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The effect of climate–carbon cycle feedbacks on emission metrics

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Abstract

The Climate–Carbon cycle Feedback (CCF) affects emission metric values. In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change metric values for Global Warming Potentials (GWP) and Global Temperature Potentials (GTP) are reported both with and without CCF for non-CO_2 climate forcers, while CCF is always included for CO_2. The estimation of CCF for non-CO_2 climate forcers in AR5 is based on a linear feedback analysis. This study compares that approach with an explicit approach that uses a temperature dependent carbon cycle model. The key difference in the CCF results for non-CO_2 climate forcers is that, with the approach used in AR5, a fraction of the CO_2 signal induced by non-CO_2 forcers will persist in the atmosphere basically forever, while, with the approach based on an explicit carbon cycle model, the atmospheric CO_2 signal induced by non-CO_2 forcers eventually vanishes. The differences in metric values between the two model approaches are within ±10% for all well-mixed greenhouse gases when the time horizon is limited to 100 yr or less, for both GWP and GTP. However, for long time horizons, such as 500 yr, metric values are substantially lower with the explicit CCF model than with the linear feedback approach, up to 30% lower for GWP and up to 90% lower for GTP.

1. Introduction

Emission metrics are used to compare climate forcers that have different atmospheric adjustment times, often using carbon dioxide (CO_2) as a reference gas. These comparisons are helpful when trying to assess the impact on the climate of different anthropogenic activities that cause emissions of various climate forcers. For the metrics to be as relevant as possible, they need to be well-defined and consistent in their structure and calculation.

Historically, the treatment of the Climate–Carbon cycle Feedback (CCF), considered to be one of the most important positive biogeochemical feedbacks in the climate system (Arneth *et al* 2010, Ciais *et al* 2013), has been inconsistent when calculating metrics (Myhre *et al* 2013). Since the fourth assessment report (AR4) of the IPCC (Solomon *et al* 2007), the climate–carbon cycle feedback has been taken into account when estimating the Absolute Global Warming Potential (AGWP) for CO_2 but not when estimating the AGWP for the other gases. However, there have been calls for the inclusion of the CCF for non-CO_2 gases when calculating metric values (Gillett and Matthews 2010, Collins *et al* 2013). Gillett and Mathews (2010) find approximately a 20% increase in the GWP values for methane (CH_4) and nitrous oxide (N_2O) when including the CCF for non-CO_2 forcers. Recently a task force initiated by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) on 'Global guidance on environmental life cycle impact assessment indicators' added to the calls. The task force recommended that metrics that include the CCF effect for non-CO_2 greenhouse gases be used when conducting Life Cycle Assessments (LCAs) (Levasseur *et al* 2016). Hence, it is important to assess how the CCF affects emission metrics in detail since it

is possible that metric values that include the CCF will be industry standard in the near future.

In the AR5, the inconsistent treatment of the CCF for CO_2 versus non-CO_2 forcers was discussed and dealt with by presenting metric values that included the CCF (Myhre *et al* 2013) for all but the Short-Lived Climate Forcers (SLCFs)[2]. The approach used for estimating the contribution of CCF to metric values was based on the Linear Feedback Analysis (LFA) presented in Collins *et al* (2013). In this approach the temperature perturbation induced by an emission pulse of a non-CO_2 forcer causes a net release of carbon to the atmosphere, without any details about from where this carbon came. Further, the carbon added to the atmosphere is assumed to be removed from the atmosphere in the same way as an emission pulse of fossil carbon.

In this study we compare metric values, for the Global Warming Potential (GWP) and Global Temperature change Potential (GTP), estimated with two different approaches to including the CCF. We contrast the LFA approach with an approach based on a Coupled Climate–Carbon cycle Model (CCCM) that models the interaction between the climate and the carbon cycle explicitly. Our prime interest lies in the difference in CCF relaxation time scales between the two model approaches and what effect this has on absolute and relative metric values.

In section 2, we introduce the CCCM, and in section 3, we present the methods used for the numerical evaluation of the metrics. section 4 contains results and analysis, and we end with conclusions in section 5. In the supplementary material available at stacks.iop.org/ERL/12/034019/mmedia (SM) we present details of the model, elaborate on the results in more detail, and show some additional results.

2. A coupled climate–carbon cycle model

This study utilizes an Upwelling-Diffusion Energy Balance Model (UDEBM) presented in Sterner *et al* (2014) and Johansson *et al* (2015) coupled to a carbon cycle model based on Siegenthaler and Oeschger (1987), Jain *et al* (1995), and Joos *et al* (1996). We first present the UDEBM and then the carbon cycle model (model equations are given in SM 1.1). For the greenhouse gases explicitly studied in this paper (CH_4, N_2O, and sulfur hexafluoride, SF_6), we use simple gas cycle models in line with those used in IPCC AR5 (Myhre *et al* 2013), while for Black Carbon (BC) we calculate a radiative forcing pulse using the specific forcing and adjustment time of Fuglestvedt *et al* (2010). The LFA approach utilizes the same climate model but with a different setup of the carbon cycle model (see section 3.3) that represents the CCF using a linear relationship between temperature change and the induced carbon release.

2.1. Upwelling diffusion energy balance model

The UDEBM has two surface layers, one layer for land areas and the atmosphere above it and one for the mixed-layer ocean and the atmosphere above it. The ocean below the mixed layer has been discretized into 39 layers of equal size. The structure of the UDEBM and its calibration are based on Shine *et al* (2005), Hoffert *et al* (1980), Baker and Roe (2009), Olivié and Stuber (2010), Johansson *et al* (2015) and MAGICC Meinshausen *et al* (2011a). We use a climate sensitivity of 3 °C for a doubling of atmospheric CO_2 concentration. The UDEBM is tuned as in Sterner *et al* (2014)[3] to give a global annual mean surface temperature over the period 1880–2005 that is roughly in line with observations reported in the NASA GISS series (Hansen *et al* 2010) (see SM 1.3). The UDEBM calibration is described in greater detail in the supplementary material of Sterner *et al* (2014).

