

# Assessment of urgent impacts of greenhouse gas emissions—the climate tipping potential (CTP)

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## Abstract

**Purpose** The impact of anthropogenic greenhouse gas (GHG) emissions on climate change receives much focus today. This impact is however often considered only in terms of global warming potential (GWP), which does not take into account the need for staying below climatic target levels, in order to avoid passing critical climate tipping points. Some suggestions to include a target level in climate change impact assessment have been made, but with the consequence of disregarding impacts beyond that target level. The aim of this paper is to introduce the climate tipping impact category, which represents the climate tipping potential (CTP) of GHG emissions relative to a climatic target level. The climate tipping impact category should be seen as complementary to the global warming impact category.

**Methods** The CTP of a GHG emission is expressed as the emission's impact divided by the 'capacity' of the atmosphere for absorbing the impact without exceeding the target level. The GHG emission impact is determined as its cumulative contribution to increase the total atmospheric GHG concentration (expressed in CO<sub>2</sub> equivalents) from the emission time to the point in time where the target level is expected to be reached, the target time.

**Results and discussion** The CTP of all the assessed GHGs increases as the emission time approaches the target time, reflecting the rapid decrease in remaining atmospheric capacity and thus the increasing potential impact of the GHG emission. The CTP of a GHG depends on the properties of the GHG as well as on the chosen climatic target level and background scenario for atmospheric GHG concentration development. In order to enable direct application in life cycle assessment (LCA), CTP characterisation factors are presented for the three main anthropogenic GHGs, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O.

**Conclusions** The CTP metric distinguishes different GHG emission impacts in terms of their contribution to exceeding a short-term target and highlights their increasing importance when approaching a climatic target level, reflecting the increasing urgency of avoiding further GHG emissions in order to stay below the target level. Inclusion of the climate tipping impact category for assessing climate change impacts in LCA, complimentary to the global warming impact category which shall still represent the long-term climate change impacts, is considered to improve the value of LCA as a tool for decision support for climate change mitigation.

**Keywords** Climate change · Climate tipping points · Climate tipping potential · Global warming potential · Impact category · Life cycle impact assessment

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## 1 Introduction

The global climate is changing these years, and we are quickly approaching expected climate tipping points (Hansen et al. 2008). A climate tipping point is a level of forcing in the climate system beyond which dramatic changes continue to occur without further forcing due to the initiation of positive feedback loops (Hansen et al. 2008; US DOT CCCEF 2009). Crossing such tipping points may lead to irreversible climate

changes (Meehl et al. 2007; Hansen et al. 2008). An example of a climate tipping point is given for the extent of the Arctic sea-ice cover. The continued melting of the ice cover clears a growing area of darker ocean surface with lower ability to reflect solar radiation, which again leads to further warming of the ocean (Hansen et al. 2008). The positive feedback loop may eventually bring the ice cover to the point where it becomes unstable, leading to an ice-free Arctic (US DOT CCCEF 2009).

The assessment of the contribution from different greenhouse gas (GHG) emissions to the man-made climate change impacts typically applies the global warming potential (GWP) as a metric. This metric is also generally applied in life cycle assessment (LCA) and related approaches like ‘carbon footprint’, and it was recently recommended as the best existing practice for midpoint modelling of climate change impact in LCA by the European Commission (Hauschild et al. 2013). GWP represents the time-integrated contribution of a gas to the radiative forcing of the atmosphere over a certain time horizon, most often 100 years. As it gives equal weight to GHG emissions regardless of emission time, the use of GWP for modelling of climate change impacts does however not support pursuing political targets in terms of keeping below a certain critical atmospheric average temperature increase, and it does not reflect the increased importance of short-lived GHGs as the critical level is approached (Shine et al. 2007). In recent years, the need for developing alternative climate change impact assessment metrics which include the consideration of such climatic target levels has been increasingly recognised (e.g. Shine et al. 2007; Peters et al. 2011; Cherubini et al. 2012; Jørgensen and Hauschild 2013). One example of an attempt to include a target level in climate change impact assessment is given in Shine et al. (2007), where a target time has been applied to the global temperature potential (GTP) metric, yielding the so-called time-dependent GTP metric.

To account for both long-term climate change impact and impacts related to passing climate tipping points, we suggest supplementing the well-established global warming impact category by a new target level impact category, as discussed by Jørgensen and Hauschild (2013) and presented by Jørgensen and Hauschild (2010) at an expert workshop on temporary carbon storage. Presentations and conclusions are summarised in Brandão and Levasseur (2011). The climate change impacts from GHG emissions would thus be represented by two sub categories—one addressing the long-term climate impacts (using GWP as midpoint characterization factor) and one addressing the urgency caused by contribution of increased GHG concentration level impacts to exceeding critical tipping points in the climate change impact pathway (also at midpoint level).

While the timing of GHG emissions of products is of little importance for long-term impacts and is not included in the normal GWP, it may be very relevant in relation to avoiding a certain climate tipping point. In many cases, GHG emissions and uptakes of a product happen at different points in time during a products lifetime. One example is bio-based energy, where there can be a considerable time difference between emission of CO<sub>2</sub> from combustion and the following uptake of CO<sub>2</sub> during regrowth of, for instance, wood biomass. Another example is when CO<sub>2</sub> is captured in biomass and stored for a shorter or longer period in, for instance, wood or bio-based plastic products. In both cases, the timing of emission and uptake relative to approaching a climate tipping point will have an impact. This will be reflected by the new subcategory, where the GWP will be used to assess long-term impacts and thus not consider emission timing. Suggestions for including timing of emissions in GWP have been given by e.g. Levasseur et al. (2010) and for biogenic CO<sub>2</sub> emissions by Cherubini et al. (2011), but none of those consider the emission timing relative to a climatic target.

The aim of this paper is to present the climate tipping impact category expressing the contribution of a GHG emission to pass a climatic target level and develop characterisation factors for use in life cycle impact assessment (LCIA), as supplement to the long-term climate change impacts expressed by the GWP.

The need for staying below a certain atmospheric GHG target level means that the difference between that level and the current atmospheric GHG concentration level, i.e. the atmospheric ‘capacity’ for taking up GHG emissions before reaching the target level, can be seen as a constrained resource. Thus, the climate tipping potential (CTP) metric applied for the climate tipping impact category should reflect the absolute cumulative contribution from a GHG emission to fill the remaining gap up to the climatic target level. It should model this contribution taking into account the foreseeable future development in atmospheric GHG concentration due to other activities up to the point in time where the target level is expected to be reached, the target time. The time-dependent GTP, which expresses the impact of a GHG emission in terms of temperature potential relative to a climatic target level (Shine et al. 2007), meets the requirement of including a target time but does not meet the other requirements needed here as it is neither cumulative nor taking into account future atmospheric GHG development (except for the target time setting).

The CTP uses a target time approach similar to that used for the time-dependent GTP by Shine et al. (2007) but further takes a cumulative, capacity-oriented approach. The difference between the time-dependent GTP and CTP is discussed in an impact assessment context.

