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Future changes in global warming potentials under representative concentration pathways

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Abstract

Global warming potentials (GWPs) are the metrics currently used to compare emissions of different greenhouse gases under the United Nations Framework Convention on Climate Change. Future changes in greenhouse gas concentrations will alter GWPs because the radiative efficiencies of marginal changes in CO₂, CH₄ and N₂O depend on their background concentrations, the removal of CO₂ is influenced by climate–carbon cycle feedbacks, and atmospheric residence times of CH₄ and N₂O also depend on ambient temperature and other environmental changes. We calculated the currently foreseeable future changes in the absolute GWP of CO₂, which acts as the denominator for the calculation of all GWPs, and specifically the GWPs of CH₄ and N₂O, along four representative concentration pathways (RCPs) up to the year 2100. We find that the absolute GWP of CO₂ decreases under all RCPs, although for longer time horizons this decrease is smaller than for short time horizons due to increased climate–carbon cycle feedbacks. The 100-year GWP of CH₄ would increase up to 20% under the lowest RCP by 2100 but would decrease by up to 10% by mid-century under the highest RCP. The 100-year GWP of N₂O would increase by more than 30% by 2100 under the highest RCP but would vary by less than 10% under other scenarios. These changes are not negligible but are mostly smaller than the changes that would result from choosing a different time horizon for GWPs, or from choosing altogether different metrics for comparing greenhouse gas emissions, such as global temperature change potentials.

Keywords: GWPs, RCPs, UNFCCC, climate change metrics, global warming potential, multi-gas mitigation strategies

1. Introduction

Multi-gas mitigation strategies can achieve long-term stabilization targets at lower costs than emission reductions of CO₂ only [1–4], and provide greater flexibility as they allow emissions trading between different gases not only internationally but also domestically [5, 6]. To achieve this

tradability, multi-gas mitigation strategies require metrics that compare the emissions of different greenhouse gases through a common unit. Despite several identified shortcomings [7–10], global warming potentials (GWPs) with a 100-year time horizon are the most widely applied metric, including in reporting and accounting of national greenhouse gas emissions inventories under the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, which

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use numeric values as given in the IPCC's Second Assessment Report [11–14].

Changes in the relative weights placed on different greenhouse gases would affect the timing and extent of CO₂ and non-CO₂ mitigation action at national, regional and global levels. This applies particularly to CH₄ and N₂O, which are the most important non-CO₂ gases and have strong sources in agricultural activities. Such changes could result from a one-off policy decision to change the metric or time horizon or gradual changes resulting from the use of flexible time horizons that focus on a particular target year [15, 16].

Such decisions could result in large changes in the values for relatively short-lived gases such as CH₄ and some hydrofluorocarbons [17, table 2.14]. Apart from policy choices, changes in GWPs could also arise from changes in our scientific understanding of how these gases affect the overall radiative forcing of Earth's climate and from already foreseeable changes due to further changes in atmospheric composition and associated changes in the radiative efficiency of these gases, temperature-related feedbacks on their lifetime, e.g. of CH₄, and climate–carbon cycle feedbacks [18–24].

GWPs are defined as the ratio of the absolute GWP (AGWP; the radiative forcing integrated over a given time horizon following a pulse emission) of the target gas, compared to the AGWP of CO₂. The radiative efficiency of CO₂ decreases approximately logarithmically with its concentration, but saturating ocean CO₂ uptake and climate–carbon cycle coupling increase the fraction of a pulse emission that remains in the atmosphere. An earlier study [24] had estimated that declining radiative efficiency and saturating ocean CO₂ uptake would roughly cancel, and hence the denominator of all GWPs would remain broadly constant over time. We are going to test this finding based on an emulation of the range of latest coupled climate–carbon cycle and atmosphere–ocean general circulation models.

Furthermore, GWPs can also change because of a change in the numerator, i.e. the radiative efficiency of the target gas itself can depend on its concentration and other aspects of radiative balance in the atmosphere such as cloud cover. In addition, the atmospheric lifetime of the target gas can depend on atmospheric temperature or chemistry and the concentrations of other trace gases. This is well established for the two most important non-CO₂ greenhouse gases, CH₄ and N₂O, whose radiative efficiency decreases roughly with the square root of their concentrations and whose absorption bands overlap [25, 26]. More complex atmospheric chemistry processes that could further affect the atmospheric lifetime and radiative efficiencies of CH₄ and N₂O were not modelled in this study due to the inconclusive state of research on such effects (see section 2 for details).