2.2. The carbon cycle model

The reduced-complexity carbon cycle model used in this study consists of two parts: a four-box terrestrial biosphere model (Siegenthaler and Oeschger 1987) and an upwelling-diffusion model (UDM) (Jain *et al* 1995, Joos *et al* 1996).

The box model representing the biospheric part of the carbon cycle consists of four carbon reservoirs: 'ground vegetation plus leaves,' 'wood,' 'detritus,' and 'soils' (denoted G, W, D, and S respectively). The pre-industrial values of the carbon reservoirs and the fluxes between them are based on Siegenthaler and Oeschger (1987). In order to examine the CCF we assume that decomposition and respiration rates for the D and S boxes are temperature dependent with a relationship stating the change in the rates of decomposition and respiration for a ten degree increase in global mean annual land surface temperature (so-called effective Q_{10}-factors) (Harvey 1989, Friedlingstein *et al* 2006). The strength of the effective Q_{10}-factors is highly uncertain, and recent studies (Friedlingstein 2015) indicate that the CCF may be lower than found in older literature (Friedlingstein *et al* 2006, Ciais *et al* 2013). The Net Primary Production (NPP) increases with increasing atmospheric CO_2 concentration due to the CO_2-fertilization effect. The strength of the CO_2 fertilization effect in the model is controlled with a biota growth factor, β (see SM 1.1) (Bacastow and Keeling 1973). We assume that NPP is independent of changes in the global temperature, since the effect of climate change (besides CO_2 fertilization) on NPP varies from positive to negative among various studies

[2] IPCC AR5 uses the term near-term climate forcer, but we find this misleading since all climate forcers, including the so-called long-term forcers, cause forcing in the near term.

[3] The only change in parameter values is a reduction of the upwelling velocity to 3.5 m per year here.

and models (Friedlingstein *et al* 2006, Meinshausen *et al* 2011a).

For the ocean part of the carbon cycle, the model is conceptually identical to the UDEBM, but instead of modeling energy fluxes it models vertical flows of carbon (as in Jain *et al* 1995). The inorganic carbon-chemistry of the ocean surface controlling the exchange between the ocean and the atmosphere is parameterized based on Joos *et al* (1996), while the temperature dependence of the partial pressure of sea surface CO_2 is from Joos *et al* (2001) (see SM 1.1 for more information).

Two key parameters that control fluxes of carbon in the carbon cycle model[4] are calibrated to capture the CO_2 increase in the atmosphere since 1765 (using emissions and concentrations from Meinshausen *et al* 2011b) and to give a similar uptake in the biosphere and the ocean as reported in AR5 (Ciais *et al* 2013) (see SM 1.3).

The model does not include the slow sedimentation processes and the reactions with silicate rocks that over time scales of 10 000 to 100 000 yr cause atmospheric CO_2 perturbations to relax back to zero. Further, the model does not include the hydrologic cycle, so it does not capture changes in precipitation and soil moisture that could have important effects on CCF. Hence, the climate–carbon cycle model is relatively simple. However, related simple climate models have proven to be useful for various sorts of analyses of climate change (cf. Meinshausen *et al* 2009), including for analysis of emission metrics (Joos *et al* 2013, Reisinger *et al* 2010, Reisinger *et al* 2011, Tanaka *et al* 2009). The quantitative results should nevertheless be interpreted with some care.

3. The carbon cycle feedback and its impact on metric values

We evaluate the metrics (A)GWP and (A)GTP with a set of climate forcers that cover the whole scale of adjustment times, from the short-lived BC to the long-lived sulfur hexafluoride (SF_6) and CO_2 (see table SM 1). Metric values are contingent upon the background scenario used (Joos *et al* 2013, 2011). We use the emissions from the RCP 4.5 scenario with additional pulse emissions of 10^6 kg = 1 Kilo ton (Kt) on top of the scenario to calculate metric values. The background scenario for the climate forcers not explicitly studied here is given by the RCP 4.5 radiative forcing scenario (Meinshausen *et al* 2011b).

The model's time resolution is 0.1 yr. We assume that the emission pulses of the different forcers occur in the first tenth of year 2015. The atmospheric BC stock is assumed to reach its equilibrium level directly, and then it falls back to zero in the subsequent time step.

We run the model both without (described in section 3.2) and with (described in section 3.3) the CCF for non-CO_2 forcers. The CCF is in turn included in two different ways: a) by calculating it with the CCCM where the warming induced by an emissions pulse of a non-CO_2 forcer explicitly affects the different carbon reservoirs (referred to as the Explicit Carbon–Climate Feedback (ECCF) approach) and b) by calculating the CCF using an LFA approach similar to the method used in IPCC AR5 (Myhre *et al* 2013) and Collins *et al* (2013).

3.1. Absolute metric values for CO_2

When studying emission pulses of CO_2, which is the reference gas for the relative metric values, we consistently use the CCCM with the explicit temperature dependence of the carbon cycle as in the ECCF approach. To calculate $AGWP_{CO_2}$ and $AGTP_{CO_2}$, we run the CCCM with an extra emission pulse of CO_2 in addition to the emissions in the background scenario and calculate the impacts on CO_2 concentration, radiative forcing, and temperature. This is in principle similar to how the Impulse Response Function (IRF) for CO_2 used for emissions metrics in IPCC AR5 was estimated (Joos *et al* 2013)[5].

