

# The Paris warming targets: emissions requirements and sea level consequences

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**Abstract** The Paris Agreement states that, relative to pre-industrial times, the increase in global average temperature should be kept to well below 2 °C and efforts should be made to limit the temperature increase to 1.5 °C. Emissions scenarios consistent with these targets are derived. For an eventual 2 °C warming target, this could be achieved even if CO<sub>2</sub> emissions remained positive. For a 1.5 °C target, CO<sub>2</sub> emissions could remain positive, but only if a substantial and long-lasting temperature overshoot is accepted. In both cases, a warming overshoot of 0.2 to 0.4 °C appears unavoidable. If the allowable (or unavoidable) overshoot is small, then negative emissions are almost certainly required for the 1.5 °C target, peaking at negative 1.3 GtC/year. In this scenario, temperature stabilization occurs, but cumulative emissions continue to increase, contrary to a common belief regarding the relationship between temperature and cumulative emissions. Changes to the Paris Agreement to accommodate the overshoot possibility are suggested. For sea level rise, tipping points that might lead to inevitable collapse of Antarctic ice sheets or shelves might be avoided for the 2 °C target (for major ice shelves) or for the 1.5 °C target for the West Antarctic Ice Sheet. Even with the 1.5 °C target, however, sea level will continue to rise at a substantial rate for centuries.

## 1 Introduction

The primary goal of negotiations to reduce the magnitude of future climate change is to avoid dangerous anthropogenic interference (DAI) with the climate system. To this end, the UNFCCC Paris Agreement states that mitigation efforts should be directed towards “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels

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and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels ...” (Article 2.1a; UNFCCC 2015). Even if these goals are achieved, however, as I show here, they will still not be sufficient to avoid DAI arising from sea level rise.

This raises two questions: what emissions reductions might be required to (1) keep global mean warming to below the 2 or 1.5 °C thresholds and (2) stabilize, or at least minimize, the rate of sea level rise. Papers that have addressed the first item have concluded that, even for the 2 °C target, a period of negative emissions would be required (e.g., Peters (2016)). Likewise, Smith et al. (2016) state that the 2 °C target would “require large-scale deployment of negative emissions technologies.” Numerous other papers have drawn the same conclusion (e.g., Rogelj et al. (2015a, 2016)). Are negative emissions really necessary?

A key issue here is whether an initial overshoot of the final warming target is allowable (Clarke et al. 2014; Rogelj and Knutti 2016; Schlessner et al. 2016). Schlessner et al. question whether a warming overshoot would be legal within the wording of the Paris Agreement. This is an important point, and I show here that a temperature overshoot is virtually unavoidable. The emissions scenarios produced here (notwithstanding the legal concern raised by Schlessner et al.) all involve a temperature overshoot. I use the word “target” extensively here, which, to be consistent with the overshoot likelihood refers always to the eventual warming.

The primary goal of this paper is to derive emissions scenarios that are consistent with the 2 and 1.5 °C targets. This requires considering not just CO<sub>2</sub>, but the range of non-CO<sub>2</sub> gases that also contribute towards climate change. A standard approach here is to use an integrated assessment model that considers all (or the bulk of) climatically active gases, begins with a reference no-climate-policy scenario, and applies internally consistent policies to reduce emissions and reach some forcing or climate target (e.g., Clarke et al. (2007)).

I will use an alternative approach predicated on the simplifying principle of *ceteris paribus*, “change only one thing at a time.” I first consider the non-CO<sub>2</sub> gases and choose a single emissions scenario for these gases. I then consider a range of emissions scenarios for CO<sub>2</sub> alone that stabilize CO<sub>2</sub> concentrations at different levels, and combine these with the non-CO<sub>2</sub> scenario to allow an assessment of future temperature and sea level change under different (stringent) multi-gas mitigation assumptions. The temperature results span the two Paris targets, so perturbing the emissions for these initial cases allows one to derive CO<sub>2</sub> emissions scenarios that meet the Paris targets.

The following section considers CO<sub>2</sub> concentration stabilization profiles, updating Wigley et al. (1996). (Further details are given in ESM item 1.) I then consider the non-CO<sub>2</sub> gases and choose a single scenario for this contribution to radiative forcing. This is scientifically preferable to using global warming potentials (GWPs) to combine the emissions of multiple species, given flaws in the GWP concept (e.g., Smith and Wigley (2000a, b); Myhre et al. (2013)). In the next section, I use the coupled gas-cycle, energy-balance climate model MAGICC (Wigley et al. 2009; Meinshausen et al. 2011) to derive temperature and sea level changes for the 250, 350, and 450 ppm stabilization scenarios. (Additional MAGICC details are given in ESM item 2.) The next section uses these results to derive emissions scenarios that are consistent with the 1.5 °C target. The final sections discuss the results and draw conclusions.

## 2 CO<sub>2</sub> concentration stabilization

Enting et al. (1994) and Wigley et al. (1996) were among the first to estimate the CO<sub>2</sub> emissions required to stabilize atmospheric CO<sub>2</sub> concentrations. The Wigley et al. emissions required for

stabilization at “xxx” parts per million are referred to as the “WRExxx” scenarios. Related work on stabilization of radiative forcing includes projects such as those conducted by Stanford University’s Energy Modeling Forum (Clarke and Weyant 2009; Schlesinger et al. 2007) and under the U.S. Climate Change Science Program (Clarke et al. 2007).