We present an evaluation of currently foreseeable changes in the AGWP of CO₂ and the GWPs of CH₄ and N₂O over the course of the 21st century related to changing background concentrations and rising atmospheric temperatures, based on a multi-model ensemble emulation. We use a definition of GWPs that is based on the Intergovernmental Panel on Climate Change (IPCC) [11, 17] and evaluate changes in GWPs for four representative concentration pathways (RCPs), which have

been developed to inform climate change scenario studies and span a broad range of potential future greenhouse gas emissions and concentrations [27–29].

We first evaluate changes in the AGWP of CO₂, and then present results for GWPs of CH₄ and N₂O. We conclude with a brief discussion of the implications of these changes and contrast them with other metrics and time horizons that could be used to compare emissions of different greenhouse gases.

2. Methods

We used the climate model MAGICC [30–32] to simulate the radiative forcing and resulting climate responses to pulse emissions of CO₂, CH₄ and N₂O. MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean and is coupled to a simple carbon cycle model including CO₂ fertilization and temperature feedback parameterizations of the terrestrial biosphere and oceanic uptake. We use MAGICC version 6 and its calibrations to 19 atmosphere–ocean general circulation models (AOGCMs) [33] and nine C4MIP coupled climate–carbon cycle models [34] used in the IPCC Fourth Assessment Report, as described in Meinshausen *et al* [31]. The simplified carbon cycle model used in MAGICC6 incorporates climate–carbon cycle feedbacks as well as temperature-dependent CO₂ fertilization and the buffering effect of ocean CO₂ uptake [31, 32].

To calculate AGWPs, we first ran MAGICC with prescribed concentrations of all greenhouse gases following each of the four RCP trajectories up to the target years 2000, 2020, 2040, 2060, 2080 and 2100, and with concentrations set constant thereafter at the levels reached in those target years. These runs were used to infer, for each AOGCM and carbon cycle calibration, the emissions of CO₂, CH₄ and N₂O that would give rise to those prescribed concentration pathways. We then ran MAGICC in forward mode with those inverse emissions, and added a further emissions pulse of 10 Gt CO₂, 100 Mt CH₄ or 1 Mt N₂O in the target years to minimize numerical round-off errors, after confirming that AGWPs were related linearly to pulse heights up to these values [35]. The difference in radiative forcing between the runs with and without pulse emissions allows us to calculate the integrated radiative forcing for each gas at various times in the 21st century, and for the different atmospheric background concentrations based on alternative RCP trajectories and attendant temperature increases.

We integrated the change in radiative forcing over time horizons of 20, 100 and 500 years following each pulse emission to derive the standard AGWPs for CO₂, CH₄ and N₂O. These calculations were performed for each RCP trajectory and separately for each AOGCM and carbon cycle parameter combination, which allows us to derive median and average AGWPs as well as the spread across the current range of complex climate models. The spread derived in this way is limited as the only radiative forcing parameter we varied relates to CO₂ but not to the other greenhouse gases (see table B1 in [31]). The spread of 100-year GWPs obtained in this way (i.e. the 'model range' in [35]) is only about two-thirds of the spread obtained from more complex Monte Carlo type methods

that include uncertainty estimates for the radiative forcing from all gases based on historical constraints, but the average and median GWPs are very similar [35].

2.1. Treatment of indirect effects

A pulse emission of CH₄ results in indirect forcing of the climate system through the extension of its own atmospheric lifetime due to its effect on tropospheric OH, as well as additional forcing due to its influence on tropospheric ozone levels and the production of stratospheric water vapour from CH₄ oxidization [17]. These indirect effects are parameterized in MAGICC consistent with values provided in the Fourth Assessment Report (AR4) [17] and are added to the direct forcing.

A key uncertainty in future changes to the indirect effects arises from potential changes in the atmospheric abundance of the hydroxyl radical (OH), which acts as the dominant sink for atmospheric CH₄. The Fourth Assessment Report used the parameterization of the previous assessment [36] but included a broader discussion on future uncertainties in OH abundances that highlights the range of competing factors that could result in either increases or decreases in OH concentrations [17, 37]. Given these uncertainties, we assumed in our model study that the relative magnitude of these indirect feedbacks would not change in future, as there is insufficient information to quantify such changes reliably [38, 39]. We note, however, that based on the range of mechanisms currently identified, future changes in OH concentrations in the order of $\pm 15\%$ appear well possible and could occur rapidly as a result of non-linear atmospheric chemistry processes. Such changes in OH abundance would translate directly into changes in the perturbation lifetime for CH₄ and hence its AGWP and GWP.