3.2. Metrics without CCF for non-CO_2 forcers

When calculating metric values without the CCF for non-CO_2 forcers, we first run the CCCM with emissions from the RCP4.5 scenario to establish the background concentrations for the climate forcers we explicitly consider in the analysis. In the next step, we add emission pulses for different forcers to estimate absolute metric values, i.e. AGTP and AGWP, from which GTP and GWP values can be calculated equations (1) and (2):

$$GTP_X^H = \frac{AGTP_X^H}{AGTP_{CO_2}^H} \quad (1)$$

$$GWP_X^H = \frac{AGWP_X^H}{AGWP_{CO_2}^H} \quad (2)$$

Here X is the climate forcer studied, H is the time horizon, $AGTP_X$ is the absolute global temperature change potential and $AGWP_X$ is the absolute global warming potential of climate forcer X.

The absolute metric values are estimated differently for CO_2 and the non-CO_2 forcer since the CCF is included for $AGWP_{CO_2}^H$ and $AGTP_{CO_2}^H$ but not for $AGWP_X^H$ and $AGTP_X^H$. When estimating $AGWP_X^H$ and $AGTP_X^H$ we only use the gas cycle model of the studied forcer along with the UDEBM to estimate the impacts on concentration, radiative forcing, and temperature of the extra emission pulse and neglect possible interactions with the carbon cycle.

[4] The CO_2-fertilization parameter, β, and the polar water parameter, π_o, the ratio of the change in carbon concentration in sinking polar water to the change in concentration in the global average ocean surface water.

[5] However, in Joos *et al* (2013) an assumption of constant CO_2 background concentration was used.

In this paper we present metric values for a time horizon up to 500 yr, while in IPCC AR5 metric values were only presented for time horizons up to 100 years for reasons related to uncertainty and potential limitations of the chosen approach to calculating metrics (Myhre *et al* 2013).

3.3. Metrics including the CCF for all forcers

3.3.1. The ECCF approach

When including CCF for non-CO_2 forcers using the ECCF approach, the full CCCM (i.e. the temperature dependent version of the CCCM) is used. The metric values for a non-CO_2 forcer are calculated by using the full CCCM with an extra emission pulse of the non-CO_2 forcer in 2015. The impacts on the concentration of both the analyzed non-CO_2 forcer and CO_2, through the CCF, and subsequent impact on radiative forcing and temperature are assessed. From these values we can estimate the absolute metric values for the non-CO_2 forcer with the CCF included. Hence, the direct temperature impact of emissions of a non-CO_2 forcer on decomposition and respiration rates in the terrestrial biosphere model and the temperature dependence of the oceanic inorganic carbonate chemistry are explicitly modeled in the same way as they are for an emissions pulse of CO_2.

3.3.2. The LFA approach

The LFA approach to including carbon cycle feedbacks for non-CO_2 forcers is based on Collins *et al* (2013), with the CCF parts of AGTP and AGWP for non-CO_2 forcer X evaluated according to equations (3) and (4).

$$\Delta\mathrm{AGTP}_{\mathrm{ind\,CO_2}} = \int_0^H \Gamma \cdot \mathrm{AGTP}^*_X(t) \cdot \mathrm{AGTP}_{\mathrm{CO_2}} (H-t)\mathrm{d}t \quad (3)$$

$$\Delta\mathrm{AGWP}_{\mathrm{ind\,CO_2}} = \int_0^H \Gamma \cdot \mathrm{AGTP}^*_X(t) \cdot \mathrm{AGWP}_{\mathrm{CO_2}} (H-t)\mathrm{d}t \quad (4)$$

Here $\mathrm{AGTP}_X^*(t)$ is the AGTP_X with no CCF at time t after the emission pulse, calculated as described in section 3.1. To emphasize that the CCF part of AGTP and AGWP estimated in this way are caused by the CCF induced CO_2, they are denoted $\Delta\mathrm{AGTP}_{\mathrm{ind\,CO_2}}$ and $\Delta\mathrm{AGWP}_{\mathrm{ind\,CO_2}}$ respectively. The method utilizes results on an estimated linear feedback factor, Γ, between global mean temperature change and carbon cycle response (Arora *et al* 2013, Boer and Arora 2012). Collins *et al* (2013) and Myhre *et al* (2013) use a climate–carbon cycle feedback Γ of 1 GtC K yr^{-1}, based on Arora *et al* 2013. In SM 1.2, based on an approach similar to Boer and Arora (2012), we show that a linear feedback factor of 1 GtC K yr^{-1} is also a decent approximation of the CCF feedback strength in our CCCM. Hence, we use this value when applying the LFA approach (figure 1) in our study. Note that the feedback factor, Γ, estimated in Arora *et al* (2013) and Boer and Arora (2012) is based on Earth System Models (ESMs) that have a far more elaborate description of the global carbon cycle than our CCCM.

In the LFA approach, absolute metric values for CO_2 are still estimated using the full CCCM as described above (see section 3.1). This is analogous to the procedure followed by Collins *et al* (2013) and Myhre *et al* (2013) who use an impulse response function for CO_2 that includes the CCF (Joos *et al* 2013). When estimating the absolute metric for the non-CO_2 forcers using the LFA approach, we do not use an explicit impulse response function for $\mathrm{AGTP}_{\mathrm{CO_2}}$ as in Collins *et al* (2013) and Myhre *et al* (2013). Instead, utilizing our CCCM, we evaluate the effect on concentration, radiative forcing, and temperature of the induced CO_2 release, calculated using the feedback factor approach (figure 1). These values are then added to the corresponding values for the non-CO_2 forcer as estimated for the case with no CCF (i.e. the case presented in section 3.2), see equations (5) and (6) and figure 1. The LFA approach and our ECCF approach include the same feedbacks, but in different ways. In section 4 we compare the metric values they produce.

$$\mathrm{AGTP}_X^{\mathrm{LFA}} = \mathrm{AGTP}^*_X + \mathrm{AGTP}_{\mathrm{ind\,CO_2}} \quad (5)$$

$$\mathrm{AGWP}_X^{\mathrm{LFA}} = \mathrm{AGWP}^*_X + \mathrm{AGTP}_{\mathrm{ind\,CO_2}} \quad (6)$$

Here the $\mathrm{AGTP}_{\mathrm{ind\,CO_2}}$ ($\mathrm{AGWP}_{\mathrm{ind\,CO_2}}$) is the AGTP (AGWP) of the induced CO_2 emission release due to the emission pulse of climate forcer X calculated using the LFA approach.

