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The danger of overvaluing methane's influence on future climate change

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Abstract Minimizing the future impacts of climate change requires reducing the greenhouse gas (GHG) load in the atmosphere. Anthropogenic emissions include many types of GHG's as well as particulates such as black carbon and sulfate aerosols, each of which has a different effect on the atmosphere, and a different atmospheric lifetime. Several recent studies have advocated for the importance of short timescales when comparing the climate impact of different climate pollutants, placing a high relative value on short-lived pollutants, such as methane (CH_4) and black carbon (BC) versus carbon dioxide (CO_2). These studies have generated confusion over how to value changes in temperature that occur over short versus long timescales. We show the temperature changes that result from exchanging CO_2 for CH_4 using a variety of commonly suggested metrics to illustrate the trade-offs involved in potential carbon trading mechanisms that place a high value on CH_4 emissions. Reducing CH_4 emissions today would lead to a climate cooling of approximately ~0.5 °C, but this value will not change greatly if we delay reducing CH_4 emissions by years or decades. This is not true for CO_2, for which the climate is influenced by cumulative emissions. Any delay in reducing CO_2 emissions is likely to lead to higher cumulative emissions, and more warming. The exact warming resulting from this delay depends on the trajectory of future CO_2 emissions but using one business-as usual-projection we estimate an increase of 3/4 °C for every 15-year delay in CO_2 mitigation. Overvaluing the influence of CH_4 emissions on climate could easily result in our "locking" the earth into a warmer temperature trajectory, one that is temporarily masked by the short-term cooling effects of the CH_4 reductions, but then persists for many generations.

1 Introduction

Humans emit a wide variety of climate pollutants, each with different influences on Earth's radiative balance and, often, greatly differing atmospheric lifetimes. Of these, carbon dioxide (CO_2) is responsible for the most warming to date and has become the reference against

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which all other GHG's are measured. However, the long atmospheric lifetime of CO_2, in which 40 % of a given CO_2 injection is removed within 10 to 50 years (Joos et al. 2013) while the remainder persists, some for centuries and some for millennia (Archer and Brovkin 2008), makes its status as the reference particularly problematic (Wigley 1998; Lashof and Ahuja 1990). Comparing the climate impact of emissions of different GHGs is therefore dependent on the timescale over which the analysis is carried out, particularly when considering short-lived gases, such as CH_4 (Forster et al. 2007). The best choice from a climate perspective is the obvious one: reduce all GHG emissions as much as possible, as quickly as possible, eliminating any need to try and equate them. However, the real world is complicated; difficult choices will have to be made with limited political and economic capital, and certain GHGs will be reduced at the expense of others, creating a demand for a comparative metric. Effort must be undertaken to understand the possible impact of these choices over all timescales so that we understand the true costs and benefits.

The most widely used tool for comparing GHGs is the Global Warming Potential (GWP) (Derwent 1990; Fisher et al. 1990; Lashof and Ahuja 1990; Wuebbles 1989; see also Forster et al. 2007), a measure, not of "warming", but of the integrated radiative forcing (RF) resulting from a pulse emission of a chosen GHG relative to a pulse emissions of CO_2. GWP's have most commonly been evaluated over 100 years, although the Intergovernmental Panel on Climate Change (IPCC) also publishes 20 and 500-year GWP's. The GWP undervalues both the short- and long-term consequences of GHG emissions. With no discount rate, GWP places equal value on all time within the integration period. All RF effects beyond the integration period are valued at zero. The problem with this metric is that it is often used in ways that directly violate the assumptions on which it is based (O'Neill 2000). Understanding how a change in RF influences global temperature (or "warming") requires a climate model and all its associated uncertainties, and using integrated RF requires an assumption of what timescales are important.

Several comprehensive literature reviews (Peters et al. 2011; Shine 2009; Fuglestvedt et al. 2003) have been published focusing on the GWP and the many alternative metrics that have been suggested. The Global Temperature Potential (GTP) (Shine et al. 2005, 2007) evaluates the relative impact on global temperature of a pulse emission of a GHG compared to CO_2 at a chosen time in the future. The primary argument against temperature-based metrics has been that they require a climate model for evaluation, the results of which are non-transparent and potentially model-dependent. However, because this is a relative metric, the GTP has been shown to be somewhat independent of the climate sensitivity of the model used for its calculation (Shine et al. 2005), although other studies have shown considerable dependence for particular species (Fuglestvedt et al. 2010). Unlike the GWP, the GTP is an endpoint metric evaluating the relative differences between temperature trajectories at a single point in the future. The Mean Global Temperature Potential (MGTP) (Gillett and Matthews 2010) and the integrated GTP (iGTP) (Peters et al. 2011) are more directly comparable to the GWP, defined as the ratio of the temperature trajectories resulting from the emission of a GHG relative to that of CO_2 integrated over the chosen time horizon (TH). Some recent studies have suggested that there may be only small differences between the MGTP/iGTPs and GWPs (Peters et al. 2011; Azar and Johansson 2012). In each case, as with the GWP, all climate impacts beyond the reference timescale are neglected. Although the need for climate models may translate into larger published uncertainties on temperature-based metrics than RF-based metrics, this can be viewed as an improvement. If the goal is to assess the relative impacts of various GHG emissions on climate and temperature, not on the global integrated radiative forcing balance, then these larger uncertainties are the correct ones and it is important that they are addressed overtly.