Consistent with the definition of the CH₄ GWP used by the IPCC [17], radiative forcing from CO₂ produced in the oxidization of CH₄ is excluded from our calculations. Including CO₂ from the oxidization of fossil CH₄ would increase 100-year GWP of CH₄ by just over 10% [40].

To a first approximation, the radiative efficiencies of CH₄ and N₂O decrease with the square root of their background concentrations [25, 26]. Departures from this simple dependence result from an overlap of the absorption bands of CH₄ and N₂O. In addition, the CH₄ chemical loss processes depend on ambient concentrations of NO_x, CO and volatile organic compounds (VOCs) as well as atmospheric temperature. These effects are also parameterized and modelled in MAGICC [31, 41] and imply a dependence of the AGWP of CH₄ not only on emissions trajectories but also on the specific AOGCM being emulated, because this will affect the rate of temperature-dependent loss processes. In this study, we assumed a net effect of CH₄ concentrations on the CH₄ lifetime (via OH) as well for comparatively low CH₄ concentrations, i.e. historical pre-1990 levels, as they occur in the RCP3-PD scenario, and adapted MAGICC version 6 accordingly.

The definition of GWPs used by the IPCC assumes that pulse emissions occur in an atmosphere with constant background concentrations. One may assume, even though this

is not stated explicitly by the IPCC, that this definition also assumes a constant background state of the climate system. Our methodology for calculating GWPs also applies constant background concentrations from the time an emissions pulse occurs, but we allow the climate system to change following an emissions pulse to realize the ‘committed warming’ from increasing background concentrations up to the time the emissions pulse occurs [33]. Our method of calculating GWPs is thus based on but not fully identical to that of the IPCC, since these further changes in ambient temperature alter the carbon cycle feedbacks and loss processes for CH₄ and N₂O following emissions pulses of those gases, and thus affect the modelled AGWPs of CO₂, CH₄ and N₂O.

Gas–aerosol interactions, as well as more complex interactions between different greenhouse gases and with land-use or land-cover could also significantly influence the total radiative forcing from a pulse emission of CH₄ [42–44]. Some of these complex interactions and feedbacks have the potential to alter GWPs significantly but require further scientific investigation to substantiate and quantify their ranges across different models and scenarios. Since our main aim was to study already foreseeable changes in GWPs using a definition that is based on that currently employed in IPCC assessments [17], we did not attempt to model such additional effects in our study, nor did we include the indirect effects of non-CO₂ emissions on the airborne fraction of CO₂ via climate–carbon cycle coupling [19].

3. Results

3.1. Changes of the CO₂ AGWP as a function of CO₂ concentration

Figure 1 shows the median 20-, 100- and 500-year CO₂ AGWPs as a function of CO₂ background concentration along the four RCP trajectories, across all AOGCMs and coupled climate–carbon cycle model emulations. The RCP trajectories span CO₂ concentrations from 369 ppm in the year 2000 up to 936 ppm in 2100 under the highest RCP. The climate warming associated with those trajectories ranges from about 1 to more than 6 °C above pre-industrial levels by the end of the 21st century for the range of AOGCMs and carbon cycle models emulated in our study.

The 20-year AGWP of CO₂ declines roughly logarithmically with concentration, indicating that the dominant cause for changes in the 20-year AGWP is the declining radiative efficiency of CO₂. The 100- and 500-year AGWPs decline less strongly and their concentration dependence is better approximated by linear rather than logarithmic fits, suggesting that climate–carbon cycle feedbacks increasingly, but only partially, compensate for the reducing radiative efficiency at higher concentrations.