To answer the questions posed above, I first update the WRE concentration stabilization pathways and determine their implied emissions. Updating is required to account for observed concentration and emissions changes that have occurred since the original development of the WRE scenarios (ESM item 1). A pathway for stabilization at 250 ppm, not previously considered, is added here. Concentration pathways and the corresponding fossil fuel CO<sub>2</sub> emissions are shown in Fig. 1.

For WRE350 and 250, meeting the concentration targets for the prescribed concentration pathways requires negative emissions for some portion (350 case) or all (250 case) of the next several centuries. Negative emissions pose serious technological challenges; some of which have been addressed in Smith et al. (2016) and references therein, and by Rogelj et al. (2015b).

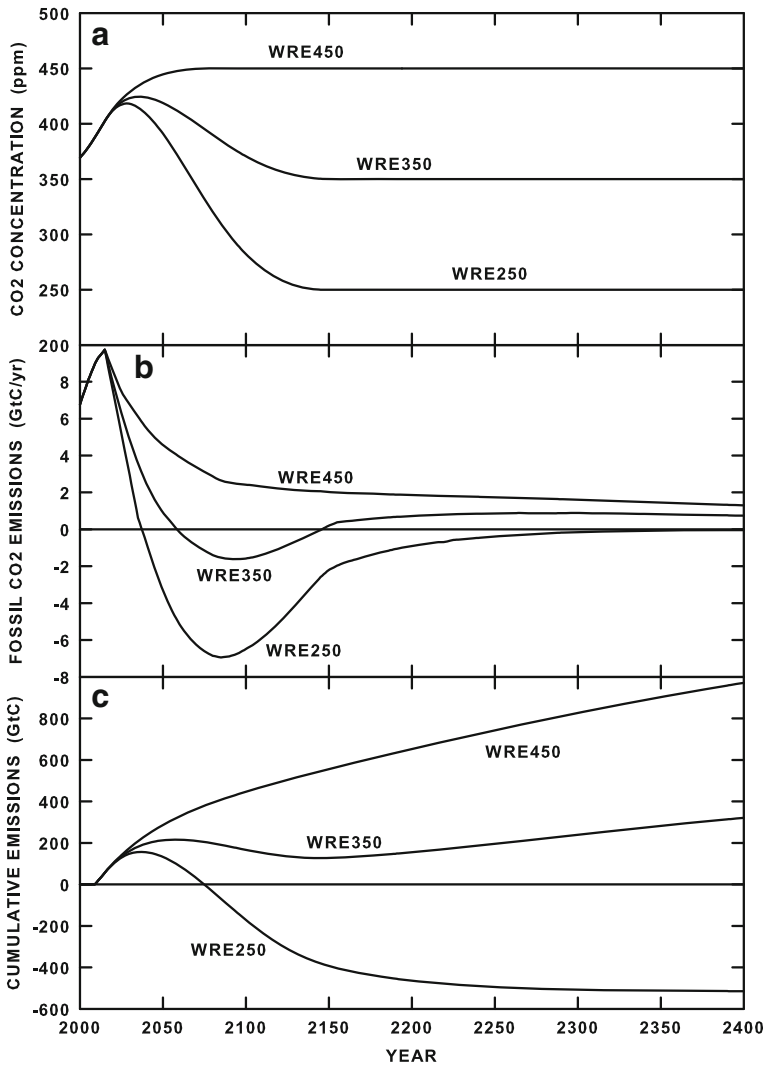
### 3 Non-CO<sub>2</sub> gases

Many gases other than CO<sub>2</sub> affect the climate either through direct effects on the planet’s radiation balance, or by influencing, through atmospheric chemical processes, the buildup or decay of these gases. The main non-CO<sub>2</sub> gases are the following: CH<sub>4</sub>, N<sub>2</sub>O, and a large range of halocarbons; aerosol precursors (mainly SO<sub>2</sub> that produces sulfate aerosols); the reactive gases CO, NO<sub>x</sub>, and VOCs that affect atmospheric chemistry; and both tropospheric and stratospheric ozone. Integrated assessment (IA) models consider most of these. But, even when such models are set up with a common set of well-defined goals, they can lead to quite different results for projected non-CO<sub>2</sub> radiative forcing. Data from the U.S. Climate Change Science Program (CCSP) Report 2.1a (Clarke et al. 2007) can be used to illustrate this and to make a choice for future non-CO<sub>2</sub> forcing.

The CCSP exercise gave three IA models (MiniCAM, EPPA, and MERGE) the same ground rules and targets for the future. Each modeling group was directed to devise a baseline, reference scenario (“Ref”) for emissions that would occur with no new climate mitigation policies, and then to apply multi-gas, cost-optimized policies to reach increasingly stringent forcing targets by 2100 (with forcing calculated using only those gases that are covered by the Kyoto Protocol). The policy cases, with their equivalent CO<sub>2</sub> forcing targets in parentheses, are referred to as level 4 (750 ppm), level 3 (650 ppm), level 2 (550 ppm), and level 1 (450 ppm) scenarios. The MiniCAM level 1 case is the most relevant to the Paris Agreement’s 2 °C warming target, as it leads to a 50% probability of stabilizing global mean warming at this level (Wigley et al. 2009).

