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Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases

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Abstract
Greenhouse gases other than CO_2 make a significant contribution to human-induced climate change, and multi-gas mitigation strategies are cheaper to implement than those which limit CO_2 emissions alone. Most practical multi-gas mitigation strategies require metrics to relate the climate warming effects of CO_2 and other greenhouse gases. Global warming potential (GWP), defined as the ratio of time-integrated radiative forcing of a particular gas to that of CO_2 following a unit mass emission, is the metric used in the Kyoto Protocol, and we define mean global temperature change potential (MGTP) as an equivalent metric of the temperature response. Here we show that carbon–climate feedbacks inflate the GWPs and MGTPs of methane and nitrous oxide by ∼20% in coupled carbon–climate model simulations of the response to a pulse of 50 × 1990 emissions, due to a warming-induced release of CO_2 from the land biosphere and ocean. The magnitude of this effect is expected to be dependent on the model, but it is not captured at all by the analytical models usually used to calculate metrics such as GWP. We argue that the omission of carbon cycle dynamics has led to a low bias of uncertain but potentially substantial magnitude in metrics of the global warming effect of other greenhouse gases, and we suggest that the carbon–climate feedback should be considered when greenhouse gas metrics are calculated and applied.

Keywords: carbon feedback, global warming potential, global temperature change potential, metrics

1. Introduction

Over the historical period the forcing from non-CO_2 greenhouse gases was 37% of the total greenhouse gas forcing [1], and multi-gas mitigation strategies are estimated to be 30–40% cheaper to implement than those which regulate CO_2 only [2]. Metrics can be used to relate the climate effects of CO_2 to the climate effects of other greenhouse gases [3]. While an economically optimal metric might take into account the costs of climate impacts with an appropriate discounting rate [4], the enhanced complexity and uncertainty associated with such metrics may make them less suitable as a basis for regulation [5, 6]. The Kyoto Protocol regulates emissions of CO_2, methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride and the halocarbons, with equivalence to CO_2 based on their GWPs, or the ratios of their time-integrated radiative forcing to that of CO_2 following a pulse emission over a 100 yr period. GWPs used in the Kyoto protocol and shown in IPCC assessments [1, 7] assume that the CO_2 remaining in the atmosphere following a pulse emission decays as a sum of exponentially decreasing terms. This response function was obtained by fitting to the response to a pulse emission in

the Bern carbon cycle model [8] at a present day background CO_2 concentration [1, 7]. These GWPs neglect carbon cycle feedbacks on the climate response to non-CO_2 greenhouse gases.

Various criticisms have been levelled at GWPs, in particular that equivalent emissions of short and long-lived greenhouse gases based on GWPs give rise to very different climate effects, that the values of GWPs are sensitive to the period over which they are calculated, and that GWPs are based on radiative forcing which is remote from climate impacts [4, 9–13]. In an attempt to address the latter of these criticisms, Shine *et al* [12] proposed the global temperature change potential (GTP) as an alternate metric. GTP is defined as the ratio of the temperature response to a unit mass pulse emission of a given greenhouse gas to the temperature response to a unit mass pulse emission of CO_2 at a given time horizon: since it is defined in terms of temperature change rather than radiative forcing, it is one step closer to climate impacts than GWP. Furthermore, the GTP is referenced to the temperature change per unit mass of CO_2 emitted, which has been shown to be approximately constant and well constrained by observations [14, 15]. Despite being a function of temperature change rather than radiative forcing, GTP is relatively insensitive to climate sensitivity [12] since the effects of climate sensitivity on the temperature response to each gas and to CO_2 tend to cancel. However, the GTP of a gas is in general a strongly varying function of time, of the amount of gas emitted, and of the time-profile of the emissions, and in its original formulation the GTP is defined using a very simple analytical climate model and carbon cycle model.