3.3.3. Comparing the ECCF and the LFA approaches

In the ECCF approach, the CCF consists of an increase in the decomposition rate of terrestrial organic carbon and a shift towards a higher partial pressure of dissolved CO_2 for a given level of Dissolved Inorganic Carbon (DIC) in ocean surface waters. Given a fixed background level of the atmospheric carbon stock, this implies a small release of carbon from the biosphere and the ocean to the atmosphere, which results in an increased atmospheric CO_2 concentration and additional radiative forcing and warming.

In the LFA approach, however, the net CO_2 released to the atmosphere due to the CCF is calculated by using the assumption of a linear relationship between the CO_2 flux and the direct temperature perturbation caused by the non-CO_2 forcer according to equations (3) and (4). The induced atmospheric CO_2 caused by the non-CO_2 forcer is assumed to have the same characteristics, i.e. atmospheric adjustment times, as regular emissions of fossil CO_2 and will hence end up elevating the atmospheric carbon stock basically forever (figure 3).

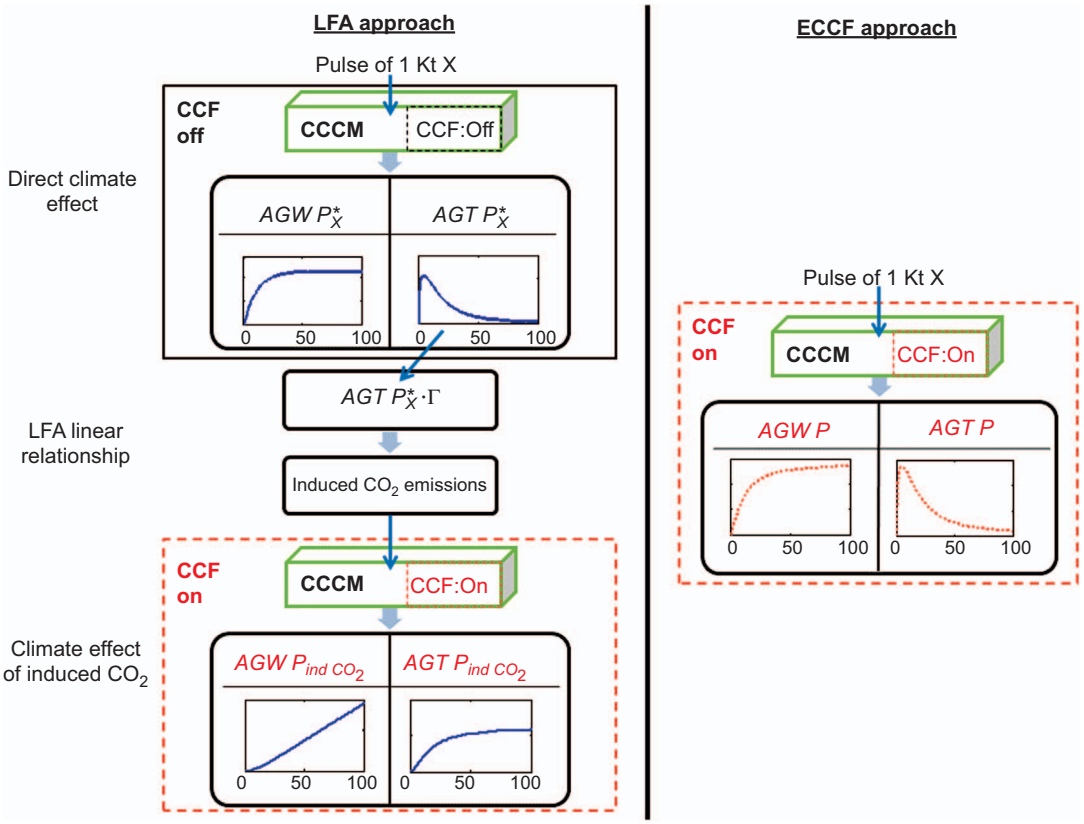

Figure 1. Schematic illustration of the calculation of absolute metric values (AGWP and AGTP) for the two climate–carbon cycle feedback (CCF) approaches compared. Left: The LFA-based approach, where the CCCM climate model is first used to calculate $AGWP_X^*$ and $AGTP_X^*$ for the studied non-CO_2 forcer *X* without the CCF. Then the warming-induced CO_2 release is calculated based on the estimated $AGTP_X^*$ and the linear feedback factor Γ. Finally, $AGTP_{ind\,CO_2}$ and $AGWP_{ind\,CO_2}$ are calculated by assessing the temperature and integrated radiative forcing response of the warming-induced CO_2 release with CCCM, but now with CCF turned on. Taken together, the $AGTP_X^*$ and $AGTP_{ind\,CO_2}$, and $AGWP_X^*$ and $AGWP_{ind\,CO_2}$, give the AGTP and AGWP of climate forcer *X* for the LFA approach. Right: Our alternative approach, the ECCF approach, uses the CCCM with the CCF turned on for the emission pulse of the climate forcer studied and produces the AGTP and AGWP absolute metric values.

The differences in the CCCM setups for the LFA and the ECCF approaches are presented in figure 1.

4. Results and metrics evaluation

We first present the AGTP and AGWP values based on different assumptions for the CCF for non-CO_2 forcers, followed by an analysis of the physical mechanisms behind the atmospheric CO_2 concentration induced by non-CO_2 forcers. Finally, we present the GWP and GTP metric values obtained when including CCF for non-CO_2 forcers using the full CCCM (i.e. the ECCF) and LFA (i.e. IPCC) approaches.