For each CCSP model, the results for the five different scenarios are internally consistent. Because of this, the Ref and different level-*i* scenarios can be compared directly to gain insights into the effects of increasingly strong, policy-driven mitigation measures. This is not possible, for example, with the more recent RCP emissions scenarios (van Vuuren et al. 2011). With such a well-formulated set of ground rules and targets, one might expect the CCSP models to give similar results, but this is not the case.

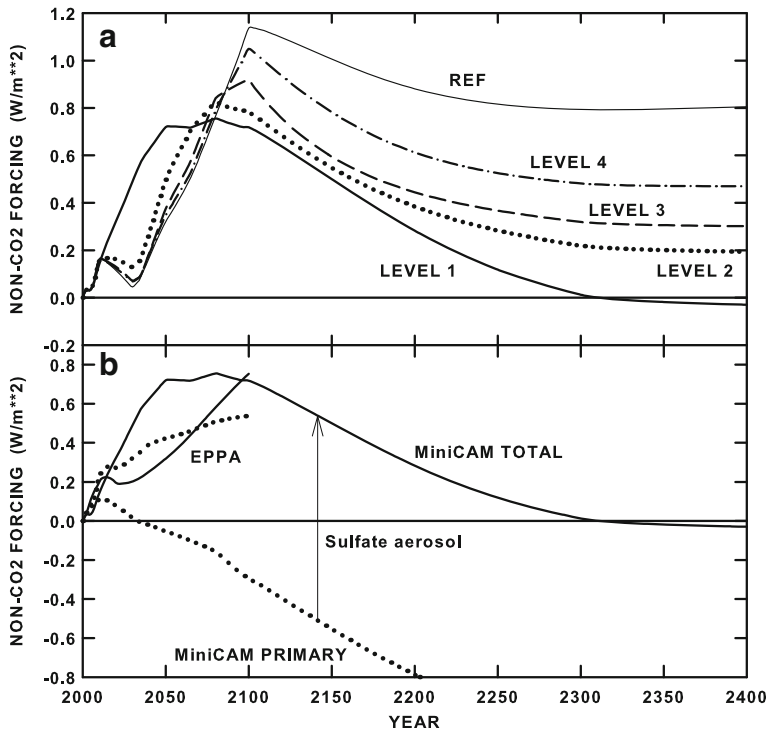
Only two of the CCSP models have data that are complete enough to calculate total non-CO<sub>2</sub> forcing (viz., MiniCAM and EPPA). For MiniCAM (Kim et al. 2006), the emissions



**Fig. 1** **a** CO<sub>2</sub> concentration stabilization profiles, **b** corresponding fossil fuel CO<sub>2</sub> emissions, and **c** cumulative emissions (from and including 2010)

scenarios have been extended to 2300 (Wigley et al. 2009). Beyond this, I assume no further changes in emissions. For EPPA (Paltsev et al. 2005), the scenarios go out only to 2100. Radiative forcing results are shown in Fig. 2: Fig. 2a shows total non-CO<sub>2</sub> forcing for the MiniCAM scenarios (see also ESM item 3), while Fig. 2b shows (for both the MiniCAM and EPPA level 1 scenarios) the breakdown into forcing from SO<sub>2</sub>-derived sulfate aerosols and the remainder, “primary” non-CO<sub>2</sub> forcing.

As noted, the MiniCAM level 1 scenario for non-CO<sub>2</sub> emissions is appropriate for the 2 °C target case. This scenario is also appropriate for the 1.5 °C case. Why is this? First, aerosol forcing peaks by around 2300 in this scenario when SO<sub>2</sub> emissions return to close to their pre-industrial level. Thus, further significant changes in this component of non-CO<sub>2</sub> forcing are unlikely even if CO<sub>2</sub> levels continue to be reduced. Second, for primary non-CO<sub>2</sub> forcing, CH<sub>4</sub>