Here, we investigate the robustness of these metrics to the use of realistic nonlinear forcing functions, and the use of a more realistic climate model with a coupled carbon cycle. We argue that a time-integrated version of GTP [6], which we define as the mean global temperature change potential (MGTP), has some advantages over both the GTP and the more widely used GWP. This metric is related to the TEMP metric of [16], which is chosen such that when used to convert CH_4 or N_2O emissions to CO_2-equivalent emissions over the historical period, the match to simulated global mean temperature is optimized. Finally, we investigate the effects of accounting for carbon cycle feedbacks on the climate response to the non-CO_2 greenhouse gases in the calculation of these metrics.

2. Results

We start by comparing the temperature responses to pulses of 50 × 1990 emissions of CO_2, CH_4 and N_2O (1302 Pg CO_2, 15.5 Pg CH_4, and 1.05 Pg N_2O). We assume pre-industrial background concentrations of 276.8 ppm CO_2, 715 ppb CH_4 and 270 ppb N_2O. A pulse experiment was chosen for comparison with standard GWP calculations [1], and a pulse of this magnitude was chosen such that the temperature response to the N_2O forcing was not obscured by noise in the climate model. We first calculate concentrations, forcings and temperatures following [12]. For most greenhouse gases, we assume that their concentrations after a pulse emission follow an exponential decay, and for CO_2 we use a four-term pulse-response model tuned to the Bern carbon cycle model [8]. We use the Shine *et al* [12] values for the specific radiative forcings of the greenhouse gases, and for the greenhouse gas lifetimes. This approach is the same as that used in the IPCC assessment to derive GWPs [7]. We use the simplest possible representation of the global mean surface temperature response to global mean radiative forcing (equation (1) in [12]). Rather than solving the equations analytically, following [12], we solve them numerically, in order that various approximations may be relaxed, and the solutions made more realistic. We also repeat our calculations using an energy balance model (EBM) with a diffusive ocean [17], using the same values for the climate sensitivity parameter and heat capacity as [12], and a diffusivity of 0.6 based on the results of [17]. As expected, the addition of a diffusive ocean tends to reduce the peak temperature response to the pulse emissions, and enhance the delayed response (figure 1). These results are qualitatively consistent with the EBM results of [12], though results are quantitatively different since we use a different EBM. Note that GTPs and GWPs derived using the Shine *et al* model are the same as those reported by [12] (table 1): the calculation is linear so our use of a different pulse size makes no difference here. The EBM is also linear, and metric calculations based on the EBM are thus also independent of pulse size.

Figure 1 compares the simulated temperature response to the pulse emissions in the Shine *et al* [12] model with the

Table 1. Comparison of GWP, GTP and MGTP for 100 yr for CH_4 and N_2O following a pulse emission of 50 times 1990 emissions. Metrics are evaluated based on the Shine *et al* [12] method (Shine), based on Shine *et al* [12] method but using an EBM with a diffusive ocean (EBM), based on the Shine *et al* [12] method but using the nonlinear IPCC [7] forcing functions (nonlinear forcing), based on the UVic model with prescribed nonlinear forcings (UVic), based on simulations of the coupled carbon version of the UVic model (UVic-CC), and using simulations of UVic-CC for CH_4 and N_2O only, and simulations of the uncoupled UVic model for CO_2 (UVic-CC M&N). The CO_2 column shows the radiative forcing per unit mass of CO_2 emitted integrated over 100 yr, the warming at 100 yr per unit mass of CO_2 emitted, and the mean warming over 100 yr per unit mass of CO_2 emitted. The best observational estimate of the warming per unit mass emissions of CO_2 of 1.5 °C per TtC [14] is 0.41 °C per Tt CO_2. All values are shown to 2 s.f.

