

We thank the editor and referees for their helpful reviews. Given that our revision addresses the Reviewers' concerns, it is disappointing that the paper must go out again for another round of independent reviews. New referees are likely to have their own perspectives, opening the possibility of still further iterations, a questionable state of affairs, considering that the science of our paper does not seem to be at issue.

Our response here follows the order of the issues described in:

**Editor's Decision: Reconsider after major revisions** (16 March 2017) by James Dyke

We agree that the increased length of the paper detracts from its readability. We note that the increased length resulted from a very long list of requested explanations and clarifications by the referees of our original paper (ESDD version, published on 4 October 2016). The best approach now is probably, as suggested by the Editor, to move less essential material to the Appendix or Supplementary Material. Supplementary Material is less convenient to readers, and thus not opened by most readers, so we have chosen to use the Appendix, but it would not be difficult to instead put some of the Appendix into Supplementary Material, if the Editor so instructs us.

**Reviewer #2 Major Comments**

**(1) Paring down, distilling the main message**

Reviewer #2 suggests that our criteria for the dangerous level of warming or CO<sub>2</sub> could be made clearer. An outline of our message follows:

- (a) T (global temperature) provides the fundamental constraint; we use Holocene T and Eemian T as guides to help define the allowable T.
- (b) We show that current T has already reached Eemian T and is far above the Holocene T range.
- (c) CO<sub>2</sub> is the principal forcing that affects T, and because fossil fuel CO<sub>2</sub> remains in the climate system for millennia (a period exceeding the expected response time of ice sheets) CO<sub>2</sub> is the crucial climate forcing whose amount needs to be constrained if eventual large changes of ice sheet volume are to be avoided.
- (d) Other climate forcings alter the safe range for CO<sub>2</sub>, but the potential for reducing these other forcings to permit larger CO<sub>2</sub> concentrations is very limited.
- (e) As a result, the burden on future generations (to somehow extract atmospheric CO<sub>2</sub>) will be very high unless fossil fuel emissions are reduced rapidly.

As Reviewer #2 concludes at the end of his point f), the Abstract was already close to this outline, so only moderate change of the Abstract is required. In rewording the Abstract, space limitation prevents us from explicitly going into the trade-off between CO<sub>2</sub> and other forcings. However, we have edited the Introduction to make these points clearer.

**(2 and 3) Cut tangential material**

Co-authors have reviewed the manuscript with the specific objective of finding material that can be pared and/or moved to the Appendix. This has improved the readability beyond the

proportion of shortening, because the material removed from the main text is less central to the main theme.

We have followed Reviewer #2's suggestion, making the Introduction and Discussion sections clearer statements of the distilled main message, as summarized under (1) above, while avoiding an increase in the length of the Abstract.

### **The two other general concerns of Referee #2**

**(1) Are we using an Eemian-based limit or a Holocene-based limit?** We use both, and we now state this more explicitly. Eemian temperature is clearly too high for a long-term target, given the high likelihood that it would lead to multi-meter sea level rise. The appropriate initial target, for the sake of keeping shorelines close to where they have been for the past several millennia, is within or close to the Holocene range. We do not need to define the target more precisely than that, because we show that global temperature has already risen far above the Holocene range and it will take time to get the temperature moving downward. This is the same reason that the target for CO<sub>2</sub> ("less than 350 ppm") does not need to be more precise yet.

Why do we need both Eemian and Holocene comparisons? Could we just say that an appropriate target is to stay in or close to the Holocene range? Perhaps, but the Eemian (which is not much warmer than the Holocene maximum) reveals how substantial the consequences could be with only a moderate overshoot of the target. Because Eemian temperature was only approximately +1°C it reveals that the long-range target for global temperature must indeed be very close to preindustrial Holocene temperature.

(2) His/her second concern relates to whether sea level change should be framed as a feedback. Paleoclimate studies show that the two large slow global climate feedbacks (changes in response to global temperature change, which amplify or diminish that global temperature change) are changes of long-lived GHG (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) amount and changes of ice sheet size. We did not intend to leave an impression that sea level change was the feed, but in tightening up the slow feedback section (we agree that it was too long), we have made clear that the GHGs and ice sheet size are the principal slow feedbacks.