Some other approaches include the TEmperature Proxy Index (TEMP), the Economic Damage Index (EDI), the Forcing Equivalence Index (FEI), and Manne-Richels-type approaches. TEMP is defined in reverse, characterizing the influence that past GHG emissions have had on the temperature trajectory using paleo-temperature and atmospheric composition records (Tanaka et al. 2009). The Economic Damage Index (EDI) quantifies the reduction in CO_2 emissions required to offset the "economic damage" accompanying an increased emission of a given GHG (Hammitt et al. 1996). Manne-Richels-type indices are defined as a function of time in which relative importance of various GHG's constantly change as the chosen endpoint is approached (Manne and Richels 2001). The FEI is a timescale-independent approach that creates multi-gas emissions scenarios designed to maintain the same RF trajectory as a given reference scenario at all future timepoints (Wigley 1998).

These indices for comparing emissions of various GHG's differ both in what they are quantifying: relative change in RF, temperature, or economic impact, and in how they account for time. A time-integrated metric is capable of valuing multiple timescales, from the present to the chosen end of the integration (T_f), with all longer timescales beyond T_f valued at zero. An endpoint metric most accurately captures the climate condition at T_f but at the cost of ignoring all other timescales, shorter and longer. Of these, the value of the FEI is the least dependent on the choice of timescale. Any single scaling factor (or normalized metric) used to equate a non-CO_2 GHG with CO_2 must be clearly associated with a timescale and some discussion provided about the tradeoffs inherent in this choice.

Recently, it has been shown that the value of CH_4 relative to CO_2 increases when additional interactions with aerosols are included, an effect that is particularly marked over short timescales, increasing the 20-yr GWP value from 70 to 105 (Shindell et al. 2009; Howarth et al. 2011), and the 100-yr GWP from 25 to 33. This revaluation has been used as a critical part of an analysis suggesting that natural gas consumption is worse for the climate than burning coal (Howarth et al. 2011). Additionally, it has been suggested that mitigation of CH_4 and black carbon (BC) should be emphasized (Shindell et al. 2012). These arguments focus on the climate in the next 20 to 50 years, justified in part by the need to avoid what are referred to as dangerous "tipping points" in the earth's climate system or a "threshold" 2 °C temperature increase (Howarth et al. 2012; Shindell et al. 2012).

In this manuscript, we show results from a simple climate model, MAGICC/SCENGEN v5.3 (Wigley et al. 1997; Wigley 2008), assessing the climate impact of various choices regarding CH_4 and CO_2 emissions scenarios, over 400 years. First, we examine the hypothetical temperature impact of using a variety of proposed GWP and GTP values in direct carbon trading of CH_4 and CO_2 to illustrate the potential effects over multiple timescales. Second, we reproduce Fig. 1 from Shindell et al. (2012), expanding the time-axis from 50 to 200 years to illustrate the importance of evaluating emissions pathways over both short and long timescales. Third, we run several scenarios in which we assume that political focus on reducing CH_4 emissions results in delayed remediation of CO_2 emissions. Using these scenarios we highlight the complications of using a linear multiplier to compare gases with different lifetimes. The danger of equating CO_2 and CH_4, particularly the need to avoid delaying CO_2 emissions reductions, has been treated in other work (Berntsen et al. 2010; Daniel et al. 2012; Fuglestvedt et al. 2000; Humbert 2010; Solomon et al. 2011) many of the conclusions of which are supported and strengthened in our analysis. We demonstrate how overvaluing CH_4 emissions in the context of carbon trading for CO_2 emissions will leave us with a warmer world that persists for thousands of years.

2 Methods

To examine the climate impact of a variety of emissions scenarios, we used the MAGICC model (Model for the Assessment of Greenhouse-gas Induced Climate Change) version 5.3v2. This