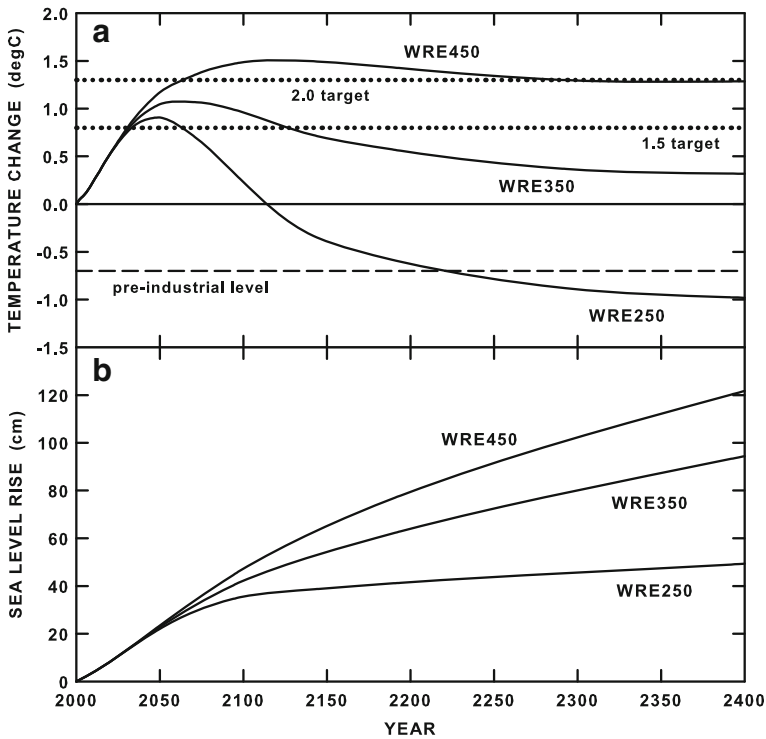
**Fig. 2** **a** Total non-CO<sub>2</sub> radiative forcing changes for the MiniCAM CCSP scenarios. **b** Comparison of forcing breakdowns for the MiniCAM and EPPA level 1 scenarios. Primary non-CO<sub>2</sub> forcing (dotted lines) is the sum of all contributions except for sulfate aerosol forcing. The MiniCAM primary forcing curve is cut off at 2200 for clarity; it reaches about  $-1.1 \text{ W/m}^2$  by 2400. The upward arrow at about 2150 identifies the positive sulfate aerosol forcing component for the MiniCAM level 1 scenario

concentrations (the main component of this forcing term) have also returned to near their pre-industrial level by 2300. The MiniCAM level 1 scenario, even though it corresponds to CO<sub>2</sub> stabilization at around 450 ppm, is therefore a reasonable estimate for non-CO<sub>2</sub> forcing for CO<sub>2</sub> stabilization levels below 450 ppm because significant future non-CO<sub>2</sub> changes beyond the level 1 case are unlikely. Further details are given in ESM item 3.

#### 4 Temperature and sea level consequences

Temperature and sea level rise projections for the three primary WRE stabilization scenarios (stabilization at 250, 350, and 450 ppm) are shown in Fig. 3.

The projections in Fig. 3 have been made using version 5.3 of MAGICC, a coupled gas-cycle, upwelling-diffusion, energy-balance climate model (Wigley et al. 2009; Meinshausen et al. 2011); see ESM item 2 for further details. To derive these results, it is necessary to make assumptions about the following: (1) future emissions from non-CO<sub>2</sub> sources and (2) climate model parameters like the climate sensitivity. As the Paris targets refer to changes from pre-industrial times (without defining “pre-industrial”), it is important also to quantify the changes that have occurred already. I have chosen the period 1880 to 1899 to define a pre-industrial level. Although an earlier period may accord better with the common perception of “pre-



**Fig. 3** Global mean temperature and sea level changes for the stabilization scenarios shown in Fig. 1. Dotted lines show the 1.5 and 2 °C Paris warming targets (assuming 0.7 °C warming to 2000). The WRE450 case, after a small overshoot, tends towards the 2 °C warming target

industrial”, an earlier period cannot be used reliably because uncertainties in global mean temperatures amplify considerably before 1880. For my 2000 base year, I use the average over 1995 to 2004. The warming between these two periods is close to 0.7 °C (see, e.g., Karl et al. (2015); Fig. 2a).

For non-CO<sub>2</sub> forcing, I use the MiniCAM level 1 emissions scenario, as explained above and in ESM item 3. For the climate model, I use best estimate model parameters, which include a climate sensitivity of 3.0 °C warming for a CO<sub>2</sub> doubling (Wigley et al. 2009; Wigley and Santer 2013; Armour 2017). A number of recent assessments have suggested that the climate sensitivity is less than 3 °C. My choice, justified by the above references, is conservative in that it would require lower (and more challenging) emissions reductions than would a lower sensitivity.

Sea level rise is the sum of oceanic thermal expansion, ice melt from glaciers and small ice sheets, melt and ice loss from Greenland and Antarctica, and changes in terrestrial water storage. The ice melt model parameters for this exercise have been recalibrated to match results given in the IPCC 5th Assessment Report, AR5 (Church et al. 2013). Further details are given in ESM item 5. MAGICC5.3 does not include any halosteric component for sea level rise. This is demonstrably important at the ocean basin scale (Durack et al. 2014; Llovel and Lee 2015), but much less important at the global mean level because salt is conserved in the ocean. MAGICC5.3 estimates for thermal expansion and total sea level rise agree well with IPCC AR5 results (see Table 1).

Table 1 shows how well version 5.3 of MAGICC (M53 in the Table) captures the AR5 results, and compares M53 results with two other analyses (Kopp et al. 2014; Nauels et al. 2017). There is excellent agreement, both in terms of total sea level rise and the various components, between AR5 and M53.

To keep long-term, global mean temperature change from pre-industrial times below 2 °C, Fig. 3a shows that CO<sub>2</sub> must stabilize at around 450 ppm. Figure 1b shows that this is possible even if CO<sub>2</sub> emissions do not drop to zero, contrary to claims cited above. This is not to belittle the challenge of meeting this temperature goal, nor is it meant to imply that negative emissions technologies should not be employed if cost-effective. Although asymptotically approaching the 2 °C threshold, the WRE450 scenario does not keep warming continuously below this threshold. As anticipated by a number of authors, some small (0.21 °C here) warming overshoot is probably unavoidable.