### **Reviewer #2 and Editor's comment re carbon fee**

Reviewer #2 suggests cutting lines 1227-1237 and 1246-1249. The editor notes that discussion of a carbon fee is within the scope of the journal, but would need to appropriately framed within the rest of the manuscript and occupy commensurate space.

Given the additional time and space that would be required to develop such a section, and the possibility that reviewers might continue to object to it, we decided to basically follow Reviewer #2's suggestion and remove that material. We still have one sentence following the historical examples of fast emission reductions, simply noting that those examples were not aided by a carbon fee or tax. The conclusion (that rapid emission reduction is conceivable) is strengthened by this notation.

### **Reviewer #3 Major Comments**

**L127:** Reviewer #3 notes that it would be interesting to compare our model's TCRE (Transient Climate Response to Cumulative CO<sub>2</sub> Emissions) to that of other models. We have now done so, calculating TCRE(t) as specified in Section 10.8.4 of IPCC (2013), specifically  $TCRE(t) = TCR(t) \times CAF(t)/C_0$ , where  $C_0$  = preindustrial atmospheric CO<sub>2</sub> mass = 590 PgC and  $CAF(t) = Catm(t)/Csum(t)$ ,  $Catm(t)$  = atmospheric CO<sub>2</sub> mass at time t minus  $C_0$  and  $Csum(t)$  = cumulative CO<sub>2</sub> emissions at time t.

These calculations yield TCRE = 1.67°C per 1000 PgC at time t = 2100 with constant emissions (which yields cumulative emissions of 1180 PgC at 2100, which is almost precisely the midpoint of the range assessed by IPCC, i.e., 0.8°C to 2.5°C per 1000 PgC (IPCC, 2013). To avoid making the paper more technical and longer, we have added one sentence in the text and defined the calculations briefly in Appendix A2.

**L150-154:** Reviewer #3 suggests that we cite the final Paris Agreement rather than the draft. Yes, that is now possible, so we have done so, and we thank the reviewer for pointing this out.

**L432-440:** Reviewer #3 suggests that we compare our estimates of observed warming with IPCC AR5 WGI estimates. We have added that comparison, which is a useful clarification.

**L508:** Reviewer #3 is right that it is possible to be more precise in comparing the PETM, a doubling of CO<sub>2</sub>, and burning all fossil fuels. We previously (Hansen et al. 2013b paper in Proc. Roy Soc.) estimated that fossil fuel reserves + resources amount to ~15,000 GtC (which is almost the same as the 15,600 GtC upper limit estimated in the AR5-WG1 report. The PETM release is usually estimated as ~5,000 GtC (though outlier studies estimate closer to 10,000 GtC), which is much greater than known reserves (~1900 GtC) but about 1/3 of all reserves + resources. Without going into all this detail, we have restated the comparisons better.

**L535-538:** Reviewer #3 asks for a clarification of the experimental results of Crowther et al. (2016) for soil carbon release with soil warming. We have expanded that sentence to achieve that clarification.

**L583-584:** Reviewer #3 suggests that it may be useful to clarify that oxidation of CH<sub>4</sub> is the atmospheric sink, which we have now done.

**L634:** Reviewer #3 is correct, the reference should be Hansen et al. (2000), not Hansen and Sato (2004). We have made that correction.

**Figure 10:** Reviewer #3 asks what airborne fraction is assumed in arriving at the scale for the right hand axis. Actually, the ppm on the right scale is just the emissions in another unit (1 ppm is ~2.12 GtC); we have clarified that in the Figure 10 caption.

**L786:** Reviewer #3 notes that atmospheric aerosols seem likely to decrease in the future as fossil fuel use declines. Although we assess the probability of this differently than Rao et al. (2017), it is a good point that only strengthens our argument that it will be difficult to obtain a decrease of the net non-CO<sub>2</sub> anthropogenic climate forcing. We also thank the Reviewer for the Rao et al (2017) reference, which we now incorporate in the first paragraph of Section 10.2.