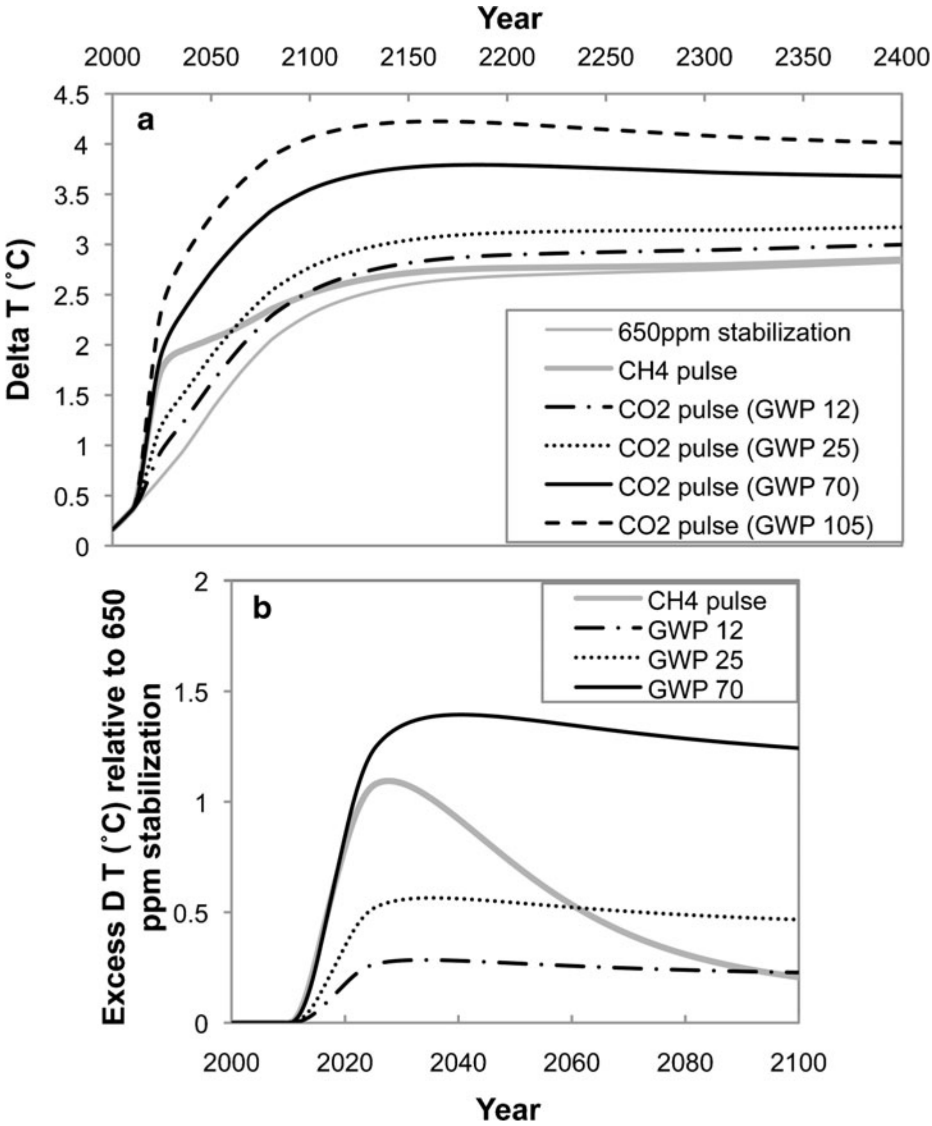

Fig. 1 Panel (**a**) shows the temperature response (ΔT relative to 1990) over 200 years to a pulse emission of 5000 Tg CH_4/yr for 10 years from 2015 to 2020 (*thick grey line*) compared to pulse emissions of CO_2 of varying magnitudes (*black lines*). The baseline 650 ppm stabilization scenario is represented by a thin grey line. The magnitude of the CO_2 emissions pulse is defined by the CH_4 emission multiplied by a scaling factor equal to 12, 25, 70 or 105. The lower panel (**b**) highlights the temperature change (in this case relative to the reference 650 ppm stabilization scenario) during the emissions pulse and the following 40 years

model is freely available for download at http://www.cgd.ucar.edu/cas/wigley/magicc/ and has been used extensively by the IPCC in their reports and analysis. We used reference stabilization scenarios provided (the WRE scenario set is derived from (Wigley et al. 1996)) and modified them according to the specifications listed in Table 1. These scenarios were selected for 2 reasons: (1) the emissions scenarios had 5-yr resolution and extended to 2400 and (2) they reasonably approximated the emissions scenarios used by Shindell and colleagues (2012).

Table 1 Description of the model scenarios used

Scenario	Label	Description
1	650 ppm stabilization	The 650WRE scenario
	CH_4 pulse	Using the 650WRE scenario as the reference, we increased the CH_4 emissions by 5000 Tg CH_4/yr for 10 years from 2015 to 2020.
	CO_2 pulse (GWP=105)	Using the 650WRE scenario as the reference, the CO_2 emissions were increased by 143 Pg CO_2-C/yr for 10 years. This increase is equivalent to 105 times the CH_4 mass added to the atmosphere in the CH_4 pulse scenario.
	CO_2 pulse (GWP=70)	Same as above with the increase in CO_2-C equal to 70 times that of CH_4 mass added to the atmosphere in the CH4 pulse scenario. (95 Pg CO_2-C/yr)
	CO_2 pulse (GWP=25)	Same as above with the increase in CO_2-C equal to 25 times that of CH_4 mass added to the atmosphere in the CH_4 pulse scenario. (34 Pg CO_2-C/yr)
	CO_2 pulse (GTP=12)	Same as above with the increase in CO_2-C equal to 12 times that of CH_4 mass added to the atmosphere in the CH_4 pulse scenario. (16 Pg CO_2-C/yr)
2	Reference — 750 ppm stabilization	The 750WRE scenario with any decrease in CH_4 emissions removed. Instead, CH_4 emissions were allowed to stabilize at 600 Tg CH_4/yr for the duration of the scenario.
	CH_4 measures	The 750WRE scenario with CH_4 emissions immediately reduced to 450 Tg CH_4/yr and then allowed to continue decreasing when the CH_4 emissions in the original 750WRE scenario fell below 450 Tg CH_4/yr.
	CO_2 measures	The 450Over (450 ppm stabilization w/overshoot) scenario with all CH_4 emissions decreases removed. As in the "reference", CH_4 emissions were stabilized at 600 Tg CH_4/yr.
	CH_4+CO_2 measures	The 450Over scenario with the same CH_4 emissions trajectory used in the "CH_4 measures" scenario.
3	Reference — 550 ppm stabilization	The 550WRE scenario was used as the reference scenario — a 550 ppm stabilization scenario with no overshoot.
	15 years delay	Based from the 550WRE scenario, we substituted CO_2 emissions from the A1 business as usual scenario from 2015 to 2030 after which we decreased CO_2 emissions using the same percentage decreases used in the reference 550WRE scenario.
	30 years delay	Same as above, but with the CO_2 emissions from the AI BAU scenario from 2015 to 2045 after which CO_2 emissions declined as above.
	50 years delay	Same as above, but with the CO_2 emissions from the A1 BAU scenario from 2015 to 2065, after which CO_2 emissions declined as above.