For WRE350, warming peaks at 0.25 °C above the 1.5 °C threshold and then declines to well below this threshold. For WRE250, warming peaks earlier at slightly above the 1.5 °C threshold. After this peak, pronounced cooling occurs bringing global mean temperature back, eventually, to well below the pre-industrial level, as would be expected given that 250 ppm is below the pre-industrial CO<sub>2</sub> concentration level. Comparing WRE350 and WRE450 in Fig. 3a suggests that emissions somewhere between these cases could lead to a long-term warming close to the 1.5 °C threshold. This possibility is explored further in the next Section.

As noted, the results given here use best estimate model parameters consistent with AR5, including those for ice melt contributions to sea level rise (ESM item 5). For the temperature projections, the main source of uncertainty arises through the climate sensitivity, where I assume a central value of 3.0 °C. Results for a climate sensitivity of 1.5 °C, approximately the fifth percentile value (Wigley et al. 2009), are given in ESM item 6.

From Fig. 3, it is clear that CO<sub>2</sub> concentration stabilization at 350 ppm or above fails to lead to anything like sea level stabilization. Sea level rise for WRE350 reaches about 80 cm by 2300 (relative to 2000) and is still rising then at about 14 cm per century. WRE250 comes closer to stabilizing sea level, but still leads to at least an additional 46 cm sea level rise by 2300 relative to 2000.

It is clear that avoiding DAI associated with sea level rise requires that the maximum global mean warming target should be appreciably less than 2 °C. Even the 2 °C target, captured by WRE450, leads to large, continuous, multi-century sea level rise. To minimize DAI associated with sea level rise requires keeping the rate of rise to a small value. To achieve this, as Fig. 3 shows, atmospheric CO<sub>2</sub> concentration must be reduced to well below 350 ppm. Of the scenarios considered, WRE250 comes nearest to achieving sea level stabilization, but, even in this case, sea level is still rising at around 4 cm/century in 2400 (Fig. 3b).

The relative contributions to sea level rise for, as an example, the WRE250 scenario are shown in ESM item 5. In general with the WRE scenarios, thermal expansion is initially the most important, but this component begins to decline about two decades after the temperature decline begins. The expansion decline continues as the surface cooling penetrates into the deeper ocean. The Antarctic contribution to sea level rise eventually becomes the most important contributor (see Fig. ESM5 for the WRE250 case). Because of the continued atmospheric cooling, contributions from glaciers and Greenland eventually stabilize and then become negative.

In the long term, the key component of sea level rise is the Antarctic dynamical term (ZDYN), which, in the present model, is a linear function of time and so independent of climate system changes. The likelihood of a multi-millennial positive sea level contribution

**Table 1** Comparison of AR5 (Church et al. 2013, Table 13.5), Kopp et al. (2014), Nauels et al. (2017, N17), and MAGICC5.3 (M53) estimates for sea level rise components. AR5 changes are over 1986–2005 to 2081–2100. “TOTAL” values here are from row 8 in Table 13.5. Changes from MAGICC5.3 are for the equivalent 1995 to 2090 period. Kopp et al. give changes over 2000 to 2100, scaled here by 95/100 for comparison with the other results. Values given are median estimates of total change in cm. Rate of sea level rise results are from row 12 of Table 13.5. The comparable M53 figures are for changes over 2090 to 2100. The N17 model was constrained to match independently modeled surface temperature changes

	RCP26				RCP45				RCP 6				RCP85											
	AR5		Kopp		N17		M53		AR5		Kopp		N17		M53		AR5		Kopp		N17		M53	
	AR5	Kopp	N17	M53	AR5	Kopp	N17	M53	AR5	Kopp	N17	M53	AR5	Kopp	N17	M53	AR5	Kopp	N17	M53				
Expansion	14	18.1	11.8	13.6	19	24.7	16.4	18.4	19	24.7	16.4	18.4	19	24.7	16.4	18.4	27	35.1	26.0	30.2				
Glaciers	10	11.4	11.4	11.4	12	12.3	12.8	12.6	12	12.3	12.8	12.6	12	12.3	12.8	12.6	16	17.1	15.2	15.7				
Greenland	6	5.7	5.7	7.2	8	8.5	7.0	8.2	8	8.5	7.0	8.2	8	8.5	7.0	8.2	12	13.3	10.7	11.5				
Antarctica (DYN)	7	7.2	7.2	7.0	7	7.2	8.3	7.0	7	7.2	8.3	7.0	7	7.2	8.3	7.0	7	7.0	11.0	7.0				
Antarctica (SMB)	-2		-2.2	-1.9	-2		-2.6	-2.3	-2		-2.6	-2.3	-2		-2.7	-2.4	-4		-3.5	-3.6				
Antarctica (total)	5	5.7	5.1	5.2	5	4.7	5.7	4.7	5	4.7	5.7	4.7	5	4.7	5.7	4.7	4	3.8	7.5	3.4				
Land water	4	4.7	5.8	3.6	4	4.7	5.8	3.6	4	4.7	5.8	3.6	4	4.7	5.8	3.6	4	4.7	5.8	3.6				
Total	40	47.5	40.9	40.9	47	56.1	49.4	47.3	48	56.1	49.4	47.3	48	56.1	49.4	47.3	63	75.1	67.0	64.5				
Rate of sea level rise	4.4			3.7	6.1			5.6	7.4			5.6	7.4			7.5	11.2			10.9				