The linear decline of the median 100-year AGWP of CO₂ corresponds to about –6% decrease for a 100 ppm increase above current concentrations, and about –8% for each 100 ppm increase above 450 ppm. This equates to a reduction of the 100-year AGWP from 2000 to 2100 by 36% for RCP 8.5, but only by 2% for RCP 3-PD. The median 500-year AGWP declines also roughly linearly but less strongly

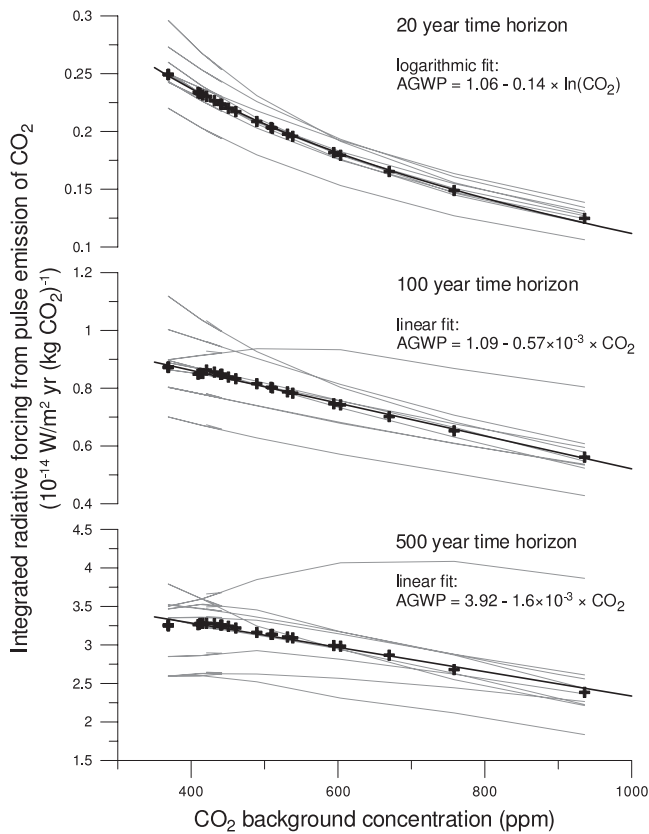


Figure 1. 20-, 100- and 500-year CO₂ AGWPs for the range of CO₂ concentrations (as well as other greenhouse gas concentrations and resulting climate warming) associated with RCP trajectories during the 21st century. Black crosses show the median AGWPs across all AOGCM and carbon cycle model emulations for the specific CO₂ concentrations attained in the years 2000, 2020, 2040, 2060, 2080 and 2100 under the four different RCPs. Solid black lines show best fits to those results (logarithmic for the 20-year AGWP, and linear for 100- and 500-year AGWPs), with fit equations given for CO₂ concentrations in ppm and AGWPs in 10⁻¹⁴ W m⁻² yr (kg CO₂)⁻¹. Individual grey lines show the median AGWPs (across all AOGCMs) for individual carbon cycle model emulations.

than the 100-year AGWP, corresponding to about -5% for a 100ppm increase above current concentrations, and about -6% as concentrations rise above 600 ppm. This equates to a reduction from 2000 to 2100 by 27% for RCP 8.5, but a small (less than 1%) increase for RCP 3-PD owing to increasing climate-carbon cycle feedbacks and the much more limited changes in CO₂ concentrations under RCP 3-PD.

The 100- and 500-year AGWPs do not depend smoothly on background concentration between 400 and 750 ppm CO₂ because the four RCP trajectories reach those concentrations at different times over the 21st century, and they are associated with different concentrations of non-CO₂ greenhouse gases. This results in different amounts of warming and hence different strengths of climate-carbon cycle feedbacks, which in turn lead to slightly different CO₂ AGWPs for a given CO₂ concentration.

Figure 1 also shows the results for specific climate-carbon cycle model emulations, which exhibit significant differences for the concentration dependence of the CO₂

AGWP particularly for longer time horizons. For example, calibrating MAGICC to emulate the Hadley coupled climate-carbon cycle model (as in the C4MIP intercomparison project) results in increasing rather than decreasing 100- and 500-year AGWPs for background concentrations up to about 600 ppm. This is because the declining radiative efficiency is more than counterbalanced by the increasing fraction of a CO₂ pulse emission that remains in the atmosphere, due to particularly strong climate-carbon cycle feedbacks in this model [31].

However, we emphasize that the time horizon over which MAGICC could be calibrated against different climate-carbon cycle models extended only to 2100 [34], and as a result, we have less confidence in our calculations of the 500-year AGWP than the 20- and 100-year AGWPs [31, 35].