3 Results

We directly substitute CO_2 emissions for CH_4 emissions using a variety of commonly used metrics, and plot the climate response in Fig. 1. The values for defining "CO_2-equivalence", were derived from the IPCC (Forster et al. 2007) and several recent publications, (Shindell et al. 2009; Shine et al. 2005) based on both proposed Global Warming Potential (GWP) and Global Temperature Potential (GTP) values. This represents an extreme version of the carbon-trading case where CH_4 emissions are exchanged for extra CO_2 emissions at a variety of values, such that for every one Pg of CH_4 emissions avoided, there is an additional X Pg of CO_2 emitted, where X is a GWP- or GTP-based multiplier. These scenarios are meant to be illustrative only, as a future jump in anthropogenic CH_4 emissions of this magnitude is neither proposed nor likely. Figure 1 shows that, using a multiplier of 70 accurately represents the climate response over the duration of the emission perturbation but, once this terminates, the trajectories quickly diverge. The temperature trajectory associated with replacing the CH_4 pulse with a CO_2 pulse of magnitude either 25 or 12 times the avoided CH_4 pulse both result in cooler temperatures in the first 50 to 100 years respectively, but a warmer world thereafter. Plots of the emissions trajectories are available in the online supplemental material (Figs S1 and S2).

To examine the climate response to CO_2 emissions reductions, CH_4 emissions reductions, or both, we based our scenarios on those used by Shindell and colleagues (2012). Here we modified only CH_4 and CO_2 emissions (omitting any BC reductions). In Fig. 2, we show the resulting temperature profiles over 200 years and compare this to the shorter subset of time displayed in Fig. 1 of Shindell et al. (2012). We show that the temperature profiles diverge quickly, with the CH_4-measures scenario resulting in much greater warming than either scenario that includes CO_2 reductions. The 50-yr and 200-year timelines give very different pictures of the climate outcomes of the various emissions reductions scenarios. For this figure, the temperature axis ΔT refers to the temperature change relative to pre-industrial levels, consistent with Shindell et al. (2012). There are slight differences between the emissions scenarios used in this study and the Shindell analysis, such that Fig. 2 is not intended to be an exact replica, rather to reproduce the general patterns and trends between the various scenarios, extended over 200 years.

Consistent with limited capital and political will, efforts to drastically curb CH_4 emissions reductions may result in delayed CO_2 emissions reductions. We evaluate the extra CO_2 emissions, future atmospheric [CO_2], and temperature trajectories that could occur if reducing

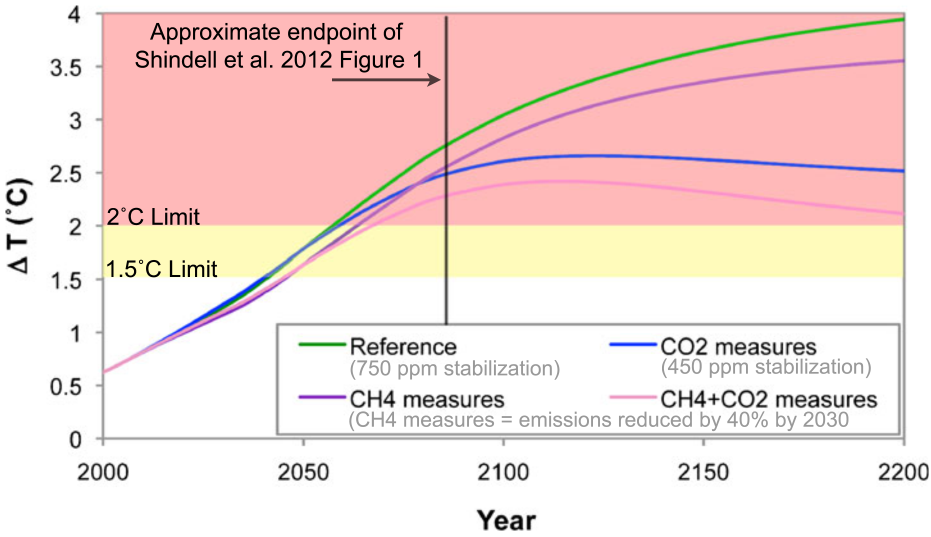

Fig. 2 The global temperature response to emissions reductions of CO_2 and CH_4 over 200 years, based on author's calculations to reproduce Shindell et al. (2012) Fig. 1. After the Shindell et al. endpoint in 2070, the trajectories diverge strongly, emphasizing the importance of CO_2 reductions to long term temperature. A choice now to focus on the CH_4 measures scenario that delays CO_2 mitigation efforts until the trajectories cross at 2070 (assuming we remain on the "Reference" trajectory during those years) would be indistinguishable from the CH_4 measures scenario. If we reach 2070 on the CH_4 measures scenario we are committed to the purple trajectory shown above even with massive CO_2 reductions on the scale of achieving the 450 ppm "CO_2-measures" scenario today. The reference scenario used here is fairly conservative; a CH_4-reduction approach paired with a "business-as-usual" CO_2 emissions scenario results in even higher temperatures