## 2 Methods

### 2.1 The climate tipping potential (CTP)

The CTP expresses the absolute impact from a marginal GHG emission based on its share of the total impact that can still take place before a predefined target level is reached. The impact of a GHG emission decreases over time due to different atmospheric removal processes, such as degradation or uptake in ocean and biosphere. However, with the current and expected future level of activities, the total GHG concentration in the atmosphere increases with time, and the remaining capacity is gradually exhausted year by year until the target level is reached. The impact per kg of GHG emission as well as the remaining capacity in the atmosphere in cumulative terms can be expressed as equivalents of atmospheric CO<sub>2</sub> concentration (ppm) over the time period from the emission time to the target time, giving the unit parts per million CO<sub>2</sub> equivalents (CO<sub>2</sub>e) years. The unit ‘ppm CO<sub>2</sub>e’ used here thus refers to equivalents in terms of the actual radiative forcing per parts per million CO<sub>2</sub> present in the atmosphere and should not be confused with the ‘CO<sub>2</sub>e’ unit used in the GWP to describe the cumulated radiative forcing impact of an emitted kg of a GHG over a specific time horizon relative to the forcing impact of a kg CO<sub>2</sub> emission over the same time horizon.

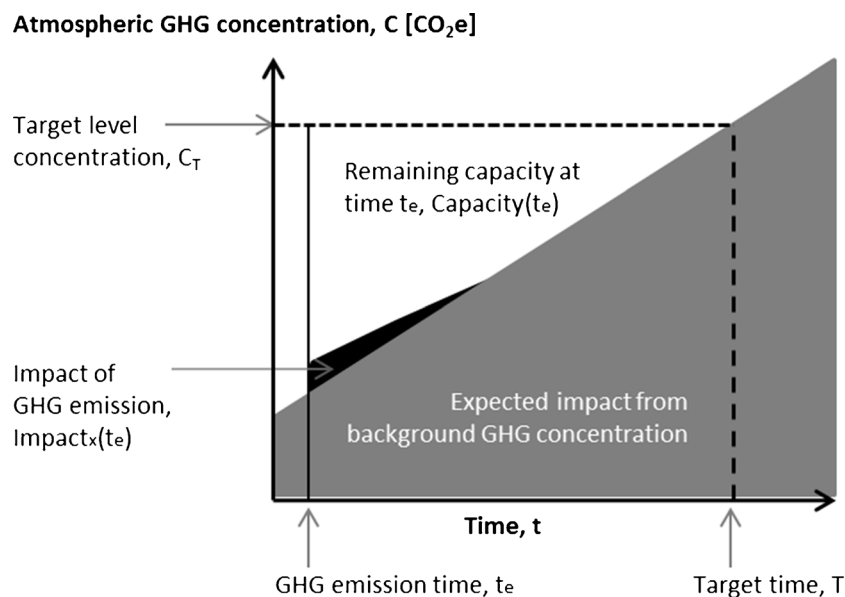
As illustrated by Fig. 1, the emission of a GHG will take up a certain part of the remaining capacity during its residence time in the atmosphere. Thus, both the induced increase in the atmospheric GHG concentration and the time that the

emission remains in the atmosphere are needed to evaluate the impact of a GHG relative to the remaining capacity. The CTP of a GHG ( $x$ ) emitted at time  $t_e$ , with the target time  $T$ , is defined as

$$CTP_{x,T}(t_e) = \frac{Impact_{x,T}(t_e)}{Capacity_T(t_e)} \tag{1}$$

where  $CTP_{x,T}(\text{kg}^{-1})$  is the climate tipping potential of emitting GHG  $x$ , for the target time  $T$  (year),  $t_e$  (year) is the emission time any year from present to the target time  $T$ ,  $Impact_{x,T}(\text{ppm CO}_2\text{e years kg}^{-1})$  is the impact of emitting GHG  $x$  for the target time  $T$  and  $Capacity_T(\text{ppm CO}_2\text{e years})$  is the remaining atmospheric capacity until the target time  $T$ .

The atmospheric capacity for receiving GHGs before a climatic target level is reached depends on the choice of target level and the development in atmospheric GHG concentration. In the literature, different tipping points are discussed, and several possible GHG concentration pathways have been developed. The method for calculating CTP has therefore been designed to be adaptable to any GHG concentration development scenario and any target level not yet passed. For demonstration of the method and calculation of CTP characterisation factors, a target level and a GHG concentration pathway scenario have, however, been chosen as described in the following two sections.



**Fig. 1** Conceptual illustration of the atmosphere’s capacity for receiving GHG emissions without exceeding the predefined atmospheric target level. The grey area illustrates the expected development in atmospheric GHG concentration from the current situation and until the target time,  $T$ ,

where the target level is reached. The white area after the GHG emission time,  $t_e$ , represents the remaining capacity of the atmosphere, while the black area illustrates the impact of a GHG emission occurring at time  $t_e$  in terms of additional capacity occupied

## 2.2 Choice of target level

For estimation of the remaining capacity, a target level must be chosen as a maximum atmospheric GHG concentration that must not be exceeded. The global climate system is complex, and there is not one climate tipping point, but many, of different type and importance and occurring at different levels of radiative forcing. Predictions of the climate change levels where such tipping points occur are rather uncertain (US DOT CCCEF 2009). However, a widely used political target is to keep the temperature rise due to anthropogenic emissions below 2 °C compared to preindustrial levels (IEA 2011). This target has been adopted by the European Union (Council of the European Union 2005), and it is supported by scientific work such as Hare (2003; 2006). It is furthermore in line with the ‘Reasons for Concern’ in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Schneider et al. 2007).

An atmospheric GHG concentration of 450 ppm CO<sub>2</sub>e is expected to have at least a 50 % chance of stabilising the climate at the 2 °C temperature increase (Marchal et al. 2012) (range ~380–510 ppm CO<sub>2</sub>e (Hare and Meinshausen 2005; Schneider et al. 2007)), and 450 ppm CO<sub>2</sub>e is hence chosen here as the target level.

## 2.3 Selection of atmospheric GHG concentration pathway scenario

Scenarios describing the development of atmospheric GHG concentrations into the future are needed for determining the development of the remaining capacity in time (see Fig. 1). Here, the so-called representative concentration pathway (RCP) scenario RCP6 is chosen. There are four RCP scenarios, which cover a range of radiative forcing values for year 2100 and have been developed in response to a request from the IPCC (van Vuuren et al. 2011). The scenarios include one mitigation scenario, two scenarios of medium stabilisation and a very high baseline scenario, and they represent different possible paths depending on global policy choices and development possibilities (further descriptions of the four RCP scenarios can be seen in Table 3). Currently, there is not much that points to sufficient political will to drive the mitigation scenario. However, it is here assumed that the vital importance of the issue and the generally increasing awareness will also prevent us from following the very high baseline scenario. The RCP6 scenario is thus chosen, as it is the medium stabilisation level scenario which assumes the highest stabilisation level, based on higher expected population growth and lower GDP than the other medium stabilisation scenario (van Vuuren et al. 2011). The RCP6 medium stabilisation level scenario is made available by Meinshausen et al. (2011), based on background data from Fujino et al. (2006).