4.1. Absolute metrics and the climate carbon feedbacks

For all non-CO_2 forcers the AGWP and AGTP values are higher when the CCF is included compared to when it is not for both approaches (figure 2). This is expected because an emission pulse of a non-CO_2 warming forcer causes a positive temperature perturbation, which, due to the CCF, causes an amount of CO_2 to enter the atmosphere (figure 3).

All climate forcers produce different temperature perturbation time profiles as a result of their different radiative efficiencies and adjustment times. This in turn causes the CCF responses to vary among the forcers (figure 3). As a consequence, the CCF effects on AGTP and AGWP differ among forcers (figure 2). Further, the differences between the two CCF approaches vary among the different forcers.

The ECCF approach results in a stronger induced atmospheric CO_2 concentration in the short run compared to the LFA approach. The time horizon over which this holds depends on the adjustment time of the non-CO_2 forcer (figure 3). This causes the AGWP and AGTP to be slightly higher for the ECCF approach than for the LFA approach over a certain time horizon, the length of which increases with the atmospheric adjustment time of the non-CO_2 forcer. The reason that the values are only slightly higher is that the effect of the differences in the induced atmospheric CO_2 concentrations are initially dwarfed by the direct RF and warming of the non-CO_2 forcers. This causes the AGWP and AGTP values, of the LFA and the ECCF approaches, to follow each other rather tightly for about 100 to 200 yr (see figure 2).

Further, with the ECCF approach the feedback-induced atmospheric CO_2 perturbation will eventually relax back to its unperturbed state for all forcers, while the LFA approach leads to an irreversible impact on

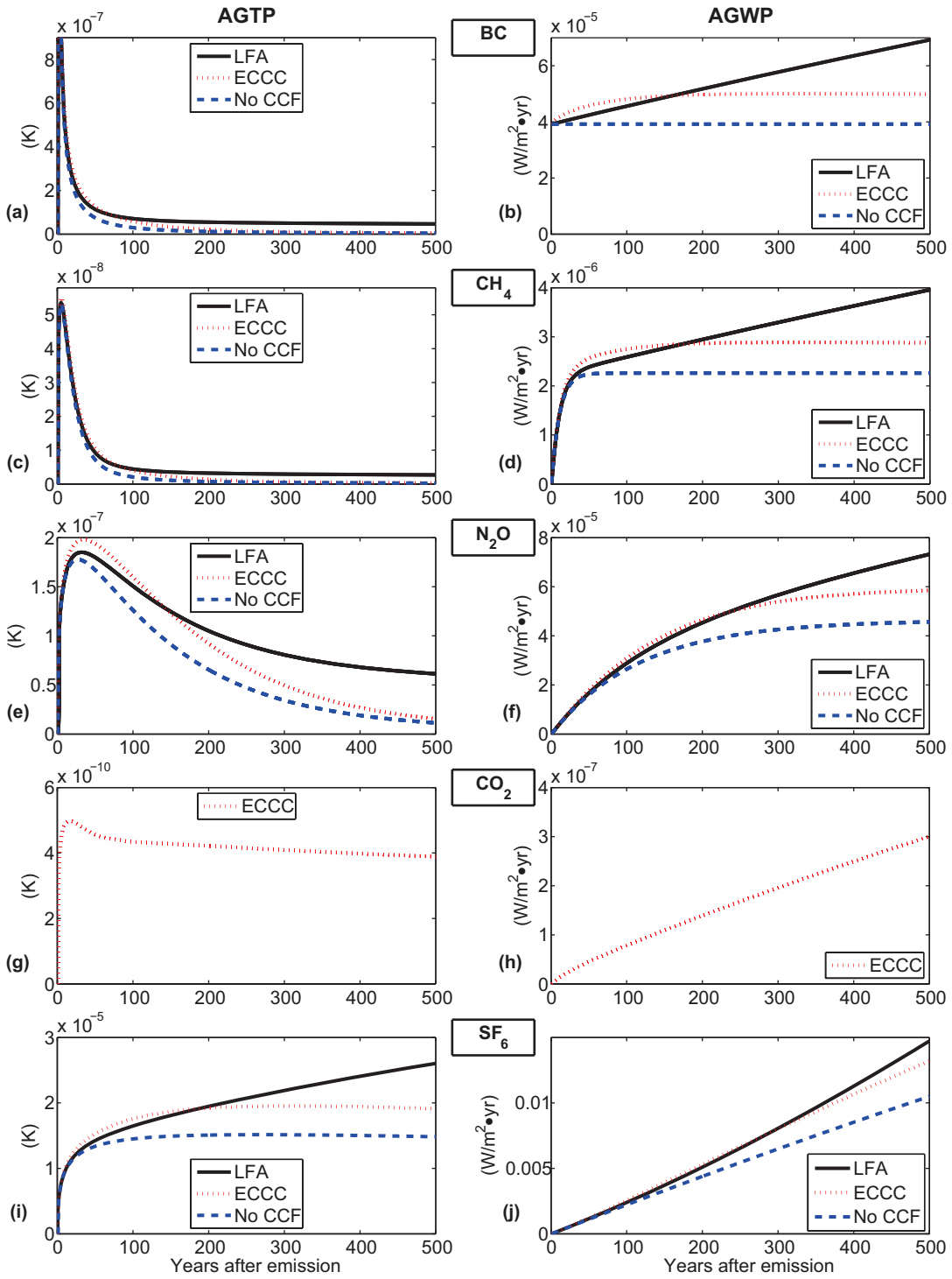

Figure 2. Absolute global mean surface temperature changes (AGTP, left side) and absolute global mean cumulative radiative forcing (AGWP, right side) following 1 Kt emission pulses of BC (*a*) and (*b*), CH_4 (*c*) and (*d*), N_2O (*e*) and (*f*), CO_2 (*g*) and (*h*), and SF_6 (*i*) and (*j*), for the three CCF assumptions studied (except for CO_2, for which there is only the one CCF assumption). Note that the temperature scale of figure 2(*a*) (BC) does not encompass the peak values in the earliest time period in order to focus on the difference in evolution over time.

the atmospheric carbon stock (figure 3). Hence, the LFA approach will for time horizons large enough generate higher values than the ECCF approach for both AGTP and AGWP for all forcers studied (figure 2).