3.2. Changes of CH₄ and N₂O GWPs over the 21st century

The CO₂ AGWPs presented above provide the denominator for calculations of GWPs of all non-CO₂ gases. The decline of CO₂ AGWPs under all scenarios and time horizons considered in this study implies that all GWPs, everything else being equal, would be expected to increase during the 21st century as CO₂ concentrations increase. However, the AGWPs of CH₄ and N₂O themselves also depend on their own background concentrations and, to a lesser extent, on ambient temperature (see section 2). Since CH₄ concentrations decrease below present concentrations in the lowest RCP scenario, but increase substantially in the highest RCP, not only the magnitude but even the direction of change of the GWP of CH₄ depends significantly on the CH₄ as well as CO₂ concentration pathways over the 21st century.

Figure 2 shows the medians of the 20-, 100- and 500-year CH₄ and N₂O GWPs calculated for the atmospheric composition and climate conditions expected in the years 2000, 2020, 2040, 2060, 2080 and 2100 under the four different RCP trajectories, along with projected changes in CH₄ and N₂O concentrations relative to year 2000 values. The figure demonstrates that relative changes in CH₄ concentrations differ markedly between RCP scenarios, while the changes in N₂O concentrations are much more similar and cover a smaller range, which explains the different evolution of CH₄ and N₂O GWPs along the four RCP trajectories.

Our results for the GWP of CH₄ for the year 2005 agree well with IPCC values for 20- and 100-year horizons, but are about 13% lower for a 500-year horizon. This is due to a greater mean 500-year CO₂ AGWP resulting from stronger climate-carbon cycle feedbacks across the C4MIP model ensemble used in our study, compared to the single default model used in the IPCC AR4 [17, 35].

The 20-year GWPs of both gases increase under all RCPs over the 21st century, indicating that for short time horizons, the strong decrease in the CO₂ AGWP dominates over changes resulting from the reduced radiative efficiency of either CH₄ or N₂O at higher concentrations, despite the large increase of CH₄ concentrations under the RCP8.5 scenario.

The 100- and 500-year GWPs of CH₄ increase by 10–20% by 2100 under all but the highest RCP (the 100-year GWP ranges from 27.1 under RCP4.5 to 30.2 under RCP6). For