CH_4 emissions took precedence over all actions to address rising CO_2 for 15, 30, or 50 years. Results are displayed in Table 2, showing that remaining on a "business as usual" CO_2 emissions trajectory for 15 years, rather than taking immediate actions towards a 550 ppm stabilization scenario (used here as the reference), results in the emission of more than 500 Pg C as CO_2. This amounts to an additional 115 ppm CO_2 at 2100 and 100 ppm at 2400, with an almost imperceptible decline trajectory at that point. A 30-year delay in addressing rising CO_2 emissions resulted in 1800 additional Pg CO_2-C and >300 ppm additional CO_2 load in the atmosphere. Each 15-yr delay results in approximately 3/4 °C of long-term additional warming, ignoring any short-term cooling resulting from reduced atm [CH_4]. Gas emission and temperature trajectories available in the supplemental material, figures S3 and S4. Further analysis in which we use various metrics to directly replace the CH_4 emissions reductions from the "CH_4 measures" scenario in Fig. 2 with CO_2 emissions and examine the resulting temperature responses is available in the supplemental material (Figs S8- S10).

4 Discussion

The climatic influence of CO_2 is dominated by the "long tail" — the 25 to 40 % of cumulative CO_2 emissions that remain in the atmosphere for thousands of years and the 10–20 % that will persist for tens of thousands of years (Archer and Brovkin 2008). Because almost 40 % of the emitted CO_2 is removed in the first decades (Joos et al. 2013), the immediate impact of CO_2 emissions is dampened. The atmospheric concentration of CH_4 resulting from an emitted pulse follows an approximately standard exponential decay curve (Prather et al. 1994). Because of the different shapes and disparate lifetimes "there is no single scaling factor that can convert between CH_4 and CO_2 emissions" (Wigley 1998) and the same applies to all short-lived GHG's — the value of the scaling factor is time-dependent. Unfortunately, the correct timescale over which to evaluate the relative impacts of different GHG emissions scenarios is not at all clear, and is likely to depend on the scientific or policy question being asked. What is certain is that in much of the recent debate, short timescales (≤50 years) have become increasingly emphasized, while the long timescale (>100 year) influences are often ignored (for example the 100-year GWP, by far the most commonly used metric, places a value of *zero* on all timescales longer than 100 years).

In Fig. 1, we show a direct comparison between increased CH_4-emissions, and a case in which the CH_4 pulse is "traded" for increased CO_2 emissions using various equivalence factors. The purpose of Fig. 1 is to elucidate the trade-offs with time of allowing carbon exchanges between short- and long-lived GHGs such as CH_4 and CO_2. Each potential trading metric has embedded within it a value judgment over the relative importance of temperature changes over different timescales. We show how using a 20-yr GWP of 70 results in a temperature response that overlaps the response to the CH_4 pulse scenario only for the duration of the prescribed pulse — after which the two temperature curves diverge with the CO_2 emission resulting in much higher temperatures. Trading CH_4 for CO_2 using the 100-year

Table 2 CO_2 emissions and atmospheric concentrations resulting from delayed emissions reductions

Delay	Additional CO_2 emitted (Pg C)	Δ [CO_2] (ppm) at 2100	Δ [CO_2] (ppm) at 2400
15 years	530	115	100
30 years	1300	265	230
50 years	1800	360	325

GWP (25) leads to less warming for the first 50 years, but higher temperatures for the centuries and millennia that follow. Minimizing both short and long-term warming is critical, GHG mitigation policies that allow us to trade near-term (impermanent) warming for delayed but permanent warming is dangerous in a political arena where short-timescales dominate decision making; for this reason every attempt should be made to restrict carbon trading of CH_4 (or any short-lived climate pollutant) with CO_2 (Daniel et al. 2012; Humbert 2010).

A recent report by Shindell and colleagues (2012) highlighted the climate benefits of immediate reduction of short-lived climate pollutants. They showed that reductions in black carbon (BC) and CH_4 would more effectively reduce climate warming in the near future than CO_2 reductions, with concomitant human-health benefits that make such actions easier to implement, and even economically profitable for society. While many aspects of their argument are correct, some of which have been argued before (Hansen et al. 2000), there are also real climate concerns related to over-emphasizing reductions of short-lived gases. As Shindell and colleagues acknowledge, long-term (in this case decades to centuries) climate stabilization is only possible through CO_2 reductions. Our concern is that by showing the reader only a timeline to 2070 (near the point at which the highlighted "CH_4+BC tech" and "CO_2 measures" trajectories cross), they avoided discussing the huge timescale tradeoffs inherent in the proposed emission reduction scenarios. In Fig. 2, we plot a similar array of scenarios as those published in Shindell et al.'s Fig. 1, but expand the timescale out to 2200. In doing so, we highlight the potential future impacts of today's decisions should (a) we choose to devalue all longer timescales in comparing GHG reduction strategies or (b) we allow actions on short-lived gases such as CH_4 to delay meaningful CO_2 reductions.