Gas		Absolute CO_2	CH_4	N_2O
GWP	Shine	91 W m^{-2} Tt^{-1} yr	22	290
	Nonlinear forcing	100 W m^{-2} Tt^{-1} yr	22	270
	UVic-CC	90 W m^{-2} Tt^{-1} yr	29	350
	UVic-CC M&N		26	320
GTP	Shine	0.55 °C Tt^{-1}	0.35	270
	EBM	0.58 °C Tt^{-1}	4.2	280
	Nonlinear forcing	0.62 °C Tt^{-1}	0.46	250
	UVic	0.49 °C Tt^{-1}	2.7	260
	UVic-CC	0.50 °C Tt^{-1}	4.7	290
	UVic-CC M&N		4.8	290
MGTP	Shine	0.66 °C Tt^{-1}	24	290
	EBM	0.62 °C Tt^{-1}	30	290
	Nonlinear forcing	0.72 °C Tt^{-1}	23	280
	UVic	0.53 °C Tt^{-1}	23	260
	UVic-CC	0.50 °C Tt^{-1}	30	330
	UVic-CC M&N		28	310

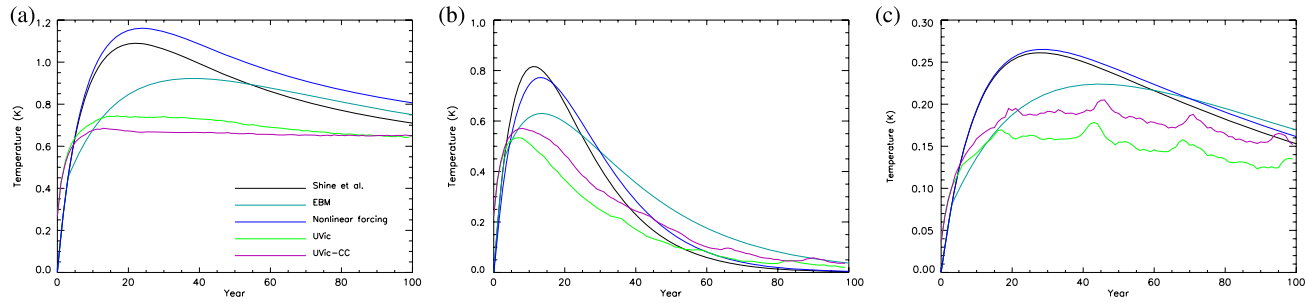

Figure 1. Simulated temperature responses to pulse emissions of (a) CO_2, (b) CH_4 and (c) N_2O of 50 × 1990 emissions. Results are shown based on the Shine *et al* [12] method (black), based on the Shine *et al* method but using an EBM with a diffusive ocean (cyan), based on the Shine *et al* method, but with nonlinear [7] forcing functions (blue), and based on simulations of the UVic model with specified CO_2 (green), and with a coupled carbon cycle (magenta).

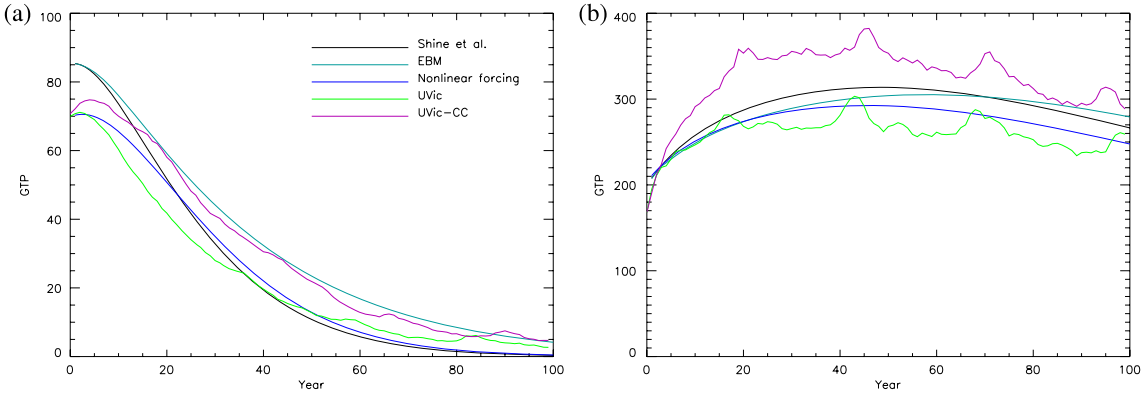

Figure 2. Global temperature change potential (GTP) for (a) CH_4 and (b) N_2O.

