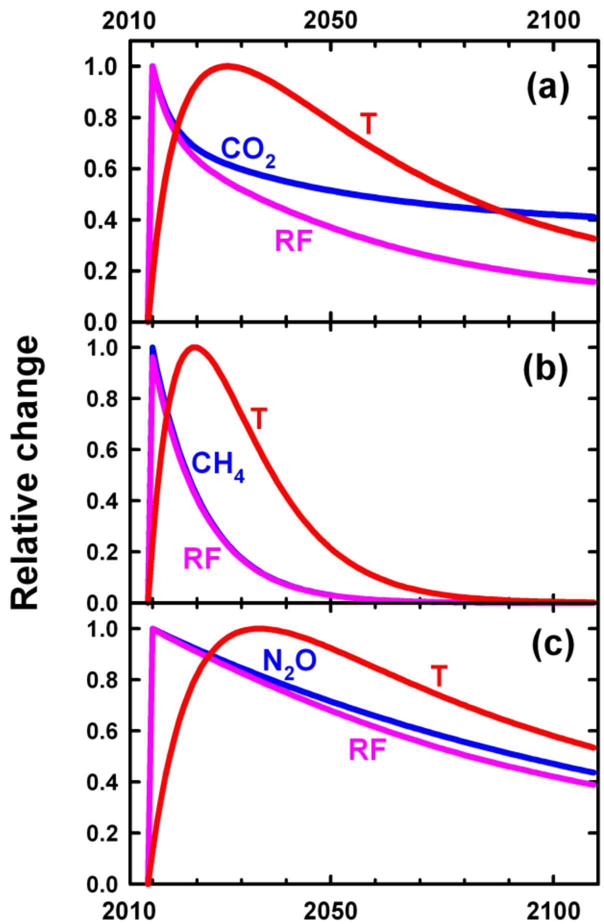


The Figure shows that under RCP6 (considered to be closest to 'Business-as-Usual'), all three kinds of impacts will continue to increase and attain their greatest impacts by 2109, which is similar to projections under older emission scenarios (Kirschbaum 2003a). The perturbations related to direct-temperature and rate-of-warming impacts increase nearly linearly over the next 100 years (Fig. 3a), but, because of the non-linear impact-perturbation relationship (Fig. 1), this translates into highly non-linear increases in impacts, with the most severe impacts found at the end of the assessment period (Fig. 3b). This is most pronounced for cumulative warming impacts.

4.2 Physico-Chemical Effects of Extra Greenhouse Gas Emissions

With an established pattern of background impacts, it becomes possible to calculate the marginal impact of the emission of an additional unit of a greenhouse gas. First, it is necessary to establish the physico-chemical consequences of adding a unit of the different greenhouse gases. For all three gases (CO_2, CH_4, N_2O), the concentration increase is greatest immediately after their emission and then decreases over time (Fig. 4). For CH_4, the decrease is quite rapid, whereas it is much slower and prolonged for CO_2 and N_2O.

Figure 4. Calculated increase in the atmospheric concentrations of CO_2 (a), CH_4 (b) and N_2O (c) due to the emission of one additional unit of each gas in 2010, together with their radiative forcing and resultant temperature increases over the next 100 years. All numbers are normalised to the highest values calculated over the next 100 years.



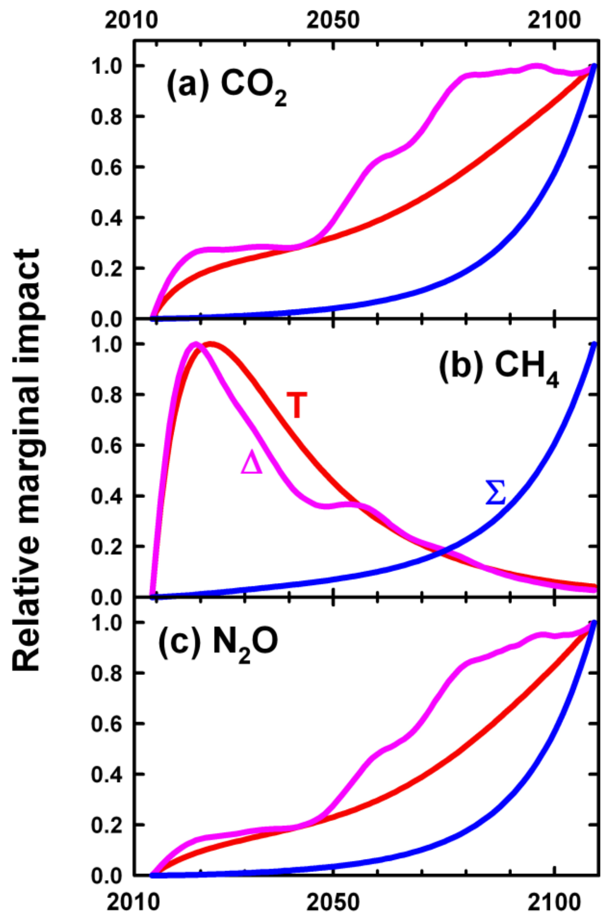
These concentration changes then cause enhanced radiative forcing (Fig. 4). It, too, is highest immediately after the emission of a unit of each gas and decreases over time thereafter. It drops proportionately faster than the concentration decrease due to partial saturation of the relevant infrared absorption bands of each gas. That is most pronounced for CO_2 (Fig. 4a), for which the projected background concentrations are expected to increase considerably over the next 100 years so that the addition of a marginal unit of CO_2 becomes progressively less effective (Reisinger et al. 2011).