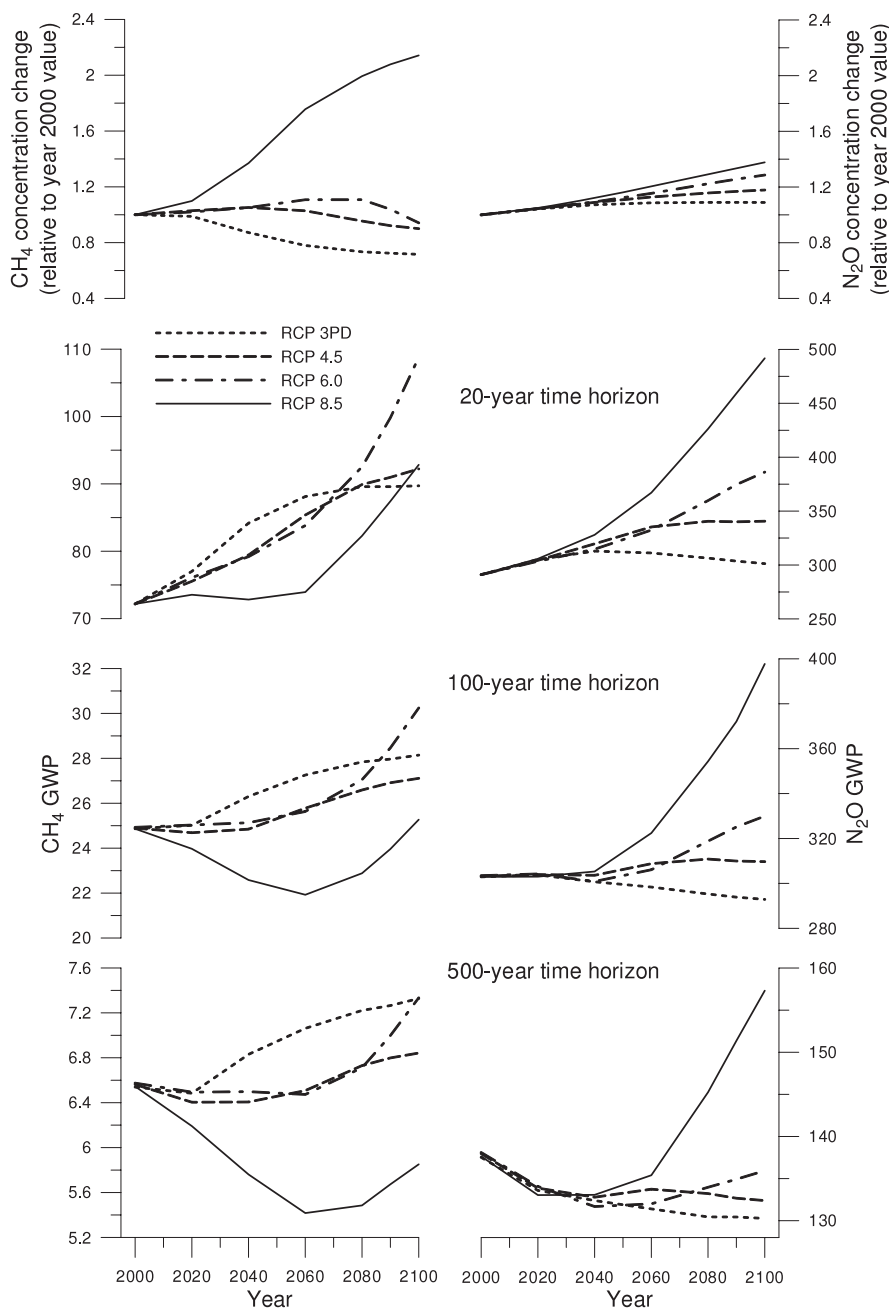


Figure 2. Changes in CH₄ and N₂O concentrations (relative to year 2000 values; top panels), and 20-, 100- and 500-year GWPs for CH₄ and N₂O (lower three panels; left: CH₄, right: N₂O), for the four RCP trajectories for the atmospheric composition, chemistry and climate conditions modelled for the years 2000, 2020, 2040, 2060, 2080 and 2100. Individual solid, dotted, dashed and dash-dotted lines in the lower three panels show the median GWPs across all AOGCM and carbon cycle model emulations, for the individual RCP trajectories.

the highest scenario (RCP8.5), the 100- and 500-year GWPs of CH₄ decrease by more than 10% by the middle of the century, mainly because of the large near-term increase in CH₄ concentrations and hence reducing radiative efficiency, but the 500-year GWP increases again by the end of the 21st century due to the compensating large increase in CO₂ concentrations and associated decline in the radiative efficiency and AGWP of CO₂.

The 100-year GWP of N₂O would vary by less than 10% under all but the highest RCP, but increase by more than 20% under RCP8.5. This is because the change in N₂O

concentrations under all RCPs is much less pronounced than those of CH₄, and hence changes in the radiative efficiency of CO₂ dominate changes in the GWP. A similar picture results for the 500-year GWP of N₂O, where all but the highest RCP result in small reductions in the 500-year GWP in mid-century but almost no change compared to present-day values by the end of the century, as declining radiative efficiency of N₂O is counterbalanced by the declining radiative efficiency of CO₂. By contrast, the highest RCP would result in no decline by mid-century and a more than 10% increase by the end of the century, mainly because the very high concentration increases

of CO₂ result in a declining CO₂ AGWP and corresponding increase in N₂O GWP in this scenario.

We also calculated the uncertainty range, expressed as 90% percentile regions, for the CH₄ and N₂O GWPs based on the ensemble of model emulations used in this study. This percentile region ranges from about -15/+20% for the 20-year GWPs of both CH₄ and N₂O to about -20/+30% for the 100- and 500-year GWPs, with slightly greater values for the two upper RCPs 6 and 8.5. However, most of the uncertainty in this analysis comes from uncertainties in the carbon cycle and hence AGWPs of CO₂ rather than AGWPs of CH₄ or N₂O, because our model emulations do not take into account uncertainties in the radiative forcing of CH₄ and N₂O (which is assumed to be the same for all emulated AOGCMs; see [31, 35]).

More comprehensive ways of evaluating uncertainties, e.g. based on historical constraints on key climate parameters and radiative forcing from all relevant greenhouse gases, would likely result in about 40% larger confidence intervals [35]. However, this has not been explored in detail for this study since our main objective is to study changes in median or best estimates of GWPs over time, which were shown to be in close agreement with those arising from such more comprehensive uncertainty assessments.