temperature response in the same model but using the more realistic nonlinear [7] forcing functions to derive radiative forcings from concentrations of greenhouse gases. Relaxing the linear forcing approximation increases the mean 100 yr forcing due to all three gases somewhat, with the largest change for CO_2, resulting in small changes in the GWPs (table 1). The temperature response to the pulse emissions is thus also modestly increased on average (figure 1). Higher simulated temperatures when using the nonlinear forcing/concentration relationship to derive the temperature response to CH_4 and N_2O emissions were also reported by [16], though the magnitude of the difference here is smaller since the concentrations used in our experiments are on average closer to the present day values about which [7] linearize than the historical values used by [16].

Keeping the same radiative forcings, but replacing the Shine *et al* model with the UVic Earth System Climate Model, which includes a full dynamical ocean and an energy–moisture-balance atmosphere [18], makes a much larger difference to the temperature responses (figure 1). This version of the UVic model has a climate sensitivity similar to that of the analytical model [12], which is consistent with the fact that the temperatures simulated by the UVic model and the Shine model are converging 100 yr after the pulse emission. However, while the Shine model warms steadily in response to the CO_2 pulse to a peak at ∼20 yr, followed by cooling, the UVic model warms more rapidly at first but reaches a plateau with only slight cooling after ∼20 yr. This difference in behaviour is due to the more realistic treatment of ocean heat uptake in the UVic model compared to the single effective heat capacity assumed in the Shine model. The UVic model response is also considerably different to the response of the EBM with a diffusive ocean [17], which also shows a peak in its temperature response to a pulse of CO_2, followed by cooling (figure 1). The simulated temperature responses to pulses of 50 × 1990 emissions of CH_4 (figure 1(b)) and N_2O (figure 1(c)) are also considerably damped by using the UVic model, with a much smaller peak temperature response. The effects of model internal variability are apparent, particularly in the simulated temperature response to the N_2O pulse (figure 1(c)). Although the Shine model appears to simulate rather different temperature responses to each of the three gases compared to the UVic model, the GTP, which is a ratio of the temperature response for each gas to that of CO_2, exhibits much less model dependence (figure 2). The Shine model overestimates the temperature response during the first 50 yr for all the gases, so the effects on GTP cancel to first order.

As is well known [12, 13], the GTP of CH_4 is strongly time-dependent, while the GTP of N_2O varies less owing to its longer lifetime (figure 2). Shine *et al* [13] argue that the GTP is most relevant to a mitigation policy which sets a particular temperature target in a particular year, and under these conditions CH_4 will have a low GTP initially, but its GTP will rise rapidly as the target date approaches [13]. The GTP of CH_4 at 100 yr is close to zero, and is somewhat higher based on the EBM or UVic model compared to the

Shine model (table 1), due to the larger thermal inertia of the ocean in these models. GWP, being a time-integrated quantity, does not exhibit such strong dependence on the period over which it is calculated. We therefore also consider an alternative metric, which was proposed but not investigated by [6]: the mean global temperature change potential (MGTP), which we define as the ratio of the mean temperature response per unit mass emission of a greenhouse gas to the mean temperature response per unit mass emission of CO_2 over some specified period following a pulse emission, here chosen to be 100 yr. The MGTP varies much less strongly with time than the GTP, and is similar to the GWP under the parameter choices shown here (table 1), indicating that the ratio of mean radiative forcing of CH_4 or N_2O to CO_2 over 100 yr is very similar to the ratio of the temperature responses to the two gases [10, 16].