from this source is consistent with the modeling results of Golledge et al. (2015) and DeConto and Pollard (2016). The latter paper employs a more sophisticated ice sheet model than previous analyses and obtains considerably larger ZDYN contributions to sea level rise than in the present analysis. For RCP4.5 (a scenario that is similar to the WRE450 scenario used here), these authors' best estimate is a contribution of  $58 \pm 28$  cm by 2100 (1-sigma uncertainty), compared with estimates of 7 cm obtained here and in the SAR (see Table 1). This is a truly alarming result.

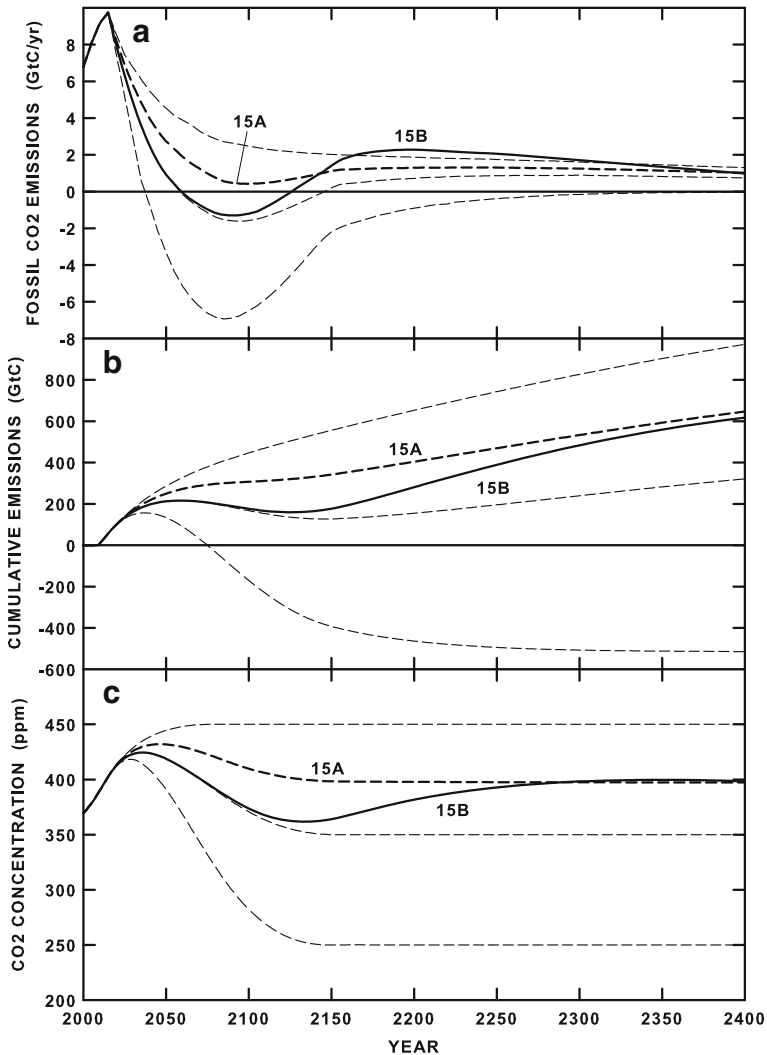
The results shown here are only best estimate results, using best or near-best estimates for the climate sensitivity and other climate and sea level model parameters consistent with AR5. Stabilization of sea level rise would, however, still be a formidable challenge even if optimistically low values were assumed for the climate sensitivity and ice melt parameters (see ESM item 6 for the 1.5 °C sensitivity case).

## 5 Emissions for the 1.5 °C target

The above results allow us to develop emissions scenarios that would lead to long-term warming of around 1.5 °C for the assumed climate sensitivity of 3.0 °C and the assumed emissions scenario for non-CO<sub>2</sub> gases. Figure 3 shows that an emissions scenario somewhere between WRE350 and WRE450 would lead to an eventual warming relative to the pre-industrial level somewhere between 1 and 2 °C. These two scenarios can therefore be used to construct emissions scenarios that meet the 1.5 °C Paris target. I consider two cases. The first case (15A) simply averages the emissions for WRE350 and WRE450, which should, based on Fig. 3a, lead to temperatures that tend asymptotically towards the 1.5 °C target. The second case (15B) prescribes a temperature trajectory that stabilizes at the 1.5 °C target level by around 2150. The emissions required for this case were estimated using an inverse version of MAGICC5.3. The results are shown in Figs. 4 and 5.