## 2.4 Determination of target time

The target time is the year in which the atmospheric GHG concentration reaches the target level according to the selected GHG concentration pathway scenario. For the RCP6 scenario and the 450 ppm CO<sub>2</sub>e target level, the target time is year 2032 (see Fig. 2).

## 2.5 Estimation of capacity( $t_e$ )

The remaining capacity of the atmosphere for receiving GHG emissions without exceeding the chosen atmospheric target level changes with the proximity of emission time  $t_e$  to the target time  $T$ . This is expressed in Eq. (2):

$$Capacity_T(t_e) = \int_{t=t_e}^{t=T} (C(T) - C(t)) dt \quad (2)$$

where  $T$  is the target time (year),  $C(T)$  is the target level concentration of atmospheric GHG, occurring at the target time (ppm CO<sub>2</sub>e) and  $C(t)$  is the concentration of atmospheric GHG at time  $t$  (ppm CO<sub>2</sub>e). Thus, the unit of the capacity becomes ppm CO<sub>2</sub>e years. Described in words, this means equivalents of atmospheric CO<sub>2</sub> concentration increase that can still take place before reaching the target level (in terms of actual radiative forcing) integrated over the time duration between the emission time,  $t_e$ , and the target time,  $T$ .

The aim here is to calculate CTP on an annual basis and the atmospheric concentration (CO<sub>2</sub>e) data we have used are discrete values given with 1 year time steps. Rather than solving the integral analytically, we therefore use an approximate discrete solution to Eq. (2). It is estimated as the sum of the differences between the target level and the RCP projected atmospheric GHG concentration for each time step multiplied by the length of the time step (1 year) from the GHG emission time up to the target time.

## 2.6 Modelling of impact( $t_e$ )

Since the CTP expresses how large a fraction of the remaining atmospheric capacity a GHG emission takes up, the impact must be calculated as the induced change in atmospheric GHG concentration (expressed in ppm CO<sub>2</sub>e) per mass of GHG emitted over the residence time of the emission until the target time.

The absolute global warming potential (AGWP) expresses the radiative forcing per kg of a specific GHG emission over a certain time horizon, taking into account the atmospheric lifetime of the GHG. It is used for determining the GWP of a GHG emission, as the quotient between the AGWP of that GHG emission and the AGWP of the same amount of CO<sub>2</sub>

over the same time horizon (Shine et al. 2005). It is calculated as

$$AGWP_x(t) = \int_0^t A_x \exp(-t'/\alpha_x) dt' = A_x \alpha_x [1 - \exp(-t/\alpha_x)] \tag{3}$$

where  $AGWP_x$  is the absolute global warming potential of GHG  $x$  ( $Wm^{-2} kg^{-1} year$ ),  $A_x$  is the specific radiative forcing of GHG  $x$  ( $Wm^{-2} kg^{-1}$ ),  $\alpha_x$  is the atmospheric lifetime for GHG  $x$  (years), which takes into account the indirect effect of the gas on its own atmospheric lifetime (also called the adjustment time) (Albritton et al. 2001) and  $t$  is the time horizon (years).

When calculating the AGWP of  $CO_2$ , a more advanced equation is necessary, due to the complex nature of the removal of atmospheric  $CO_2$ . This is given in Eq. (4) (Shine et al. 2005):

$$AGWP_{CO_2}(t) = \int_0^t A_{CO_2} \left[ a_0 + \sum_i a_i \exp(-t'/\alpha_i) \right] dt' = A_{CO_2} \left[ a_0 t + \sum_i a_i \alpha_i (1 - \exp(-t/\alpha_i)) \right] \tag{4}$$

where  $a$  and  $\alpha$  are specific coefficients and time constants for the removal processes that are active in the IPCC decay function for  $CO_2$  in the atmosphere, as reflected in the revised Bern carbon cycle model (Forster et al. 2007):  $a_0=0.217$ ,  $a_1=0.259$ ,  $a_2=0.338$ ,  $a_3=0.186$ ,  $\alpha_1=172.9$  years,  $\alpha_2=18.51$  years and  $\alpha_3=1.186$  years.

The dependency of the cumulative impacts on the distance of the emission time  $t_e$  from the target time  $T$  is included by integrating Eq. (3) from  $t_e$  to  $T$ , leading to Eq. (5), and likewise for Eq. (4) (not shown):

$$AGWP_{x,T}(t_e) = \int_{t_e}^{t=T} A_x \exp(-t'/\alpha_x) dt' = A_x \alpha_x [1 - \exp(-(T-t_e)/\alpha_x)] \tag{5}$$

In order to express the impact of GHG  $x$  in the same unit as the capacity, per kg of GHG emitted, the  $AGWP_x$  is divided by the specific radiative forcing per ppm  $CO_2$ , as given in Eq. (6):

$$Impact_{x,T}(t_e) = \frac{AGWP_{x,T}(t_e)}{A_{CO_2,ppm}} \tag{6}$$

where  $A_{CO_2,ppm}$  is the specific radiative forcing of  $CO_2$  for 1 ppm with a background concentration of 378 ppm ( $1.413 \cdot 10^{-2} (Wm^{-2} ppm^{-1} CO_2)$ ) (Forster et al. 2007) based on Myhre et al. (1998)). Thus, the unit of the impact becomes ppm  $CO_2e$

years  $kg_x^{-1}$  which is understood as equivalents of increase in atmospheric  $CO_2$  concentration (in terms of actual radiative forcing) integrated over the time duration between the emission time,  $t_e$ , and the target time,  $T$ , due to a kg GHG emission pulse at time  $t_e$ .

Inserting Eqs. (2) and (6) into Eq. (1), the expression for calculation of the CTP becomes

$$CTP_{x,T}(t_e) = \frac{\left( \frac{AGWP_{x,T}(t_e)}{A_{CO_2,ppm}} \right)}{\int_{t=t_e}^{t=T} (C(T)-C(t))dt} \tag{7}$$

Eq. (7) expresses  $CTP_x$  as a characterisation factor, i.e. per kg emission of GHG  $x$ . The meaning of the characterisation factor is equivalents of increase in atmospheric  $CO_2$  concentration integrated over the time duration between the emission time,  $t_e$  and the target time,  $T$ , due to a kg GHG emission pulse at time  $t_e$ , expressed as the fraction of the equivalent atmospheric  $CO_2$  concentration increase that can still take place before reaching the target level, integrated over the same time period.

To calculate the CTP for any emitted amount of GHG  $x$ , the characterisation factor is simply multiplied by the emitted amount, as shown in Eq. (8)

$$IS_{CTP}(x, T, t_e) = CTP_{x,T}(t_e) \cdot m_x \tag{8}$$

where  $IS_{CTP}(x, T, t_e)$  (-) is the impact score representing the CTP for target time  $T$  of an emission of  $m_x$  kg of GHG  $x$  at emission time  $t_e$ .