The reason for the irreversible impact on the atmospheric carbon stock with the LFA approach is that it models the carbon feedback as a temperature-induced CO_2 emission, where these emissions act as 'extra emission pulses of CO_2' (Collins *et al* 2013). The irreversibility is also a model artifact since it does not include the slow geochemical processes that eventually after 10 000 to 100 000 of years would remove the anthropogenic carbon emissions from the atmosphere, a property the model shares with the IRF used for metric estimates in IPCC AR5.

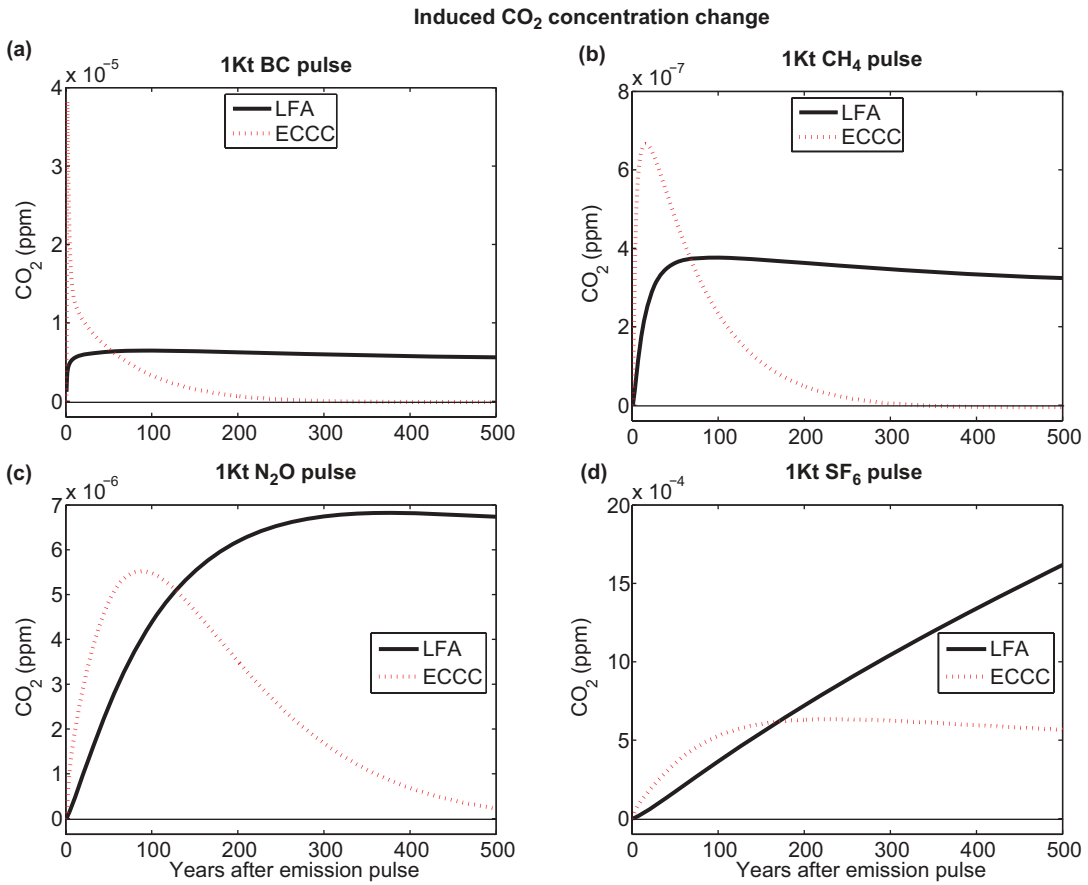

Figure 3. Comparing the effect of the LFA and ECCF approaches on atmospheric CO_2 concentration. The 1 Kt pulse emissions of (*a*) BC, (*b*) CH_4, (*c*) N_2O, and (*d*) SF_6 are emitted in 2015; the background is the RCP4.5. Note the difference in the scales on the *y*-axes.

It is possible to estimate an IRF for the CCF that reflects the CCF found with the ECCF approach. Such a function could represent an accurate physical description of the carbon cycle response to the warming by non-CO_2 forcers and could avoid problems with the LFA approach presented here. In section 3 of the supplementary material we elaborate on this approach. Recently, Gasser *et al* (2016) also published a discussion paper on such an approach.

4.2. Redistribution of carbon due to non-CO_2 climate forcers

A key conceptual difference between the LFA and ECCF approaches to the CCF is that, with the LFA, the carbon added to the atmosphere is external to the linked atmosphere-biosphere-ocean system; with the ECCF, it is instead an effect of redistribution within the system. This section explores the dynamics of this redistribution following a non-CO_2 emissions pulse.

For emission pulses of all forcers the induced temperature response causes initially a flux of carbon into the atmosphere from the biosphere due to increased rates of decomposition and respiration (figure 4). The exchange between the atmosphere and the ocean is small because of the balancing of two mechanisms working in different directions, i.e. the temperature dependence of the inorganic carbon chemistry of the surface water and the increase in partial pressure of the atmosphere due to the atmospheric CO_2 increase caused by the net biosphere release of carbon.