Over all timescales the best scenario for the climate considered here is the "CH_4+CO_2 measures" scenario in which the CO_2 emissions adhere to a 450 ppm stabilization scenario, and the CH_4 emissions are greatly reduced (see SI for plots of emissions trajectories). Timeline only becomes important when discriminating between scenarios that reduce only short-lived gases (only CH_4 in our study) or only CO_2. If we restrict the picture to the short-term, it could be interpreted that the "CH_4 measures" is preferable to, or at least approximately equal to, the "CO_2 measures" scenario. However, for all times beyond approximately 50 years, the "CH_4 measures" scenario falls only just below the "reference" scenario, in this case a 750 ppm stabilization scenario. We note that the reference scenario is roughly equivalent to the same emissions reductions required for the 450 ppm scenario, but with the start of emissions reductions delayed by ~50 years (see supplement Fig S7). This is extremely important because it means that at the point the trajectories cross, if we have chosen the "CH_4 measures" instead of the "CO_2 measures", it is not possible to reverse course — we are now locked into the higher temperature trajectory.

Another important point is that the methodology employed by the Shindell analysis, and replicated here, exaggerates the benefits of reducing CH_4 emissions in two ways: first, by underestimating the benefits of CO_2 reductions; and second, by the timings of the reductions in the scenarios. First, consistent with the Shindell analysis, we removed any CH_4 reductions in the 450 stabilization scenarios to approximate their "CO_2 measures" scenario. However, CO_2 and CH_4 emissions are linked through fossil fuel extraction and transport; more than 60 % of the proposed reductions in the "CH_4 measures" scenario are derived from the fossil fuel sector, and yet this is treated as independent of CO_2 reductions. Accounting for these linkages would result in the "CO_2 measures" temperature trajectory moving ~50 % closer to the "CO_2+CH_4 measures" trajectory (as they correctly point out in the SI) such that this methodological decision results in their undervaluing the influence of aggressive CO_2 reductions on climate. In an analysis that was merely comparing the theoretical influence of reduced emissions of CH_4 versus CO_2 (such as our Fig. 1), enforcing independence might be fair, but in presenting potential real-world mitigation scenarios, exclusion of co-reductions from drastic alteration to the fossil fuel sector ignores an important aspect of such actions that has significant impact on the resulting temperature trajectories. Second, the SLCP reduction scenario implements the 40 % reduction in CH_4 emissions and the 80 % reduction in BC emissions linearly between 2010 and 2030 while the "CO_2 measures" (IEA's 450 CO2-equivalent) scenario does not begin reducing CO_2 emissions until 2020, reaching a 40 % reduction by ~2040. The delay in the CO_2 reductions relative to the SLCP reductions further underestimates the climate benefits of immediate CO_2 mitigation. Arguments about the feasibility of implementing these dramatic emissions reductions could be made for both the SLCP and CO_2 measures.

Reducing emissions of CH_4 and other short-lived climate pollutants such as BC, has real climate benefits, as well as co-benefits for human health and ozone (Ramanathan and Xu 2010). At the same time, there are legitimate concerns that taking strong actions to reduce these emissions could delay efforts to mitigate CO_2, particularly if we overvalue the climate influence of CH_4 and BC (or undervalue the influence of CO_2 reductions as above). While the climate impacts of CH_4 emissions are essentially reversible (over a decade or two), the climate impacts of CO_2 emissions are not; CO_2 persists and accumulates. If CO_2 reductions are delayed and/or dis-incentivized by putting too high a focus (or price) on CH_4, this will exacerbate the climate crisis. Current international policy that allows methane to be traded for CO_2 at the100-yr-GWP-based price (25) could result in significantly more long-term warming (Fig. 1) depending on the volume of trading.

In Table 2 we show the "extra" CO_2 emissions that could occur if focus on CH_4 reductions results in remaining on a business-as-usual scenario for CO_2 emissions for 15, 30, or 50 years, using a 550 ppm stabilization scenario as the comparison low CO_2-emissions scenario and an A1 business as usual trajectory as the high-CO_2 scenario. Here we find that, if reducing CH_4 emissions were to result in a delay of just 15 years in addressing the growth of global CO_2 emissions, this leads to an additional 100 ppm atmospheric CO_2 that persists for thousands of years. If CO_2 emissions continue on the business-as-usual scenario for 30 years, until 2045, this leads to atm [CO_2] 230 ppm higher than the target 550 ppm of the base scenario.

The persistence of the climate system response to CO_2 emissions, compared with the near-immediate benefits from reductions of short-lived GHG's make prioritizing CH_4 and BC reductions particularly attractive from a political perspective where election timescales are short. Combining the results from Fig. 2 and Table 2 we observe that, if we take actions to reduce short-lived GHG's while remaining on either a 750 ppm trajectory, or a high-growth business-as-usual CO_2 emission trajectory, by the time the warming begins to accelerate (15–30 years), we have already committed the earth to a much greater degree of warming regardless of the actions we take from that point forward. If we wait to reduce CO_2 emissions until the warming from the CO_2 begins to exceed the cooling from the CH_4 reductions (2070 or approximately 50 years), we would already be "locked in" to more than 1.5 °C extra warming with no way to take those CO_2 emissions back except through the very expensive and inefficient technological fix of capturing of CO_2 out of the air (Socolow et al. 2011). However, if we ignore short-lived gases and focus only on reducing CO_2 emissions, we can decide in 10 or 100 years that further reductions in CH_4 (and BC) emissions are necessary and the coolest climate trajectory would still be nearly attainable. Because CH_4 emissions have little cumulative impact on climate, reducing CH_4 emissions now or in the future has essentially the same effect.