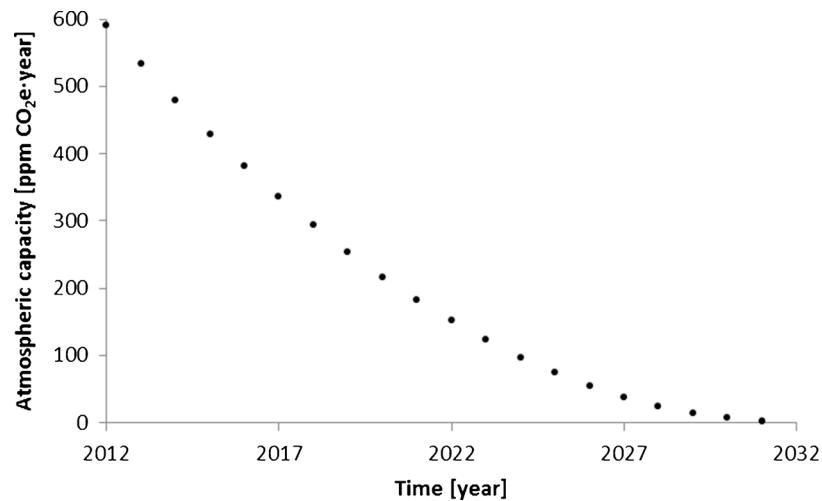
In this paper, CTP characterisation factors for the three most important anthropogenic GHGs,  $CO_2$ ,  $CH_4$  and  $N_2O$ , have been calculated using Eq. (7) and the values for  $A_x$  and  $\alpha_x$  shown in Table 1.

### 3 Results

#### 3.1 Atmospheric capacity

The remaining atmospheric capacity as a function of time according to the RCP6 scenario and the 450 ppm  $CO_2e$  target level is shown in Fig. 2:

Fig. 2 shows a rapid decrease in capacity from present until the target level is reached in year 2032, which thus becomes the target time. The choice of target level and GHG projection scenario determines the shape of the atmospheric capacity curve and thus influences the final CTP calculations.



**Fig. 2** Remaining atmospheric capacity in each year relative to the chosen target level of 450 ppm CO<sub>2</sub>e, using the RCP6 scenario giving the target time year 2032

### 3.2 Cumulative impacts of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions

Cumulative impacts of an emission of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are shown as a function of emission time in Fig. 3, for emission times between year 2012 and the target time year 2032.

Figure 3 shows how the impact of all three considered GHGs decreases as the emission time approaches the target time. This behaviour reflects that as the target time is approached, a decreasing part of the impact of the GHG is included in assessment.

### 3.3 CTP of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O

Using the results for the remaining atmospheric capacity (Fig. 2) and the impact of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O (Fig. 3), the CTP for these three GHGs is presented in Fig. 4 for emissions in the period from 2012 to the predicted target time, year 2032, using the target level of 450 ppm CO<sub>2</sub>e and the RCP6 scenario. The CTP values are given as parts per trillion (ppt) of

remaining capacity, ppt<sub>rc</sub>.

The development of CTP as a function of emission time reflects the atmospheric lifetime and specific radiative forcing of the GHGs as well as the decrease in capacity of the atmosphere, in particular in proximity of the target time. It is interesting to note that while the absolute impacts of these GHGs decrease over time (Fig. 3), they all have increasing CTPs over time because the remaining atmospheric capacity decreases even faster than the absolute impacts.

For direct application in LCA studies, a selection of CTP characterisation factors for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O for different emission years between 2012 and the target time, year 2032, is provided in Table 2.

Applying these CTP characterisation factors, the climate tipping potential of a product or system can be calculated in an LCA. For products with lifetimes of more than 1 year, a detailed inventory is necessary, specifying GHG emissions for each year separately. This is the same kind of inventory that is used in the dynamic approach, suggested by Levasseur et al. (2010).

**Table 1** Values for the specific radiative forcing  $A_x$  and the atmospheric lifetime  $\alpha_x$  for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O (Forster et al. 2007)

GHG	$A_x$ (Wm <sup>-2</sup> kg <sup>-1</sup> ) <sup>a</sup>	$\alpha_x$ (years)
CO <sub>2</sub>	$1.81 \cdot 10^{-15}$	– <sup>b</sup>
CH <sub>4</sub>	$1.82 \cdot 10^{-13}$ <sup>c</sup>	12
N <sub>2</sub> O	$3.87 \cdot 10^{-13}$	114

<sup>a</sup>  $A_x$  values are converted from Wm<sup>-2</sup> ppbv<sup>-1</sup> to Wm<sup>-2</sup> kg<sup>-1</sup> by using the approach given in Shine et al. (2005)

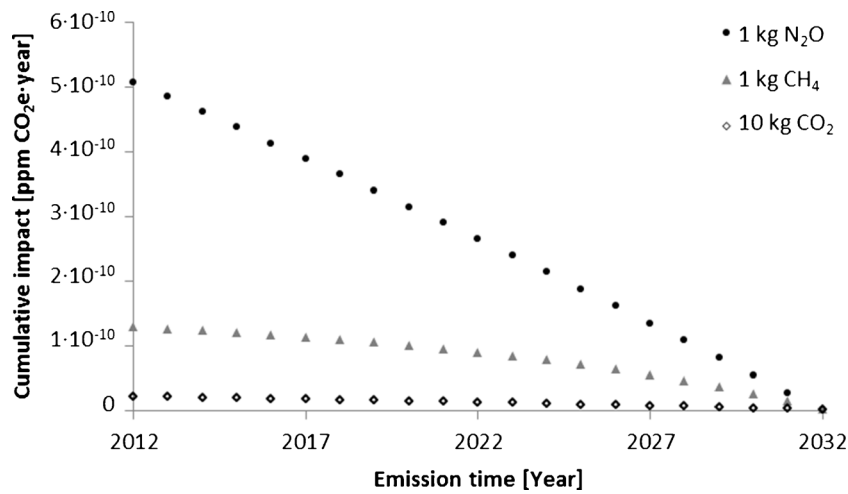
<sup>b</sup> For CO<sub>2</sub>, the lifetime is determined by the combination of a number of removal mechanisms, and the AGWP of CO<sub>2</sub> is calculated using the approach of Eq. (4)

<sup>c</sup>  $1.3 \cdot 10^{-13}$  1.4; the factor 1.4 accounts for indirect radiative effects of a methane emission (Forster et al. 2007)

### 3.4 Influence of the choice of emission scenario

The results in Fig. 4 relate to the RCP6 scenario for atmospheric GHGs. In order to illustrate the dependency of the results on the chosen scenario, CTP characterisation factors are calculated for all four RCP scenarios, which are described in Table 3. The results for CO<sub>2</sub> for all four scenarios are shown in Fig. 5.