For a time horizon of 100 yr, MGTP tends to give much more weight to CH_4 than does GTP (table 1), since the temperature response to a CH_4 pulse peaks after 5–15 yr (figure 1(b)), and declines strongly thereafter. Thus if used as a basis for controlling emissions with a 100 yr time horizon, MGTP would tend to give more incentive to reduce emissions of short-lived gases than would GTP. MGTP would be economically optimal if damages associated with climate change were linear as a function of global mean temperature, and were evaluated over a fixed period into the future with zero discounting, whereas GTP would be optimal in the case that damages of climate change were dependent on temperature at one particular time only. While both are clearly idealizations, the former may be closer to reality than the latter. MGTP is related to the TEMP metric of [16], which is defined as the multiplier of CH_4 or N_2O emissions which produces a best fit to simulated historical temperatures, when it is used to derive CO_2-equivalent emissions. TEMP thus requires a historical or future scenario of emissions before it can be calculated. TEMP would be equivalent to MGTP if defined for a fixed period following a pulse emission, and if the CO_2 response to a pulse emission could be approximated as a constant temperature. MGTP, as defined here, has the advantage that it is based on a simple ratio of mean temperature responses following a pulse emission, making its physical interpretation more transparent, but when used to derive CO_2-equivalent emissions for some particular emissions scenario, the climate response lacks the equivalence that it would have based on TEMP.

Climate warming due to CH_4 and N_2O will tend to reduce the efficiency of the natural carbon sinks, and thereby increase the concentration of CO_2 in the atmosphere, an effect which is not usually accounted for in the calculation of GWPs or GTPs. Figure 1 shows the effect of prescribing pulse emissions of CH_4 and N_2O in the coupled carbon version of the UVic model (UVic-CC), in which the CO_2 concentration is free to evolve in response to changes in climate. The carbon–climate feedback amplifies the temperature response to CH_4 and N_2O emissions. The difference between the temperature responses to CO_2 pulses in UVic-CC and UVic should not be interpreted as the result of carbon–climate feedbacks, which are implicitly included in the impulse-response function model used to prescribe CO_2 in UVic: this difference is simply a result of the different carbon cycle models used. For this reason, as well as calculating metrics using UVic-CC alone, we also calculate metrics using UVic-CC simulations of the response to CH_4 and N_2O, but the UVic model response to prescribed CO_2 concentration (table 1, rows labelled 'UVic-CC M&N'), such that the effects of carbon–climate feedbacks on the climate response to CH_4 and N_2O can be isolated. Carbon–climate feedbacks increase the MGTPs of CH_4 and N_2O by about 20% (compare rows labelled 'UVic-CC M&N' and 'UVic' in table 1). A similar enhancement of MGTP due to carbon–climate feedbacks was simulated in response to pulse emissions of 100 × 1990 emissions, indicating that the magnitude of this enhancement of MGTP is not strongly dependent on the pulse size. Because these changes in CO_2 also affect the radiative forcing, these effects also increase the GWPs of CH_4 and N_2O by about 20% (compare rows labelled 'UVic-CC M&N' and 'Nonlinear forcing' in table 1).

Friedlingstein *et al* [19] report the additional atmospheric CO_2 per K of warming at 2100 in the C4MIP coupled carbon–climate models associated with reduced land uptake ($-\gamma_L$) and reduced ocean uptake ($-\gamma_O$) and the temperature change per unit change in atmospheric CO_2 (α), allowing us to estimate the fractional increase in warming associated with carbon–climate feedbacks ($-\alpha(\gamma_L+\gamma_O)/2.12$ based on results reported in table 3 of [19]). This ratio ranges from 7% for CSM-1 to 63% for HadCM3-LC, with a value of 42% derived for the UVic-2.7 model under these conditions (similar experiments using the UVic-2.9 model version used here yield 37% (K. Zickfeld, pers. comm.)), compared to the ∼20% enhancement in temperature response we find in the CH_4 and N_2O pulse experiments. The C4MIP calculations differ from the results presented here since all C4MIP quantities are evaluated at 2100 relative to pre-industrial, under an SRES A2 scenario including CO_2, whereas our CH_4 and N_2O pulse experiments have pre-industrial background CO_2 levels, and relatively smaller temperature perturbations, and GWP and MGTP are based on 100 yr averages. We would expect γ_O and γ_L to be somewhat dependent on the evolution of temperature and CO_2 concentration, and α is also dependent on time and CO_2 concentration. Thus although the C4MIP warming enhancements due to carbon–climate feedbacks are not directly comparable with those we derive here, they illustrate that while all the C4MIP models have a positive carbon–climate feedback, the size of the effect we report is likely to be model-dependent.