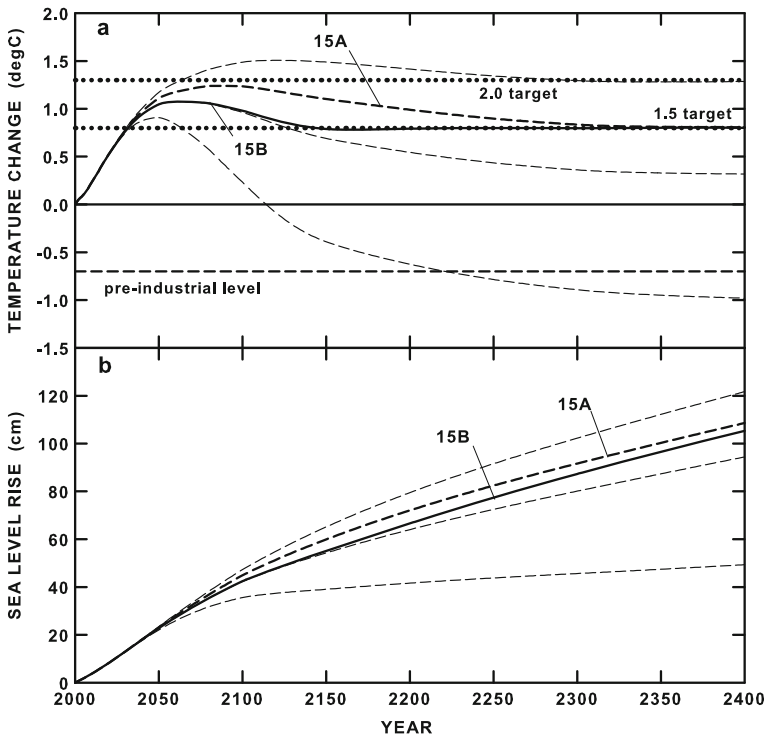
Figures 4 and 5 show a number of important results:

- (1) Scenario 15A does not require negative emissions, but has a large and long-lasting temperature overshoot.
- (2) In scenario 15B, the temperature overshoot is smaller (0.28 °C compared with 0.44 °C) and shorter (112 years) than in 15A. This is closer to being in accord with the wording of the Paris Agreement, but is still technically in violation of the Agreement's current wording. 15B requires negative emissions, maximizing at about  $-1.3$  GtC/year in 2090, so even larger negative emissions would be required to be in strict accord with the Agreement.
- (3) Both the 15A and 15B scenarios allow long periods of positive emissions of order 1 to 2 GtC/year after 2150. This is because (1) in the MAGICC5.3 carbon cycle model, the CO<sub>2</sub> fertilization effect required to balance the present carbon budget (see ESM item 1) continues into the future providing a continuing terrestrial sink, and (2) the ocean sink also remains positive (declining slowly over time). These sinks together allow a balancing positive flux from fossil fuel emissions. These results differ from, e.g., Matthews and Caldeira (2008), who find that temperature stabilization at levels up to 4 °C require CO<sub>2</sub> emissions to drop to near zero. The reason for this difference is apparently because these authors do not consider (or underestimate) the effect of a continuing terrestrial sink from CO<sub>2</sub> fertilization. Further details are given in ESM item 1.



**Fig. 4** a CO<sub>2</sub> emissions scenarios (15A and 15B) consistent with the Paris Agreement 1.5 °C warming target (although not with the requirement that warming should always remain below this eventual warming amount). 15A is derived from the WRE350 and 450 scenarios, shown here as thin dashed lines. For 15B, a temperature pathway is specified and an inverse method used to derive the emissions. Panel **b** shows cumulative emissions from and including 2010, and **c** shows the corresponding CO<sub>2</sub> concentrations. Thin dashed lines are for the WRE250, 350, and 450 scenarios. WRE450 (top thin dashed curve in all panels) is the scenario that matches the 2 °C target

- (4) After about 2300, both 1.5 °C scenarios have very similar cumulative emissions, and both tend asymptotically to concentrations of about 400 ppm (close to the present value), implying little effect on ocean pH relative to today (a drop of about 0.05 pH units would occur for an increase to 450 ppm).
- (5) For temperature, all cases show initial overshoots above the appropriate 2 or 1.5 °C asymptote. Some level of overshoot appears unavoidable. Temperature overshoot is an extension of the tipping point idea. Instead of a tipping point beyond which there is no



**Fig. 5** a, b Global mean temperature and sea level projections for the two scenarios devised to be consistent with the 1.5 °C warming target (15A and 15B; bold dashed and full lines, respectively, in both panels). The thin dashed lines in both panels show results for the WRE250, 350, and 450 scenarios for comparison. WRE450 is the scenario that matches the 2 °C target

recovery, warming overshoot raises the question, for what overshoot magnitude and duration would areas impacted by climate change be able to recover?