The RCP scenarios represent different possible atmospheric GHG concentration pathways which depend on global policy choices and development possibilities (van Vuuren et al. 2011).



**Fig. 3** Cumulative impact of emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O relative to the chosen atmospheric target level of 450 ppm CO<sub>2</sub>e, using the RCP6 scenario. Note that the impact for CO<sub>2</sub> has been given for an emission of 10 kg rather than 1 kg as for the other GHGs

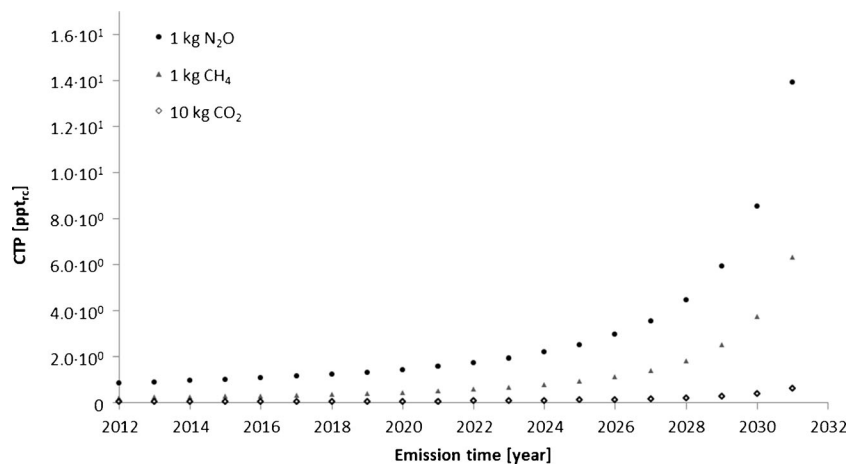
Figure 5 shows CTP of CO<sub>2</sub> emitted in different years from 2012 until the target concentration (450 ppm CO<sub>2</sub>e) is reached at the specific target times predicted by each of the four RCP scenarios

Figure 5 shows that the CTP of CO<sub>2</sub> follows the same trend towards the target time independently of the chosen GHG emission scenario, with increasing impact as the emission time approaches the target time. At the same time, it is obvious that the choice of scenario has a strong influence on the CTP characterisation factors due to the difference in assumed GHG concentration paths and resulting target times. The case of CO<sub>2</sub> has been shown here as an example; the variation with scenario shows the same trend for the CTP for CH<sub>4</sub> and N<sub>2</sub>O, and CTP characterisation factors for N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> for each year from 2012 to the target time for all four RCP scenarios are provided in the [Electronic Supplementary Material](#).

### 3.5 Comparison of CTP and the time-dependent GTP

The CTP developed in this paper has similarities with the time-dependent GTP approach by Shine et al. (2007) in terms of applying a target time, based on a chosen climatic target level. In contrast to the time-dependent GTP, however, CTP expresses the absolute impact of a GHG emission with respect to passing a climatic target level, by determining the cumulative impact as a fraction of the amount that can still be emitted (the atmospheric capacity) before passing the target level. The introduction of the capacity aspect is a key difference between the time-dependent GTP and the CTP, as further outlined in section 4.1.

In order to illustrate the difference in results when comparing the CTP to the time-dependent GTP, a constructed example is given in Fig. 6. For making a direct comparison, the absolute GTP (AGTP) is used rather than the GTP, as the latter



**Fig. 4** Climate tipping potential (CTP) of CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> for different emission times for the chosen atmospheric target level of 450 ppm CO<sub>2</sub>e, using the RCP6 scenario. Note that CTP for CO<sub>2</sub> has been given for 10 kg rather than 1 kg as for the other GHGs

**Table 2** CTP characterisation factors for N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub>, for the chosen atmospheric target level of 450 ppm CO<sub>2</sub>e, using the RCP6 scenario

Year of emission	N <sub>2</sub> O (ppt <sub>rc</sub> kg N <sub>2</sub> O <sup>-1</sup> )	CH <sub>4</sub> (ppt <sub>rc</sub> kg CH <sub>4</sub> <sup>-1</sup> )	CO <sub>2</sub> (ppt <sub>rc</sub> kg CO <sub>2</sub> <sup>-1</sup> )
2012	8.52 10 <sup>-1</sup>	2.12 10 <sup>-1</sup>	2.94 10 <sup>-3</sup>
2015	1.01 10 <sup>0</sup>	2.73 10 <sup>-1</sup>	3.53 10 <sup>-3</sup>
2020	1.44 10 <sup>0</sup>	4.51 10 <sup>-1</sup>	5.19 10 <sup>-3</sup>
2025	2.50 10 <sup>0</sup>	9.19 10 <sup>-1</sup>	9.43 10 <sup>-3</sup>
2030	8.47 10 <sup>0</sup>	3.70 10 <sup>0</sup>	3.53 10 <sup>-2</sup>
2031	1.38 10 <sup>1</sup>	6.25 10 <sup>0</sup>	6.01 10 <sup>-2</sup>
2032	–	–	–

CTP values are given as parts per trillion of remaining capacity, ppt<sub>rc</sub>. All characterisation factors from year 2012 to the target time year 2032 can be found in the [Electronic Supplementary Material](#)

only reflects impact relative to CO<sub>2</sub> as it is expressed relative to the AGTP of CO<sub>2</sub>.

While the time-dependent AGTP and the CTP shown in Fig. 6 are given in different units, they can still be compared in terms of development trend with the proximity of the emission time to the target time.

For illustrative purposes, the starting point of the comparison is the emissions of the amounts of the three GHGs which give identical AGTPs using the time-dependent AGTP metric, when the emission takes place 20 years before the target time. In this way, the development of the time-dependent AGTP with when emission time approaches the target time is easily observable. For comparing the time-dependent AGTP with the CTP, the same emitted amount of each GHG is assumed

**Table 3** The four RCP scenarios for atmospheric GHGs; RCP3PD, RCP4.5, RCP6 and RCP8.5 (Meinshausen et al. 2011), and their respective target times for the atmospheric GHG concentration target level of 450 ppm CO<sub>2</sub>e

Name	Description <sup>a</sup>	Target time, <i>T</i>
RCP3PD <sup>b</sup>	Mitigation scenario: Reaches a peak forcing level of 3 Wm <sup>-2</sup> , followed by a decline so the radiative forcing level in year 2100 is 2.6 Wm <sup>-2</sup>	2034
RCP4.5 <sup>c</sup>	Medium stabilisation scenario: The radiative forcing level in year 2100 is 4.5 Wm <sup>-2</sup> .	2028
RCP6 <sup>d</sup>	Medium stabilisation scenario: The radiative forcing level in year 2100 is 6 Wm <sup>-2</sup> .	2032
RCP8.5 <sup>e</sup>	Very high baseline scenario: The radiative forcing level in year 2100 is 8.5 Wm <sup>-2</sup> .	2025

<sup>a</sup> van Vuuren et al. (2011)

<sup>b</sup> Background data from van Vuuren et al. (2007)

<sup>c</sup> Background data from Clarke et al. (2007), Smith and Wigley (2006) and Wise et al. (2009)

<sup>d</sup> Background data from Fujino et al. (2006)

<sup>e</sup> Background data from Riahi et al. (2007)

for the CTP calculations as for the time-dependent AGTP calculations.