Radiative forcing then drives changes in temperature, but with a further delay due to the thermal inertia of the world's climate systems. Hence, maximal temperature increases lag peak radiative forcing by 15–20 years (Fig. 4).

4.3 Marginal Impacts of Extra Emissions

From the information in Figs 3 and 4, it becomes possible to calculate the marginal increase in climate-change impacts due to the addition of one extra unit of each gas (Fig. 5). This is shown here with impacts normalised to the highest extra impacts calculated over the next 100 years. The marginal extra impacts of the three different kinds of impacts follow different time courses, and show distinct differences for the three different gases.

Figure 5. Change in the three kinds of climatic impacts due to the addition of one unit of CO_2 (a), biogenic CH_4 (b) and N_2O (c) in 2010. T refers to direct-temperature impacts, Δ to rate-of-warming impacts, and Σ to cumulative-warming impacts. All numbers are normalised to the highest marginal impacts calculated over the next 100 years.



Following the addition of one of unit of CO_2 in 2010, the largest temperature increase occurs in about 2025 (Fig. 4a). However, that temperature increase occurs at a time when base temperatures are still fairly mild (Fig. 3a) so that the extra temperature increase early during the 21^{st} century is only moderately important for modifying direct-temperature impacts (Fig. 5a). Even though the temperature increase from a CO_2 addition in 2010 continues to diminish over time (Fig. 4a), it adds to a larger and larger base temperature to cause increasing ultimate impacts (Fig. 5a). That pattern is even stronger for cumulative warming impacts.

CH_4 additions, on the other hand cause increasing direct-temperature impacts only over a few decades after their emission (Fig. 5b). While temperature increases at later periods could potentially have greater impacts, the residual temperature increase several decades after the emission of CH_4 becomes so small as to have very little impact.

For cumulative warming impacts, however, the greatest marginal impact of CH_4 additions also occurs at the end of the assessment period. Even though the warming due to CH_4 emissions occurs early in the 21st century, that warming is effectively remembered in the cumulative temperature record, and leads to the largest ultimate impact when it is combined with a large base impact from cumulative warming (Fig. 5b).

The patterns for N_2O (Fig. 5c) are similar to those for CO_2. Because of its great longevity in the atmosphere, N_2O is still present many decades after its emission, when the temperature increase caused by N_2O combines with higher base temperatures to have a much greater impact than the same marginal temperature increase had at an earlier time with lower base temperatures.

For rate of warming impacts, the patterns are similar to the patterns for direct temperature impacts, and distinctly different for the different gases, but for cumulative warming impacts, the patterns are similar for all three gases. This is because cumulative warming can be increased in much the same way for contributions made earlier (for CH_4) as from on-going temperature enhancements (for CO_2 and N_2O). Even though the addition to the cumulative perturbation totals is made at different times for different gases, the increased perturbation has the largest impact when the additional cumulative warming adds to large base values (Fig. 3a) so that the largest impact increases occur at the end of the 100-year assessment period for all three gases (Fig. 5).

3.4 Climate Change Impact Potentials

The impacts shown in Figure 5 can then be summed over 100 years after the emission of a unit of each gas and expressed relative to the effect of the emission of one unit of CO_2 (Table 1). For comparison, the Table also shows summed radiative forcing over 100 years, which is comparable to GWPs. Calculated cumulative radiative forcing and GWPs are not identical, however, because cumulative radiative forcing is also affected by changes in the base-level gas concentrations, which is not included in GWP calculations, but conversely, the IPCC's calculations of GWPs employ more sophisticated models than the simplified routines used here. This particularly includes some higher-level atmospheric interactions that increase the importance of CH_4.

Table 1. Climate Change Impact Potentials calculated for a unit gas emission in 2010. All numbers are expressed as the impacts relative to corresponding impacts from the emission of CO_2. Calculations are done separately for biogenic (B) and fossil-derived (F) CH_4. The Climate Change Impact Potential (CCIP) is the average of the three individual impacts.