Figure 3 further highlights the importance of considering atmospheric chemistry and feedbacks in calculating GWPs, using 100-year CH₄ GWPs under the RCP 3-PD concentration pathway as example. The figure shows ensemble-mean GWP changes based on changes in radiative efficiency of CO₂ and CH₄ only, the additional effect of climate-carbon cycle coupling on the fraction of CO₂ that remains in the atmosphere over a 100-year time horizon, and the further effect of changes in the atmospheric lifetime of CH₄ based on feedbacks with OH and temperature-dependent loss processes consistent with the feedbacks considered in the IPCC AR4. While changes in radiative efficiencies play a key role in future changes in GWPs, the additional feedbacks evaluated in this study also modify the quantitative changes in GWPs substantially. This further emphasizes the need for a comprehensive analysis of feedbacks when considering multi-gas abatement strategies, but this is complicated by the large uncertainties associated with climate-carbon cycle feedbacks and future changes in OH concentrations [21, 34, 37, 39].

4. Discussion and conclusions

We examined the predictable changes to 20-, 100- and 500-year AGWPs of CO₂, CH₄ and N₂O, and GWPs of CH₄ and N₂O along the four RCPs over the 21st century. We found that, based on the suite of emulated AOGCMs and climate-carbon cycle models assessed in the IPCC AR4, AGWPs of CO₂ decrease for higher CO₂ concentrations because climate-carbon cycle feedbacks partially but not entirely offset the declining radiative efficiency at higher concentrations.

Our findings may be compared with the earlier results of Caldeira and Kasting [24], who concluded that the AGWP of CO₂ is nearly independent of the CO₂ emissions scenario. However, their study investigated the integrated radiative

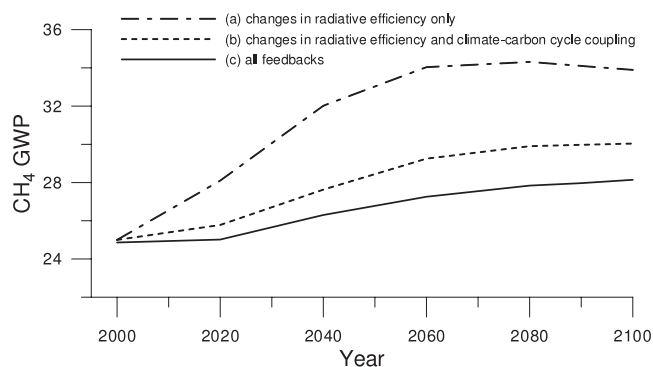


Figure 3. Changes in the model ensemble-mean 100-year GWP of CH₄ following the RCP3-PD concentration pathway, (a) for changes in radiative efficiencies of CO₂ and CH₄ only as a result of changing background concentrations (dash-dotted line), (b) for changes in radiative efficiencies as well as effects of climate-carbon cycle coupling on the fraction of CO₂ that remains in the atmosphere after a pulse emission (dotted line), and (c) for full modelling of climate and atmospheric chemistry feedbacks (solid line). See text for description of the feedbacks considered in this study and key uncertainties/assumptions.

forcing from a CO₂ emissions pulse set in the year 1990 followed by alternative background concentration trajectories over the 21st century and beyond. By contrast, our study investigated the integrated radiative forcing from emissions pulses set at various future times in the 21st century at different background concentration levels, but where background concentrations are assumed to be constant following each emissions pulse (consistent with the definition of GWPs used by the IPCC). Caldeira and Kasting found that the AGWP of CO₂ decreases for higher future concentration trajectories, which is consistent with the direction of change found in our study. However, absolute values from the two studies cannot be compared directly due to the different methodological approaches employed. The key conclusion from Caldeira and Kasting, that the declining radiative efficiency and increased airborne fraction of CO₂ mostly cancel each other out is supported by the results from our study. Nonetheless, the amount of future changes in GWPs resulting from future changes in background CO₂ concentrations and the associated net change in CO₂ AGWPs identified by our study may still be regarded as significant for policy purposes.