Impact scores over time for the CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions show different patterns between the two metrics. The time-dependent AGTP of CO<sub>2</sub> and N<sub>2</sub>O decreases over time, with that of N<sub>2</sub>O having the steepest decrease, while the time-dependent AGTP of CH<sub>4</sub> initially increases, before also decreasing towards the target time. In contrast, the CTP increases consistently for all GHGs as the emission time approaches the target time, with a very steep increase close to the target time.

## 4 Discussion

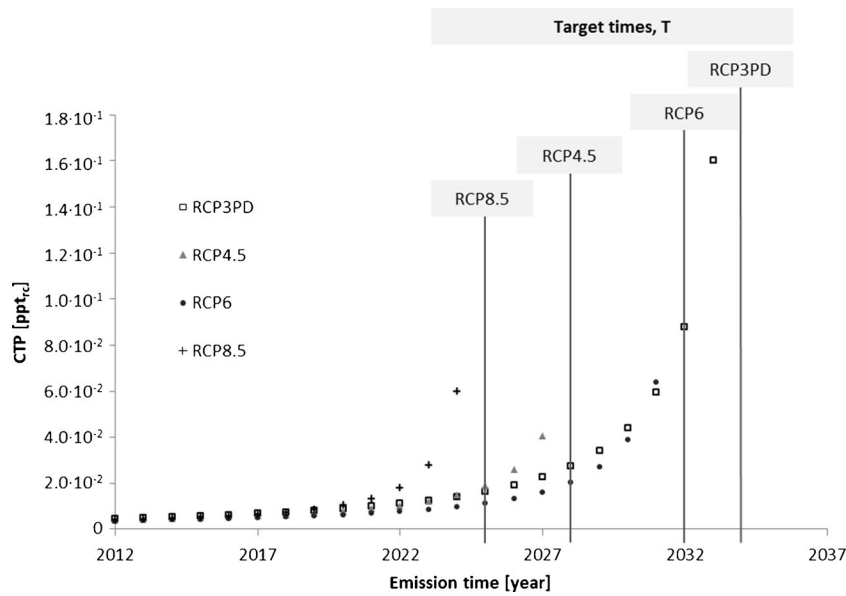
### 4.1 Importance of introducing the capacity aspect

Expressing the CTP as the fraction of remaining atmospheric capacity taken up by the absolute impact of a GHG emission means that the CTP for all GHGs increases with proximity to the target level. The increasing importance of preventing emissions as the capacity diminishes and the target level is approached is thus represented by this approach. This is in contrast to the approach followed by the time-dependent GTP (Shine et al. 2007), which represents the impact of a GHG emission according to the proximity of the emission time to the target time, but which does not consider the change in total atmospheric GHG concentration level over time. Thus, it does not reflect actual change in severity of a GHG emission depending on emission time, in terms of passing the target level. Expressing impacts relative to those of CO<sub>2</sub> can be useful for GWP comparing long-term impacts where no target level is considered, but for other applications, such a normalised metric is less useful (e.g. Peters et al. 2011; Cherubini et al. 2012). For the need of expressing the impact of GHG emissions relative to exceeding a target level, it is more relevant to make the comparison based on the fraction of remaining capacity taken up by an absolute GHG emission impact, as is proposed here. The CTP thus sees the remaining atmospheric capacity until the target level is reached as a limited ‘resource’.

### 4.2 Cumulative impact vs. impact at a specific time

The CTP takes a cumulative approach which accounts for the pathway of impacts from emission time to target time. This is in contrast to the time-dependent GTP approach by Shine et al. (2007), which accounts for the impact at the target time only. It would also have been possible to express CTP at the target time only. The cumulative approach has been selected here for the following reasons:





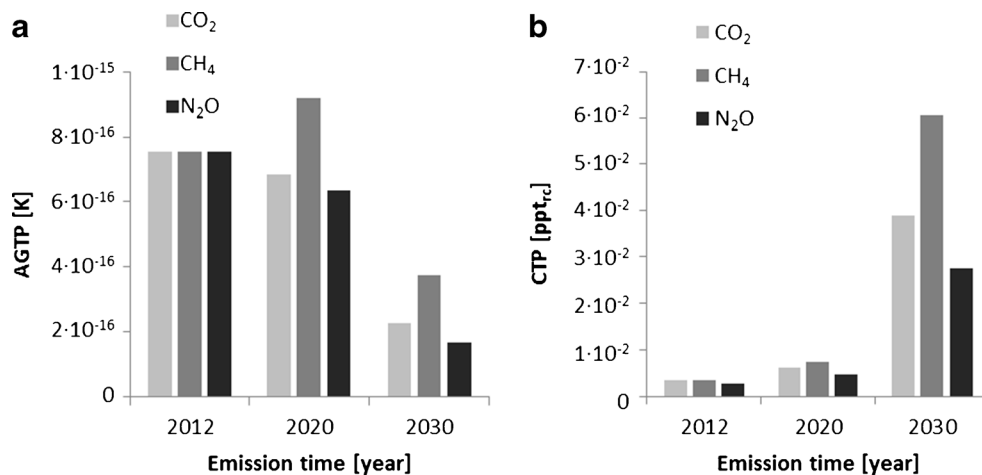
**Fig. 5** CTP of 1 kg CO<sub>2</sub> for different RCP scenarios and emission times, with the same atmospheric GHG concentration target level (450 ppm CO<sub>2</sub>e) but different target times as predicted by the different scenarios and illustrated by the vertical lines

- The background for developing the method is the need for avoiding rapidly approaching climate tipping points, and even the part of the emission that will not have an impact at the actual target time is still part of the path to get there.
- The target time has been selected to avoid certain expected climate tipping points; however, due to the uncertainty of when they exactly occur, the path of the GHG emission impact is important.
- Expressing the CTP in terms of cumulated impacts, like the GWP, makes the two approaches logically compatible which is convenient as they are suggested to complement

each other for including both long-term and urgency aspects in climate change impact assessment.