	Greenhouse Warming Potentials	Cumulative Radiative forcing	Direct T impacts	Rate of warming impacts	Cumulative warming T impacts	CCIP
CH_4 (B)	25	23	11	11	30	**17**
CH_4 (F)	25	26	13	13	33	**20**
N_2O	298	381	457	454	374	**428**

Calculated cumulative radiative forcing is similar to current GWPs for CH_4 (23-26 vs 25) but higher for N_2O (381 vs 298). For N_2O, the differences are mainly due to differences calculated for CO_2 because GWPs are calculated using constant background concentrations, whereas the expected increase in background CO_2 concentrations makes each additional molecule of CO_2 less effective at absorbing infrared radiation, and thereby increases the relative importance of other gases compared to CO_2.

The differences between biogenic and fossil derived CH_4 by about three units are due to the effect of CH_4 generation on the C cycle, which lowers the atmospheric CO_2 concentration (Boucher et al. 2009) and thereby reduces the overall warming effect of CH_4. This is not included in GWPs. Any CH_4 continues its radiative forcing as CO_2 after it has been oxidised, which increases its overall impact. Biogenic CH_4, however, first lowers the atmospheric CO_2 concentration by using one molecule of carbon to generate each molecule of CH_4. This reduces the overall impact of biogenic CH_4.

Importantly, CCIPs for biogenic and fossil CH_4 are only 17 and 20, respectively, compared to a GWP of 25. These lower values are due to the much lower direct-temperature and rate-of-warming impacts. Warming resulting from CH_4 emissions in 2010 occurs during a period when background temperature increases are still fairly mild so that even with the extra warming from CH_4, it does not reach damagingly high values (Fig. 5b). In contrast, cumulative warming impacts are 30 and 33, which is greater than the corresponding cumulative radiative forcing values (of 25 and 28). In this case, the earlier warming due to CH_4 gives more time for warming to accumulate, whereas with radiative forcing later during the 100-year assessment period, as would be the case for CO_2 and N_2O, some warming occurs after the end of the assessment period.

For N_2O, the CCIPs are substantially greater than the GWPs (428 vs 298). This is mainly due to changes in the relative infrared absorption efficiency of different gases as the calculated cumulative radiative forcing ratio of N_2O and CO_2 is already 381 and thus the major contributor to the overall higher CCIP.

4. Discussion

In this work, climate change impact potentials are presented as a possible alternative metric for comparing the effect of different greenhouse gases. Why use a new metric? Metrics for comparing different greenhouse gases are used to guide climate change mitigation efforts, and mitigation is ultimately about averting adverse climate change impacts. Hence, there is an obvious logic in starting with a clear definition and quantification of climate-change impacts. CCIPs are the numerical end result of following that procedure. CCIPs aim to combine an understanding of the underlying physics and atmospheric chemistry of climate change with an assessment of the relevant impacts on nature and society. That full assessment is needed to underpin the development of optimal mitigation strategies.

CCIPs require the definition of the most likely background conditions in order to quantify the marginal impact of an extra emission unit of a greenhouse gas. The use of CCIPs thus requires a periodic re-evaluation of expected background conditions to devise new optimal mitigation strategies. This is necessary in order to focus mitigation efforts continuously towards cost-effective climate-change impact amelioration (Johansson et al. 2006). The optimal mitigation strategy will therefore change with changing circumstances, including changes simply with the changing background concentration of greenhouse gases already in the atmosphere.

In particular, the use of CCIPs (instead of GWPs) would reduce the emphasis on the control of CH_4 and other short-lived gases as CH_4 molecules emitted in 2010 will have been removed from the atmosphere by the time the most damaging temperatures or rates of temperature changes will be reached. However, even CH_4 contributes to cumulative warming, but that contributes to only one of the three kinds of impacts. It thus reduces the importance of CH_4 but does not render it irrelevant. It also means that the importance of CH_4 is likely to increase over time as we approach the times of peak temperature increases where CH_4 can start to make increasing contributions to direct-temperature and rate-of-warming impacts as well.

5. Conclusions

Greenhouse Warming Potentials are used as the current metric to compare the importance of different greenhouse gases. They have become the default metric despite a widely accepted recognition that they are not very closely related to the ultimate impacts we are trying to avert. To achieve mitigation objectives most cost effectively requires a clearer definition and quantification of what exactly is to be avoided.

Over the years, there have been a few attempts to devise alternative accounting metrics. However, previous discussions on metrics did not systematically start from clearly defining impacts, quantifying them as a function of measurable aspects of climate change and then devising a metric based on that analysis.

This was attempted in the present analysis, with climate change impact potentials (CCIPs) as the resultant new metric. This analysis required a number of assumptions, which is a necessary part of the approach. Society uses greenhouse gas metrics to guide the mitigation strategy against adverse climatic changes. To do that effectively and to be able to target an optimal mix of greenhouse gases require an explicit definition of the timing and relative severity of different impacts. This necessitates a more complex analysis than the simple use of GWPs.

Climate change continues to be a significant threat for the future of humanity. Optimal climate change mitigation is needed to avert those threats as much as possible, yet the global community is showing a limited willingness to make short-term sacrifices in order to avert possibly serious long-term consequences for us and our children and grandchildren. The present work aims to contribute towards using the limited resources available for mitigation as optimally as possible.

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