As a result of these predictable CO₂ AGWP changes, the GWPs of non-CO₂ gases whose radiative efficiency is independent of their concentration or the concentration of other gases or other atmospheric variables will increase over time, proportional to the decline in CO₂ AGWPs. This means that mitigation of CO₂ would be valued less and mitigation of non-CO₂ gases (other than CH₄ and N₂O) more as the 21st century progresses. The amount of change would depend on the future concentration pathway. Under the RCP3-PD, which is consistent with a best-estimate global average temperature increase of somewhat less than 2°C over pre-industrial conditions, the 100-year AGWP of CO₂ would decrease by only about 2% by 2100 relative to the year 2000 value. By contrast, under the highest RCP8.5, the CO₂ 100-year AGWPs would decrease by 36% by 2100.

Changes in GWPs of the most important non-CO₂ greenhouse gases CH₄ and N₂O are more complicated because the radiative efficiency of these gases decreases with increasing concentrations and due to their overlapping absorption spectra, and because their atmospheric lifetimes would change as a result of changing atmospheric composition and temperatures. Based on our analysis, GWPs of CH₄ would increase over time for most of the RCPs, with notable exceptions for the RCP8.5 scenario, which would result in declining 100- and 500-year GWPs during mid-century due to very large relative increases in CH₄ concentrations and hence greatly reduced radiative efficiency of CH₄. By contrast, GWPs of N₂O would be relatively stable for the lowest RCP (RCP3-PD), but would increase for the higher RCPs, particularly for RCP8.5. The relative changes in N₂O concentration across RCP scenarios are much smaller than for CH₄, and hence the declining AGWP of CO₂ dominates net changes of the N₂O GWP under all RCPs.

While in this study we focus mainly on the ensemble-mean changes, we emphasize that uncertainties in the strength of climate-carbon cycle feedbacks result in large uncertainties in future changes in CO₂ AGWPs for 100- and 500-year time horizons, with corresponding uncertainties in future changes of GWPs of all gases [35].

Future changes in the GWP of CH₄ will also depend on potential changes in atmospheric chemistry, particularly OH concentrations. Current research is too inconclusive to allow quantitative projections of future changes arising from associated atmospheric chemistry processes, since competing factors could result in either increasing or decreasing concentration. A change in OH concentrations in the order of $\pm 15\%$, with similar change in the AGWP of CH₄, would be comparable in magnitude but potentially more rapid than the predictable changes in the GWP of CH₄ identified in this study. This underlines that an improved understanding of complex atmospheric chemistry interactions will be necessary to allow a more robust quantification of future changes in radiative forcings from emissions of different anthropogenic greenhouse gases.

The foreseeable changes in the 100-year GWPs of CH₄ and N₂O based on our study generally imply smaller changes in the 'exchange rate' between those gases and CO₂ than the change that would result if different time horizons were chosen. For example, switching to a 500-year time horizon would decrease the GWP of CH₄ by more than 60% and the GWP of N₂O by about 50% relative to the values used currently in emissions inventories. By contrast, switching to a 20-year time horizon would increase the GWP of CH₄ about 200% but leave the GWP of N₂O virtually unchanged [17, 35]. Changes in time horizons could result not just from one-off policy decisions but also from adopting a modification of the GWP metric that does not integrate over a fixed time horizon but where the time horizon becomes shorter as a given target year is approached [15]. Even greater changes would result if altogether different metrics were used to compare greenhouse gas emissions, such as the global temperature change potential (GTP) [16, 45]. GTPs are based on the warming at a specific future point in time and therefore

give lesser weight than GWPs to emissions of short-lived greenhouse gases. Changing from 100-year GWPs to 100-year GTPs would decrease the 'exchange rate' for CH₄ relative to CO₂ from 21 in current emissions inventories to between about four and eight [10, 35, 45], representing a drop by 60–80%. Using a time-varying GTP metric that focuses on a specific target year (e.g. the time at which atmospheric temperatures would peak under a given emissions pathway) would lead to very large changes over time [16].

The appropriateness of any given metric, and hence the value in updating such a metric over time, depends heavily on the specific climate policy goals. Updating 100-year GWPs over time would be appropriate if the primary goal of climate policy is to limit the integrated radiative forcing resulting from greenhouse gas emissions over a 100-year time horizon. If other climate policy goals are seen as more relevant, such as stabilizing long-term radiative forcing, minimizing the rate of temperature change, or limiting near- or long-term temperature increases, then the use of alternative metrics and/or alternative time horizons may be more effective than updating the 100-year GWP metric currently in use.

Further work to quantify the economic implications of using different metrics, including their predictable changes over time, to achieve different near- and long-term goals under multi-gas mitigation strategies appears highly desirable to inform climate policy decisions.

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