- (6) Cumulative CO<sub>2</sub> emissions are a good indicator of maximum warming (e.g., Allen et al. (2009); Matthews et al. (2009); Zickfeld et al. (2009)), but the relationship breaks down for (at least) periods of negative emissions (Zickfeld et al. 2016). The results here confirm the maximum warming relationship, after which the relationship is more complex, even more so than shown in the idealized cases considered by Zickfeld et al. (2016), see ESM item 4. Cumulative emissions may therefore be a poor guide to long-term temperature change. The related concept of an allowable carbon budget (e.g., Meinshausen et al. (2009); Zickfeld et al. (2009)) would appear to be an oversimplification.
- (7) Sea level rise continues for many centuries and is still rising in 2400. For the 2 °C target, the rate of rise over 2200 to 2400 is about 21 cm/century. For the 1.5 °C target, it is similar, around 18 cm/century for 15A and around 19 cm/century for 15B, rates comparable to the twentieth century rate of rise.
- (8) A suggested minimum tipping point for the inevitable collapse of the West Antarctic Ice Sheet (cumulative emissions greater than 600 GtC from today; Winkelmann et al. (2015)) could be avoided for the 1.5 °C target (see Fig. 4b). A suggested tipping point for major Antarctic ice shelves (1.5 °C warming from today; Golledge et al. (2015)) would likely be avoided for the 2 °C case (see Fig. 5a).

The long periods of allowable positive emissions (1–2 GtC/year) extending at least to 2400 in all scenarios may seem counter-intuitive. This is a direct consequence of long time-scale processes in the carbon cycle, and the long time it takes for the terrestrial and oceanic parts of the carbon cycle to establish new equilibria. The terrestrial sink and anomalous atmosphere-to-ocean CO<sub>2</sub> flux both decline very slowly, so both remain significant sinks for many centuries, thus allowing anthropogenic emissions to remain positive (see ESM item 1).

## 6 Conclusions

The results here suggest that it is possible to meet the 2 °C Paris target without any period of negative CO<sub>2</sub> emissions. This agrees with previous analyses of the CCSP emissions scenarios (Wigley et al. 2009), but conflicts with a number of more recent suggestions. The present result depends on the assumed scenario for non-CO<sub>2</sub> emissions. If the MiniCAM model used in the CCSP Report is realistic, then the 2 °C target must be judged a goal that could be achieved without having to go into negative emissions territory.

Why does the present result differ from other analyses? To understand why will require further work, but there are two possible reasons. First, many of the analyses suggesting that negative emissions will be required to meet even the 2 °C Paris target employ an “ensemble of opportunity,” namely the database of recent emissions scenarios. Some of these scenarios either lead to or deliberately constrain the consequent temperature trajectories to monotonic pathways. The scenarios developed here all involve temperature overshoots, and it is a priori obvious that a temperature overshoot must allow less stringent emissions reductions (see, e.g., Sanderson et al. (2016)).

Second, some of the previous analyses rely on the relationship between cumulative CO<sub>2</sub> emissions and temperature change. For continuously increasing temperature, this close relationship is well demonstrated. For cases where temperature overshoots and/or stabilizes, the present results suggest that, in these circumstances, the relationship breaks down. Further work is required to elucidate this issue.

Regardless of the emissions scenarios derived here, a robust result is that sea level continues to rise for many centuries even after temperature stabilizes, at about 21 cm/century for the 2 °C target. Stabilizing sea level is a virtually impossible task. Even reducing atmospheric CO<sub>2</sub> concentration to 250 ppm, well below the pre-industrial level, still leaves sea level rising at about 4 cm/century after 2200.

A number of authors have stated that even the 2 °C target requires a period of negative emissions, which is contrary to the conclusions reached here. My results show that 2 °C can be achieved without requiring negative emissions, but almost certainly requiring a temperature overshoot. For the 1.5 °C target, the 15B emissions scenario devised here does require a period of negative CO<sub>2</sub> emissions, but never more than 1.3 GtC/year, well within the limits of achievability suggested by, e.g., Smith et al. (2016). On the other hand, although we clearly gain if we can achieve the 1.5 °C target relative to the 2 °C target in terms of a reduced probability of passing a crucial Antarctic tipping point, and reduced terrestrial impacts (see, e.g., Schleussner et al. (2016)), we gain very little in terms of the rate of sea level rise. In both cases, sea level rises at close to 20 cm/century over 2200 to 2400.

## 7 Amendments to the Paris Agreement

The scenarios derived here all have a temperature overshoot, and, as a result, they have less stringent emissions reductions than suggested by previous analyses. The likely need for temperature overshoot is not a new result (see, e.g., Ranger et al. (2012); Clarke et al. (2014); Schleussner et al. (2016); Sanderson et al. (2016)). Sanderson et al., for example, show that allowing a temperature overshoot (in their case, for a limited period of 50 years) allows substantially less onerous emissions reductions than otherwise: "... the 1.5° target is made significantly easier with a 50 year permitted overshoot."

As pointed out by Schleussner et al., a strict interpretation of the Agreement does not permit a temperature overshoot, neither inadvertently because of difficulties in meeting the emissions reduction requirements, nor as part of a deliberate policy. This is an extremely serious restriction, one that is not "in accordance with the best available science" (Article 4.1). Article 4.1 goes further and adds an emissions constraint (achieving a balance between greenhouse gas sources and sinks before 2100) that is inconsistent with Article 2.1 and which also fails to be "in accordance with the best available science."

To comply with the best available science, Article 2.1 needs to be amended to account for the possibility of temperature overshoot, and the unnecessary and unjustifiable emissions constraint in Article 4.1 should be removed.

Article 2.1, should read ... "This Agreement ... aims (at) ...(a) Holding the **eventual** increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the **eventual** temperature increase to 1.5°C ...." In Article 4.1, the following words should be deleted ... "so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century ...."

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