After a number of years, depending on the atmospheric adjustment time of the climate forcer, the temperature perturbation caused by the forcing of the non-CO_2 forcer peaks and ceases (figure 2), which in turn leads to that the perturbation in all three carbon reservoirs slowly relaxes back to its unperturbed state (see figure 4).

4.3. Effects of climate carbon feedbacks on relative metric values

Our estimates of GWP and GTP give similar, but not identical, values to corresponding ones in AR5 (Myhre *et al* 2013). There are several reasons why we do not get an exact match to the values presented in AR5. We use a scenario with varying background concentration (based on the emission-driven RCP 4.5), while the AR5 uses a constant background. Further, we use a CCCM to estimate metric values, while AR5 uses an approach based on an impulse response function. Furthermore, we do not include the indirect effects of N_2O emissions on its own atmospheric lifetime and on the atmospheric lifetime of CH_4 (Prather and Hsu 2010); this contributes to making the N_2O metric values higher in this study than in AR5 where these effects are considered (Myhre *et al* 2013). Finally, the

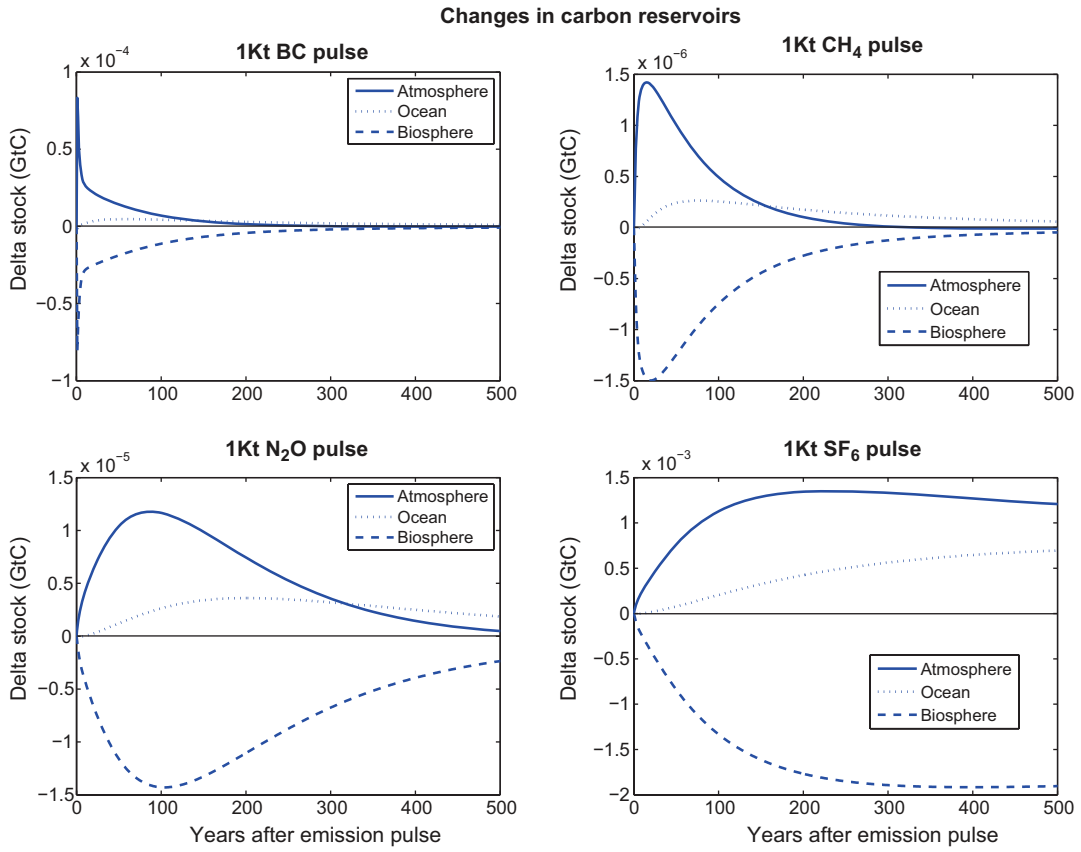

Figure 4. The redistribution of carbon between the key carbon reservoirs considered in our model i.e. the atmosphere, the ocean, and the biosphere following 1 Kt emission pulses of (*a*) BC, (*b*) CH_4, (*c*) N_2O, and (*d*) SF_6, respectively.

Table 1. Comparison of metrics for different climate forcers with different CCF implementations: **Only CO_2**—CCF only for CO_2; **ECCF**—CCF according to the ECCF approach for all forcers; **LFA**–CCF according to the LFA approach for all non-CO_2 forcers.

Climate forcer	Metric	GWP			GTP		
Time Horizon	CCF inclusion	20	100	500	20	100	500
	Only CO_2	1790	499	130	446	68	11
BC	**LFA**	1840	581	230	516	163	120
	ECCF	1960	612	166	593	134	13
	Only CO_2	86	29	7.5	57	4.8	0.63
CH_4	**LFA**	88	33	13	60	10	7
	ECCF	93	35	9.6	65	9.2	0.75
	Only CO_2	329	337	152	355	290	29
N_2O	**LFA**	334	368	243	364	347	158
	ECCF	349	392	194	385	368	40
	Only CO_2	20 200	28 300	34 900	22 900	33 400	38 100
SF_6	**LFA**	20 500	30 600	49 000	23 400	38 000	67 000
	ECCF	21 400	32 600	43 900	24 700	40 400	49 200

time scales of our UDEBM differ from those of the impulse response function used for calculating the temperature response in estimating GTP in AR5 (Myhre *et al* 2013).

From table 1 it is clear that the emission metric values depend on if and how the CCF is included for non-CO_2 forcers. As expected, the metric values are lowest when the CCF is excluded for these forcers altogether, since excluding it means leaving out a positive effect on the radiative forcing and temperature change.