Lastly we examine the effects of pulse emissions on climate compared to a plausible transient climate change scenario, using the UVic-CC model. Historical non-CO_2 greenhouse gas concentrations and other anthropogenic and natural forcings were prescribed up to 2000, and SRES A2 non-CO_2 greenhouse gas concentrations and aerosol forcing were prescribed thereafter. Historical and SRES A2 CO_2 emissions were also prescribed. Two sets of similar simulations with pulses of 50 × 1990 emissions of CO_2, CH_4 and N_2O added in 1850 and 2000 were then carried out. For the CO_2 pulse experiments, the pulse emissions were simply prescribed in the model (pulse emissions were spread over two years). For the CH_4 and N_2O pulse experiments the concentrations following the pulse emission were calculated

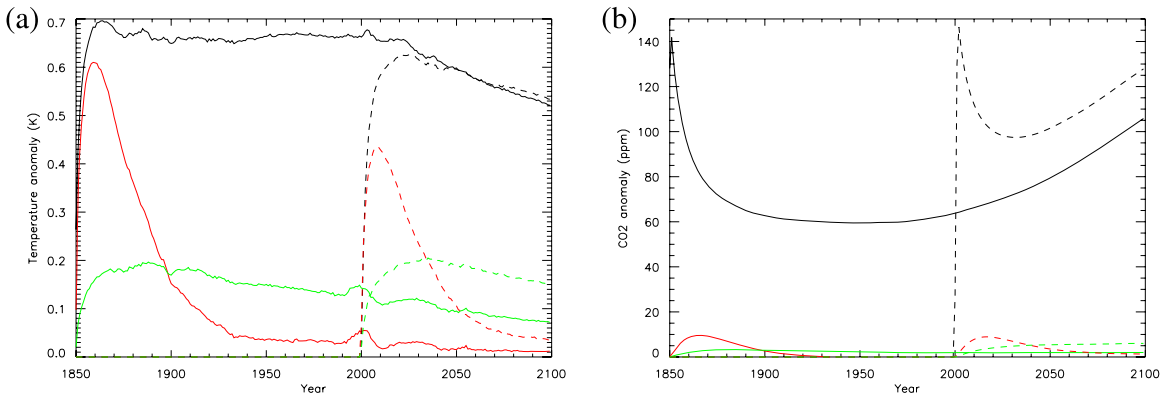

Figure 3. (a) Temperature anomalies relative to a baseline with historical forcings to 2000 and SRES A2 forcings to 2100 in simulations with a pulse of 50 × 1990 emissions of CO_2 (black), CH_4 (red), and N_2O (green) in 1850 (solid) and 2000 (dashed). (b) As (a) but showing CO_2 concentration anomalies.