#### 4.3 Temperature vs. atmospheric GHG concentration level

The CTP presented here is a midpoint metric based on expressing impacts and atmospheric capacity at the level of GHG concentrations. While it may be argued that it is more relevant to consider impacts closer to the damage level in the climate change impact pathway, such as at the level of



**Fig. 6** **a** Time-dependent AGTP and **b** CTP for GHG emissions in 2012, 2020 and 2030, using scenario RCP6 and the atmospheric target level of 450 ppm CO<sub>2</sub>e which means year 2032 is the target time for the CTP and the year in which the time-dependent AGTP is being measured. The mass of each GHG emission is that which corresponds to the time-dependent

AGTP of 1 kg CO<sub>2</sub> when the GHG is emitted in 2012 (i.e. emitted amounts: 1 kg CO<sub>2</sub>, 1.62 · 10<sup>-2</sup> kg CH<sub>4</sub> and 3.22 · 10<sup>-3</sup> kg N<sub>2</sub>O). Time-dependent AGTP values (for pulse emissions) have been calculated according to Shine et al. (2005), using the target time approach from Shine et al. (2007). Note the different units on the vertical axes

temperature impacts, this also increases the uncertainty (Shine et al. 2005). Presenting the temperature impact of an emitted GHG at a target time also does not consider the temperature impacts that will happen beyond the target time as a result of GHG emissions that have already taken place, due to the time lag of temperature impacts, i.e. a ‘temperature debt’.

#### 4.4 Choice of target level

A target level concentration of GHG in the atmosphere of 450 ppm CO<sub>2</sub>e has been used to calculate CTP characterisation factors and demonstrate the use of the CTP approach. But the method can be applied for other target levels as well, reflecting e.g. different expected climate tipping points and political targets. Clearly, such choices affect the target time, the capacity left and thus the CTP characterisation factor of the GHGs at different emission times. If e.g. using a target level of 510 ppm CO<sub>2</sub>e instead (the upper limit of the range for having 50 % chance of stabilising the climate at the 2 °C temperature increase, as described in section 2.2), the target year becomes 2052 when using the RCP6 scenario. Compared to using the 450 ppm target level, the CTP values for the three GHGs when using the 510 ppm target level decrease by ~60–70 % in year 2012 depending on GHG. The CTP values for the 510 ppm target level further decrease relative to the CTP values for the 450 ppm target level for the following years. Thus, results are quite sensitive to the chosen target level. This is not a shortcoming of the method, but rather an option for pursuing different climatic goals. But it emphasises the importance of clear and transparent reporting of what has been assumed for the target level and scenario.

#### 4.5 Implications of the marginal approach

A limitation of the CTP method presented here is that it applies to the impact of change in atmospheric GHG concentrations due to a marginal GHG emission. A marginal approach such as this is common for LCA but means that the method is not directly applicable for large scale changes. Doing so might in this case lead to the erroneous conclusion that it would be better to speed up GHG emissions than emitting them later. However, as the increasing impact with time is due to declining capacity, the development scenario is decisive, so if more were to be released earlier (breaking the assumption that the considered emission is truly marginal), the scenario would have to be updated with the modified emission path, and the target time would have to be recalculated. This is however not considered a great risk in reality. For an increase in CO<sub>2</sub> emissions today to contribute with a 1 % change in the CTP factors, using the RCP6 scenario with the 450 ppm target level, it would have to be of approximately 41 GtCO<sub>2</sub>, corresponding to 11 GtC. This is almost double of the annual global

emissions from fossil fuel consumption and cement production in the 1990s, which was 6.4 GtC (Denman et al 2007).

#### 4.6 Influence of assuming constant specific radiative forcing and atmospheric lifetime of the GHGs

In the derivation of the expressions for calculation of CTP (Eqs. (3)–(7)), both  $A_x$ , the specific radiative forcing of the GHG, and  $\alpha_x$ , the atmospheric lifetime of the GHG, are assumed constant. In reality, these assumptions are however not completely correct, as both  $A_x$  and  $\alpha_x$  depend on their own atmospheric concentrations as well as on those of other GHGs. This may introduce a systematic error, but as the approach is similar to what is done for calculation of GWP and GTP (Shine et al. 2005), it is considered a reasonable assumption for the use here.

#### 4.7 Scenario limitations of the CTP

The nature of the method presented here allows for calculating CTP characterisation factors for various background GHG concentration pathway scenarios and target levels, which increases the usability beyond just one expected outcome and enables fitting to studies based on different assumptions. The RCP scenarios used for the derivation of CTP characterisation factors in this paper start from harmonised data in 2005 (Meinshausen et al. 2011), so the modelled concentrations for today do not completely reflect actual measurements and differ between the four scenarios. However, the RCP scenarios are here considered the best available at the moment, as the development and recognition of scenarios take time, so it is natural with a certain time lag.

#### 4.8 Proper accounting for long-term global warming impacts

By introducing the CTP metric as supplement to the GWP as suggested here, we institute a dual approach accounting for both long-term and urgency issues of climate change, without neglecting either. In this duality, GWP only has to represent the long-term impacts, and therefore it should be considered to use a longer time horizon for GWP than the 100 years which are common practice today, as timescales for the removal of some of the GHGs from the atmosphere are far longer as are the long-term impacts of emitting them (e.g. Archer et al. 1997). As a first approach, IPCC’s GWP<sub>500</sub> could be used, but it could be considered to develop GWPs for even longer timescales.

## 5 Conclusions

The climate tipping impact category for inclusion in climate change impact assessment expresses the potential contribution

of different GHGs to approaching a chosen climatic target level and thereby fulfils a need for addressing the climate urgency issue that is not accounted for when only considering the global warming represented by the GWP.

The contribution of the developed climate tipping potential (CTP) is to express the cumulative impact of a GHG emission with respect to passing a climatic target level, by determining it as the fraction of the remaining atmospheric capacity to receive GHGs before passing the target level. The CTP increases for all GHGs as the target time is approached, reflecting the increasing urgency of preventing GHG emissions the closer we get to a climate tipping point.

CTP characterisation factors are presented for the main GHGs as a function of emission time, enabling a straightforward implementation of the climate change urgency aspect in LCA. The CTP metric is suggested as supplement to the established GWP metric for determining long-term climatic impacts, hereby instituting a dual approach accounting for both long-term and urgency issues of climate change, without neglecting either.

## 6 Perspectives

The CTP characterisation factors presented here for the three major anthropogenic GHGs, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, are based on a target level of 450 ppm CO<sub>2</sub>e using RCP scenarios for atmospheric GHG development, but the method that has been presented is not restricted to this. It is possible to calculate CTP characterisation factors for all relevant GHGs (given that their values for  $A_x$  and  $\alpha_x$  are available), as well as for other target levels and atmospheric GHG development scenarios.

The CTP treats the remaining atmospheric capacity for receiving GHG emissions up to the point where the target level is reached as a limited ‘resource’. With this perception, the developed approach lends itself to use together with the proposal of defining absolute limits to environmental impacts in terms of ‘planetary boundaries’ aiming to maintain a safe operating space for humanity (Rockström et al. 2009). The CTP is thus based on a planetary boundary for climate change that aims to avoid crossing dangerous climate tipping points. The approach developed for the CTP could also be applied to other impact categories for which boundaries have been set, by quantifying the associated remaining capacities.