Beyond the timescales associated with GHG emissions and the climate response to them, there are also timescales associated with energy infrastructure. Implementing significant reductions in CO_2 emissions requires huge changes to the fundamental structure of the global energy system. Even assuming great political will across all the world's major economies, and future technological advances in CO_2-free energy sources, these changes are likely to take decades to centuries to complete. This infrastructure timescale would further exacerbate the climate impact of turning attention away from reducing CO_2 emissions, and must be considered when we search for the best path to a carbon-free energy future (Schrag 2012; Davis et al. 2010).

Another argument used to support immediate emissions reduction of short-lived GHG's such as CH_4 and BC is the necessity of avoiding a global temperature increase of >2 °C, which could trigger certain "tipping points" in the climate system (Shindell et al. 2012; Ramanathan and Xu 2010). This argument has 2 flaws: First, it misses the crucial point that it is only possible to use short-lived GHG emissions reductions to avoid a future "peak" in climate warming if we are already on the down-slope of the CO_2 emissions trajectory (acknowledged in Ramanathan and Xu 2010). Otherwise, the only effect is to delay reaching this "tipping point" by a few years or decades, depending on the CO_2 emissions trajectory. Second, there simply is not enough known about the exact nature of climate feedbacks to make a compelling scientific argument either that a line must be drawn at 2 °C or that any particular temperature threshold is going to tip us over the edge of a given binary feedback (Kriegler et al. 2009). The warmer the world, the greater the probability of catastrophic consequences and the only way to take the heater off is to reduce CO_2 emissions.

5 Conclusion

As Allen et al. (2009) showed concisely in their "trillionth ton" analysis, climate responds to cumulative CO_2 emissions over approximately 100 years. Short-lived gases also play an important role in contributing to climate change, and reducing these emissions could have a substantial cooling effect over the short-term. But if we overvalue the influence of CH_4 on climate, this is likely to delay the imperative for CO_2 reduction and lead to higher cumulative emissions and more long-term warming. Of course, methane emissions (and BC emissions) should be reduced, do not weaken efforts to reduce CO_2 emissions. Otherwise, too much focus on reducing CH_4 emissions will only delay for a short time the temperature peak we had hoped to avoid, while the extra CO_2 emitted ensures that we remain above that temperature for a very, very long time.

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References

Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, Meinshausen N (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458(7242):1163–1166. doi:10.1038/nature08019

Archer D, Brovkin V (2008) The millennial atmospheric lifetime of anthropogenic CO2. Clim Chang 90(3):297. doi:10.1007/s10584-008-9413-1

Azar C, Johansson DJA (2012) On the relationship between metrics to compare greenhouse gases – the case of IGTP, GWP and SGTP. Earth Syst Dynam 3(2):139–147. doi:10.5194/esd-3-139-2012

Berntsen T, Tanaka K, Fuglestvedt JS (2010) Does black carbon abatement hamper CO(2) abatement? A letter. Clim Chang 103(3–4):627–633

Daniel J, Solomon S, Sanford T, McFarland M, Fuglestvedt J, Friedlingstein P (2012) Limitations of single-basket trading: lessons from the Montreal Protocol for climate policy. Clim Chang 111(2):241–248. doi:10.1007/s10584-011-0136-3

Davis SJ, Caldeira K, Matthews HD (2010) Future CO(2) emissions and climate change from existing energy infrastructure. Science 329(5997):1330–1333. doi:10.1126/science.1188566

Derwent RG (1990) Trace gases and their relative contribution to the greenhouse effect. Atomic Energy Research Establishment, Document: AERE R 13716, Harwell

Fisher DA, Hales CH, Wang W-C, Ko MKW, Sze ND (1990) Model calculations of the relative effects of CFCs and their replacements on global warming. Nature 344:513–516

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, Dorland RV (2007) Changes in atmospheric consituents and in radiative forcing. paper presented at the climate change 2007: the physical science-basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

Fuglestvedt JS, Berntsen TK, Godal O, Skodvin T (2000) Climate implications of GWP-based reductions in greenhouse gas emissions. Geophys Res Lett 27(3):409–412. doi:10.1029/1999gl010939

Fuglestvedt JS, Berntsen TK, Godal O, Sausen R, Shine KP, Skodvin T (2003) Metrics of climate change: assessing radiative forcing and emission indices. Clim Chang 58(3):267–331. doi:10.1023/a:1023905326842

Fuglestvedt JS, Shine KP, Berntsen T, Cook J, Lee DS, Stenke A, Skeie RB, Velders GJM, Waitz IA (2010) Transport impacts on atmosphere and climate: metrics. Atmos Environ 44(37):4648–4677. doi:10.1016/j.atmosenv.2009.04.044

Gillett NP, Matthews HD (2010) Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. Environ Res Lett 5(3). doi:10.1088/1748-9326/5/3/034011

Hammitt JK, Jain AK, Adams JL, Wuebbles DJ (1996) A welfare-based index for assessing environmental effects of greenhouse-gas emissions. Nature 381:301–303

Hansen J, Sato M, Ruedy R, Lacis A, Oinas V (2000) Global warming in the twenty-first century: an alternative scenario. Proc Natl Acad Sci 97(18):9875–9880