following [12], added to the baseline concentrations, and used to calculate forcings following [7]. Although the temperature anomaly resulting from the pulse emission of CO_2 in 1850 is approximately constant for the first 150 yr (figure 3), both CO_2 pulse experiments show some relative cooling during the 21st century. Two opposing factors are important here. Firstly, as the background CO_2 concentration increases rapidly through the 21st century and the climate warms, the carbon sinks become less effective and are able to store a smaller fraction of the additional CO_2 associated with the pulse emission (figure 3(b)). This effect is so strong that it leads to an increase in the CO_2 anomaly associated with the 2000 pulse after an initial decrease for 2–3 decades, with a CO_2 anomaly close to the initial peak by the year 2100 (figure 3(b)). Secondly, the logarithmic dependence of radiative forcing on the CO_2 concentration leads to a decreasing forcing anomaly per unit change in CO_2 concentration as the baseline CO_2 concentration increases. The latter effect appears to dominate. The effects of the CH_4 and N_2O pulse emissions on atmospheric CO_2 are also apparent in figure 3(b): as expected, warming due to these pulse emissions increases the concentration of atmospheric CO_2, thereby increasing the temperature and forcing response to the pulse emissions of CH_4 and N_2O. The effects of these processes on GWP and MGTP for the 1850 and 2000 pulses are shown in table 2. Nonlinearities in the forcing/concentration relationship strongly reduce the temperature response to the CH_4 pulse in 2000 compared to the 1850 pulse (figure 3(a)), resulting in a smaller GWP and MGTP for CH_4 in 2000 (table 2), while the N_2O GWP and MGTP are larger in 2000, since the temperature response to the two N_2O pulses is similar, while the temperature response to the 2000 CO_2 pulse is reduced.

Table 2. As table 1, but showing GWP and MGTP from UVic-CC based on pulse emissions in 1850 and 2000 compared to a transient baseline simulation with historical anthropogenic and natural forcings until 2000 and SRES A2 forcings thereafter.

Gas		Absolute CO_2	CH_4	N_2O
GWP	1850	87 W m^{-2} Tt^{-1} yr	26	370
	2000	75 W m^{-2} Tt^{-1} yr	23	390
MGTP	1850	0.50 °C Tt^{-1}	31	310
	2000	0.43 °C Tt^{-1}	25	380

3. Conclusions

We define mean global temperature change potential (MGTP) as a time-averaged GTP, and demonstrate that it is numerically similar to GWP when evaluated over a 100 yr period: this is consistent with the temperature response being proportional to the radiative forcing over a sufficiently long time period [10, 16]. We further demonstrate that using a climate model with a dynamical ocean considerably modulates the temperature response to pulse emissions of each greenhouse gas, but that MGTPs of CH_4 and N_2O are little affected, since differences in the temperature responses to pulse emissions of each gas and CO_2 tend to cancel out in the calculation of MGTP. We find that the radiative forcing and temperature responses to pulse emissions of CH_4 and N_2O are significantly inflated when carbon feedbacks on climate change are taken into account: their GWPs and MGTPs are inflated by ∼20% in our experiments with the UVic-CC model. The magnitude of this effect is similar for pulse emissions twice as large, but is expected to be sensitive the strength of the carbon–climate feedback in the model: while the UVic-CC model exhibits a relatively strong feedback [19], it is not inconsistent with observational constraints [20]. When we apply pulse emissions in a baseline simulation with plausible past and future emissions, we find that the airborne fraction of the pulse emission of CO_2 increases after a decline for 2–3 decades. Thus CO_2 emissions today may lead to a larger increase in atmospheric CO_2 levels in 2100 than in 2030. This complex behaviour is not captured by the impulse-response function models usually used to calculate the atmospheric CO_2 response to pulse emissions [12, 1]. Standard calculations of greenhouse gas metrics therefore miss both the effects of carbon cycle feedbacks on the responses to non-CO_2 GHGs, and some of their effects on the response to CO_2 itself. We note that because of the different lifetimes of the greenhouse gases, in particular the very long lifetime of atmospheric CO_2, as well as nonlinear relationships between concentrations and radiative forcings, metrics such as GWP and GTP are time-dependent,

scenario-dependent and subject to large uncertainties [9–11]. Nonetheless, we find that carbon cycle dynamics, and positive carbon–climate feedbacks in particular, have an important bearing on the global warming effects of non-CO_2 greenhouse gases. While we do not advocate that metrics from a single carbon–climate model are directly used in climate policy, we recommend that carbon–climate feedbacks should at least be considered when such metrics are calculated and used, and that the carbon–climate feedback might be parameterized in the simple models usually used to derive metrics.

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