An interesting aspect of the CTP is its potential for expressing the climate change mitigation potential of temporary carbon storage in e.g. bio-based products, for which no consensus has been reached (Brandão et al. 2012; Guest et al. 2013). A climate change mitigation potential of temporary carbon storage only exists if it can help avoiding the passing of climate tipping points by either providing a bridging potential to a future with lower atmospheric GHG concentration or buying time for lasting solutions to be developed

(Jørgensen and Hauschild 2013). With its lack of consideration of climate tipping points, GWP does not provide a fitting framework for assessing the possible value of such temporary carbon storage, and it is a contentious issue how to combine assessment of long-term climate change and the short-term mitigation from the temporary carbon storage (e.g. Cherubini et al. 2012). The dual approach introducing the CTP metric as supplement to the GWP could be a solution to this. This application of the CTP is beyond the scope of this paper and is an option for further work.

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## References

- Albritton DL, Meira Filho LG, Cubasch U, Dai X, Ding Y, Griggs DJ, Hewitson B, Houghton JT, Isaksen I, Karl T, McFarland M, Meleshko VP, Mitchell JFB, Noguer M, Nyenzi BS, Oppenheimer M, Penner JE, Pollonais S, Stocker T, Trenberth KE (2001) Technical summary. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate change 2001 - the scientific basis. contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 21–83
- Archer D, Kheshgi H, Maier-Reimer E (1997) Multiple timescales for neutralization of fossil fuel CO<sub>2</sub>. *Geophys Res Lett* 24:405–408
- Brandão M, Levasseur A (2011) Assessing temporary carbon storage in life cycle assessment and carbon footprinting: outcomes of an expert workshop. Publications Office of the European Union, Luxembourg. ISBN 978-92-79-20350-3. <http://lct.jrc.ec.europa.eu/assessment/publications>
- Brandão M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Jørgensen SV, Hauschild MZ, Pennington DW, Chomkham Sri K (2012) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *Int J Life Cycle Assess* 18:230–240
- Cherubini F, Peters GP, Berntsen T, Strømman AH, Hertwich E (2011) CO<sub>2</sub> emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* 3: 413–426
- Cherubini F, Guest G, Strømman AH (2012) Application of probability distributions to the modeling of biogenic CO<sub>2</sub> fluxes in life cycle assessment. *GCB Bioenergy* 4:784–798
- Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1A of synthesis and assessment product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington DC
- Council of the European Union (2005) Climate change: medium and longer term emission reduction strategies, including targets: council conclusions. Information note. Council of the European Union, Brussels, Document number 7242/05

- Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob A, Lohmann U, Ramachandran S, da Silva Dias PL, Wofsy SC, Zhang X (2007) Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007 - the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 499–587
- Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007 - the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 129–234
- Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multi-gas mitigation analysis on stabilization scenarios using AIM global model. *Multigas mitigation and climate policy. The Energy Journal Special Issue*
- Guest G, Cherubini F, Strømman AH (2013) Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life. *J Indust Ecol* 17:20–30
- Hansen J, Sato M, Kharecha P, Beerling D, Berner R, Masson-Delmotte V, Pagani M, Raymo M, Royer DL, Zachos JC (2008) Target atmospheric CO<sub>2</sub>: where should humanity aim? *Open Atmos Sci J* 2:217–231
- Hare W (2003) Assessment of knowledge on impacts of climate change - contribution to the specification of article 2 of the UNFCCC: impacts on ecosystems, food production. *Water and Socio-Economic Systems. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Potsdam*. ISBN 3-936191-03-4
- Hare B (2006) Relationship between increases in global mean temperature and impacts on ecosystems, food production, water and socio-economic systems. In: Schellnhuber HJ, Cramer W, Nakicenovich N, Wigley T, Yohe G (eds) *Avoiding dangerous climate change*. Cambridge University Press, Cambridge, pp 177–185
- Hare B, Meinshausen M (2005) How much warming are we committed to and how much can be avoided? *Clim Chang* 75:111–149
- Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Joliet O, Margni M, De Schryver A, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modelling in life cycle impact assessment. *Int J Life Cycle Assess* 18(3): 683–697
- IEA (2011) *World energy outlook 2011 – executive summary*. In: IEA, world energy outlook 2011. OECD/IEA, International Energy Agency, Paris Cedex
- Jørgensen SV, Hauschild MZ (2010) Need for relevant timescales in temporary carbon storage crediting. Presentation held at the Expert Workshop on Temporary Carbon Storage for use in Life Cycle Assessment and Carbon Footprinting, at the Joint Research Centre of the European Commission, Ispra October 2010. Abstract available in Brandão and Laveasseur (2011)
- Jørgensen SV, Hauschild MZ (2013) Need for relevant timescales when crediting temporary carbon storage. *Int J Life Cycle Assess* 18:747–754
- Laveasseur A, Lesage P, Margni M, Deschênes L, Samson R (2010) Considering time in LCA: dynamic LCA and its application to global warming impact assessments. *Environ Sci Technol* 44: 3169–3174
- Marchal V, Dellink R, van Vuren D, Clapp C, Château J, Magné B, Lanzi E, van Vliet J (2012) *Climate change*. In: OECD (ed) *OECD environmental outlook to 2050: the consequences of inaction*. OECD Publishing, pp 71–152
- Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) *Global climate projections*. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007 - the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 747–845
- Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Thomson A, Velders GJM, van Vuuren DPP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2500. *Clim Chang* 109:213–241
- Myhre G, Highwood EJ, Shine KP, Stordal F (1998) New estimates of radiative forcing due to well mixed greenhouse gases. *Geophys Res Lett* 25:2715–2718
- Peters GP, Aamaas B, Lund MT, Solli C, Fuglestedt JS (2011) Alternative “global warming” metrics in life cycle assessment: a case study with existing transportation data. *Environ Sci Technol* 45: 8633–8641
- Riahi K, Gruebler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol Forecast Soc Chang* 74:887–935
- Rockström J, Steffen W, Noone K et al. (2009) Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc* 14(2):32
- Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F, Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson SE (2007) Assessing key vulnerabilities and the risk from climate change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson SE. (eds.), *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 779–810
- Shine KP, Berntsen TK, Fuglestedt JS, Skeie RB, Stuber N (2007) Comparing the climate effect of emissions of short- and long-lived climate agents. *Phil Trans R Soc A* 365:1903–1914
- Shine KP, Fuglestedt JS, Hailemariam K, Stuber N (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim Chang* 68:281–302
- Smith SJ, Wigley TML (2006) Multi-gas forcing stabilization with the MiniCAM. *Energ J* 27:373–391
- US DOT CCEF (2009) *Climate tipping points: current perspectives and state of knowledge*. U.S. Department of Transportation, Center for Climate Change and Environmental Forecasting
- van Vuuren D, den Elzen M, Lucas P, Eickhout B, Strengers B, van Ruijven B, Wonink S, van Houdt R (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim Chang* 81:119–159
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: an overview. *Clim Chang* 109:5–31
- Wise MA, Calvin KV, Thomson AM, Clarke LE, Bond-Lamberty B, Sands RD, Smith SJ, Janetos AC, Edmonds JA (2009) Implications of limiting CO<sub>2</sub> concentrations for land use and energy. *Science* 324: 1183–1186