Howarth RW, Santoro R, Ingraffea A (2011) Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Chang 106(4):679–690. doi:10.1007/s10584-011-0061-5

Howarth R, Santoro R, Ingraffea A (2012) Venting and leaking of methane from shale gas development: response to Cathles et al. Clim Chang 113(2):537–549. doi:10.1007/s10584-012-0401-0

Humbert R (2010) Losing time, not buying time. http://www.realclimate.org/index.php/archives/2010/12/losing-time-not-buying-time/

Joos F, Roth R, Fuglestvedt JS, Peters GP, Enting IG, von Bloh W, Brovkin V, Burke EJ, Eby M, Edwards NR, Friedrich T, Frölicher TL, Halloran PR, Holden PB, Jones C, Kleinen T, Mackenzie FT, Matsumoto K, Meinshausen M, Plattner GK, Reisinger A, Segschneider J, Shaffer G, Steinacher M, Strassmann K, Tanaka K, Timmermann A, Weaver AJ (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos Chem Phys 13(5):2793–2825. doi:10.5194/acp-13-2793-2013

Kriegler E, Hall JW, Held H, Dawson R, Schellnhuber HJ (2009) Imprecise probability assessment of tipping points in the climate system. Proc Natl Acad Sci 106(13):5041–5046

Lashof DA, Ahuja DR (1990) Relative contributions of greenhouse gas emissions to global warming. Nature 344(6266):529–531

Manne AS, Richels RG (2001) An alternative approach to establishing trade-offs among greenhouse gases. Nature 410(6829):675–677

O'Neill B (2000) The jury is still out on global warming potentials. Clim Chang 44(4):427–443. doi:10.1023/a:1005582929198

Peters GP, Aamaas B, Berntsen T, Fuglestvedt JS (2011) The integrated global temperature change potential (iGTP) and relationships between emission metrics. Environ Res Lett 6(4). doi:10.1088/1748-9326/6/4/044021

Prather M, Derwent R, Ehhalt D, Fraser P, Sanhueza E, Zhou X (1994) Other trace gases and atmospheric chemistry. Climate Change 94:77–126

Ramanathan V, Xu Y (2010) The Copenhagen accord for limiting global warming: criteria, constraints, and available avenues. Proc Natl Acad Sci 107(18):8055–8062

Schrag DP (2012) Is shale gas good for climate change? Daedalus 141(2):72–80. doi:10.1162/DAED_a_00147

Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE (2009) Improved attribution of climate forcing to emissions. Science 326(5953):716–718. doi:10.1126/science.1174760

Shindell D, Kuylenstierna JCI, Vignati E, van Dingenen R, Amann M, Klimont Z, Anenberg SC, Muller N, Janssens-Maenhout G, Raes F, Schwartz J, Faluvegi G, Pozzoli L, Kupiainen K, Hoglund-Isaksson L, Emberson L, Streets D, Ramanathan V, Hicks K, Oanh NTK, Milly G, Williams M, Demkine V, Fowler D (2012) Simultaneously mitigating near-term climate change and improving human health and food security. Science 335(6065):183–189. doi:10.1126/science.1210026

Shine K (2009) The global warming potential—the need for an interdisciplinary retrial. Clim Chang 96(4):467–472. doi:10.1007/s10584-009-9647-6

Shine KP, Fuglestvedt JS, Hailemariam K, Stuber N (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Clim Chang 68(3):281–302. doi:10.1007/s10584-005-1146-9

Shine KP, Berntsen TK, Fuglestvedt JS, Skeie RB, Stuber N (2007) Comparing the climate effect of emissions of short- and long-lived climate agents. Phil Trans R Soc A Math Phys Eng Sci 365(1856):1903–1914. doi:10.1098/rsta.2007.2050

Socolow R, Desmond M, Aines R, Blackstock J, Bolland O, Kaarsberg T, Lewis N, Mazzotti M, Pfeffer A, Sawyer K, Siirola J, Smit B, Wilcox J (2011) Direct air capture of CO2 with chemicals. American Physical Society

Solomon S, Pierrehumbert RT, Matthews DL, Daniel JS (2011) Atmospheric Composition Irreversible Climate Change and Mitigation Policy. WCRP OSC Climate Research in Service to Society (24–28 October 2011. Denver, United States

Tanaka K, O'Neill BC, Rokityanskiy D, Obersteiner M, Tol RSJ (2009) Evaluating Global Warming Potentials with historical temperature. Clim Chang 96(4):443–466. doi:10.1007/s10584-009-9566-6

Wigley TML (1998) The Kyoto Protocol: CO2, CH4 and climate implications. Geophys Res Lett 25(13):2285–2288. doi:10.1029/98gl01855

Wigley TML (2008) MAGICC/SCENGEN 5.3: user manual (version 2). . UCAR Climate and Global Dynamics Division

Wigley TML, Richels R, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. Nature 379(6562):240–243

Wigley T, Raper S, Salmon M, Hulme M (1997) MAGICC: Model for the Assessment of Greenhouse-gas Induced Climate Change: Version 2.3. Climatic Research Unit, Norwich, United Kingdom

Wuebbles DJ (1989) Beyond CO2—the other greenhouse gases. Lawrence Livermore National Laboratory report UCRL-99883; Air and Waste Management Association paper 89–119.4