**L917:** Reviewer #3 notes that burning of biofuels at power plants is only one option for BECCS. We have reworded the sentence to clarify that.

**L975:** Reviewer #3 notes that costs of CO<sub>2</sub> extraction might decline in the future, and it would be helpful to discuss the potential for falling costs. We agree that it is conceivable that costs might decline below the range estimated by current experts, but given the energy requirements for CO<sub>2</sub> removal there is reason to believe that the cost will remain substantial. However, we have added a caveat sentence about possible cost reduction.

**Figure 14:** Reviewer #3 asks that we clarify the energy accounting method used to compare fossil fuel and renewable energy amounts. We are uncertain what is meant by that, unless perhaps it refers to the difference between “nameplate” (maximum potential) renewable energy as opposed to the energy actually produced. The Boden et al. and BP energies refer to total energy produced. BP likes to add the adjective “primary” (primary energy consumption), so we have added that for possible clarification.

**Figure 15:** Reviewer #3 is correct that the RCP scenarios do not include natural sources and feedbacks. We now note this in the figure caption and add a brief comment at the end of the relevant paragraph, which is now the second paragraph in Appendix A14.

**L1100-1103:** Reviewer #3 notes that references are needed here. The principal appropriate reference is perhaps Prather et al. (2013), which is Annex II to IPCC (2013). However, this paragraph was removed in distilling the paper.

**L1120:** Reviewer #3 notes that a reference is needed. An appropriate reference is to tables in the same Annex II to IPCC (2013) that we noted just above. Note that these paragraphs, which were in the main paper, are now in the Appendix.

**L1136:** Reviewer #3 asks if it is possible to provide a range for the aerosol negative forcing of the order of 1 W/m<sup>2</sup>. “Of the order of” was meant to imply only order of magnitude knowledge, but in fact we can provide a good reference, Boucher et al., the aerosol and cloud chapter of AR5, specifically Figure 7.19 is a good summary.

Note that the large uncertainty in the aerosol forcing, and in the history of the anthropogenic aerosol forcing, is not quite as damning for projections of the future as it may appear at first glance. We have good knowledge of the present planetary energy imbalance, so the issue is primarily how the aerosol forcing will change from its present value going forward.

**L1238-1240:** Reviewer #3 notes that the policies that led several countries to rapidly reduce CO<sub>2</sub> emissions were not adopted with that objective, but rather for the objective of energy independence from oil. We agree that the earlier period is not a perfect analogue, and have now so noted, but the present situation actually has even more comprehensive incentives.

**L1295:** Reviewer #3 suggests that we may want to update Fig. A1 with data from Le Quere et al. (2016). We do update that figure (and others) using data of BP, which allows our graphs to go one year further than Le Quere et al. (2016), but we also note now that the data we use are in good agreement with Le Quere et al. (2016) for the prior years. The BP data are preliminary for

the most recent year (2016), but our experience from prior years is that the adjustments of final data have been small.

### **Reviewer #1 Minor Comments**

**L490-492:** Part of the text is missing. Yes, we apologize for that typographical error, which has been corrected.

**L768-769:** Role of Montreal Protocol could be made clearer, i.e., that it does not explicitly address emissions but rather production of certain substances. That is true, and we have reworded the description accordingly.

**L1055:** Referee #1 correctly points out that gases other than CH<sub>4</sub> and CO<sub>2</sub> in recent years have together been providing as much forcing as CH<sub>4</sub>. That is true, but our sentence here refers to the surge in the growth rate of GHG climate forcing. As Figure 9 shows, the increase in the growth rate of GHG climate forcing in the past decade is due to increased growth rates of CO<sub>2</sub> and CH<sub>4</sub>. The picture (Figure 9) is probably worth more than our words, but we do try to make clear also the potential merit of slowing or stopping the growth of these other GHGs.