On short time scales (such as a 20 yr time horizon), GWP and GTP are slightly higher with the ECCF than with the LFA approach. On long time scales (GWP and GTP with a 500 yr time horizon), the results are the opposite, i.e. the LFA approach generates higher metric values than the ECCF approach because the LFA approach gives a greater AGTP and AGWP than with ECCF after a certain time horizon, see section 4.1. In general, the difference in metric values between the two approaches is greater for GTP than GWP, reaching an order of magnitude

for the short-lived forcers for GTP, for the 500 yr time horizon. This is because GWP is an integrated metric, while GTP assesses the climate effect at a certain point in time (thus disregarding everything before that). After 500 yr, the temperature signal (AGTP) from a short-lived climate forcer is virtually gone using the ECCF approach, while it has a clear positive temperature signal with LFA, causing a large relative difference between the approaches (see figures 2 and 3). However, for GWP, which integrates all past radiative forcing impacts up to the end year, the ECCF's larger CCF signal during the initial years balances to a large extent the weaker signal in the long run. Neither GTP_{500} nor GWP_{500} is presented in AR5 (Myhre *et al* 2013), a decision taken, at least in part, due to the uncertainty in long-run climate consequences of emission pulses occurring in the near-term. However, GTP_{500} can be a relevant metric for assessing long-term, and close to irreversible, climate impacts.

For a 100 yr time horizon, the GWP metric values are higher with ECCF than with LFA for all forcers. For GTP, the results are mixed. The GTP metric values are higher with LFA approach than with ECCF for CH_4 and BC, while the opposite holds for the long-lived greenhouse gases (N_2O and SF_6).

The metric values are sensitive to the choice of parameter values in the model. For example, increasing or decreasing the climate sensitivity value used in the model has a large impact on the absolute metric values, but a much smaller effect on relative ones. This has been shown by Karstensen *et al* (2015) to hold when not considering CCF. There is no reason that this general conclusion would not also hold when including CCF. In the sensitivity analysis presented in SM 2, we focus on the sensitivity with respect to Q_{10} (the temperature dependence of the rates of decomposition and respiration) and β (the fertilization factor) using the ECCF approach. These are two of the most critical parameters in the carbon cycle model for its response to emissions and are directly relevant to various CO_2- and temperature-induced feedbacks analyzed in this study. Other factors, such as NPP, pre-industrial carbon content of the various carbon reservoirs, and the decomposition or respiration rates in the various reservoirs, are of course important for the general functioning of the carbon cycle model, but less directly involved in the feedback mechanisms (Bodman *et al* 2013). We vary Q_{10} and β simultaneously in order to keep a good fit to the observed historical atmospheric CO_2 concentration (see SM 2) and estimate the sensitivity of the metric values. We find that the GWP and GTP metric values, using the ECCF approach, are relatively robust to changes in Q_{10} (1.5, 2, or 2.5) and β (0.47, 0.55, or 0.62). For most relative emission metric values the changes are less than 5%, but they reach 15% in the case of GTP for a 100 yr time horizon, while absolute metric values are more sensitive.

5. Conclusions

The two different approaches to including the CCF for non-CO_2 forcers give different emission metric values. The differences between the metric values obtained using the LFA approach and the ECCF approach tend to be larger for GTP than for GWP for most time horizons.

Further, in the short run, somewhat higher metric values for both GWP and GTP are obtained using the ECCF approach compared to the LFA approach because the initial CCF is stronger with the ECCF approach than with the LFA approach. However, with the ECCF approach, the elevated atmospheric CO_2 will eventually relax back to zero, while this is not the case for the LFA approach. This causes both GTP and GWP metric values to be higher with the LFA than with the ECCF approach after certain time horizons, which depend on the atmospheric adjustment times of the non-CO_2 forcers. For a 100 yr time horizon the results are mixed: for GWP the ECCF approach yields higher metric values than the LFA for all forcers, while for GTP the LFA approach yields higher metric values for BC and CH_4, but for N_2O and SF_6 the ECCF yields higher values.

The LFA approach treats the warming induced by the non-CO_2 forcers as if it induces extra CO_2 emissions into the combined atmosphere-biosphere-ocean system that with time are distributed among the carbon reservoirs similarly to a pulse emission of fossil CO_2. Hence, use of the LFA approach will result in that a fraction of the induced CO_2 emission will remain in the atmosphere basically forever. The ECCF, on the other hand, captures the CCF in a physically consistent way as a redistribution of carbon within the atmosphere-biosphere-ocean system.

Although the LFA approach as used in IPCC AR5 has clear shortcomings for long time horizons it works reasonably well for time horizons up to ~100 (~200) years for GTP (GWP). This is perhaps to be expected since the feedback factor used in the LFA approach is estimated from a climate scenario that follows a certain pathway of over a period of about 100 yr (Arora *et al* 2013).

Uncertainties and possible limitations of the LFA approach for time horizons beyond 100 yr were acknowledged in IPCC AR5 (Myhre *et al* 2013), and no metric values for time horizons beyond 100 years were presented. Hence, given the large uncertainties in the size and the dynamics of carbon cycle feedbacks, the LFA approach, as used in IPCC AR5, gives decent estimates of the carbon cycle impact of non-CO_2 greenhouse gases for time horizons limited to about a century.

However, the use of an approximate method like the LFA approach, as used in IPCC AR5, draws attention to the issue of simplicity and transparency versus accuracy and comprehensiveness when calculating emission metric values. How far simplicity can

be stretched at the expense of comprehensiveness is up to the judgment of the scientists involved and likely depends on the context in which the metric is to be used. If and how carbon cycle feedbacks and other feedbacks within the climate system (Shindell *et al* 2009, Collins *et al* 2010, Arneth *et al* 2010) should be included in emission metrics is likely one of the key research issues for the development of refined emission metrics leading up to the next assessment report of the IPCC.

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