**L1117:** Yes, thank you we have added “stratospheric” before ozone for clarity. (This paragraph is now in the Appendix).

**L114:** Comma added.

**L252:** Comma added

**L256:** for clarification, parentheses have been imbedded

**L265:** missing degree symbol corrected

**L322:** “is” → “are” correction is made

**L410:** “unknown unknowns” is useful terminology, but perhaps it is an Americanism popularized by a perhaps unpopular Secretary of Defense. Simple unknowns are those factors that we know about, but have not quantified well enough. Unknown unknowns are additional uncertainties, which we are not presently aware of. However, we will change it, if the editor thinks it is advisable to do so.

**L595:** Comma added (this subsection is now in the Appendix)

**L778:** Comma added (this reference is now in the Appendix)

### **Reviewer #2 Minor Comments**

**L133:** We have added “magnitude and” for clarity, as suggested.

**L193:** Observed global temperature data are now several months further advanced, so that phrase no longer appears in the description of the data.

**L270-277:** The suggestion is that we could move this paragraph to the section on feedbacks. Because the sensitivity of sea level to temperature change is so crucial to our rationale, including our choice of the dangerous level of warming, we feel that it is better to have this brief paragraph near the beginning of the paper.

**L282-284:** Reviewer #2 notes that the empirical temperature data for the past century (Fig. A2a), which we use to compare the magnitude of warming over land and ocean, refers to a transient case in which the ocean has had insufficient time to reach its equilibrium response. However, the land also has not had time to reach its equilibrium response, because, to a substantial degree, the land responds to the ocean temperature (more so than to the direct radiative forcing).

To help quantify the equilibrium ocean and land responses, we have calculated the ocean and land warmings in years 901-1000 (close to equilibrium response) of the GISS ModelE-R for both the coarse resolution version of the model used in our “Ice Melt” paper (Hansen et al., 2016) and the fine resolution used for CMIP5 model comparisons. The ratio of land/ocean warming is 1.75 and 1.82 for these two cases, so indeed it is less than a factor of two, but not enough to qualitatively alter the conclusions. Using 1.8 for the ratio SAT(land)/SST yields 1.24 as the factor by which global temperature change exceeds SST change, as compared to the factor 1.3 obtained from observed temperature change of the past century. To avoid making the text longer, we make a brief statement in the paper and give the model results in Appendix A6.

**L303:** Reviewer #2 asks what (global) temperature would correspond to 350 ppm.

The choice of 350 ppm as an initial target for CO<sub>2</sub> amount is based mainly on the fact that (if the net of all other forcing changes is zero) reduction of CO<sub>2</sub> to this amount would restore Earth’s energy balance. Thus to first order we might expect global temperature to stabilize at about the present (smoothed) value (about +1°C relative to the 1880-1920 mean).\* The complete story is not so simple, for example, slow feedbacks may not yet be in equilibrium, but it seems useful to give this approximate correspondence. The best place for this seems to be earlier in the paper: we have added a statement near the end of the second paragraph of the Introduction.

\*It also happens that, if climate sensitivity is 3/4°C per W/m<sup>2</sup> (3°C for doubled CO<sub>2</sub>), the change from preindustrial CO<sub>2</sub> (278 ppm) to 350 ppm yields +1°C. This way of reaching ~1°C requires the assumption that the net of non-CO<sub>2</sub> forcings is small. Although that assumption happens to be true for current estimates of the non-CO<sub>2</sub> forcings, the uncertainty in aerosol forcing is so large as to make this approach less meaningful.

**L346:** Reviewer #2 suggests rewording this sentence to remove possible confusion about the roles of climate forcing and planetary energy imbalance. We have reworded the first two sentences to accomplish that objective, while using fewer words.

**L476-478:** Reviewer #2 questions the interpretation of the CO<sub>2</sub>/sea level relationship in paleoclimate data and notes that it is not central to our arguments. Given that modern forcings other than CO<sub>2</sub> are not negligible, we are instead relying on the relationship between sea level

and global temperature. So we agree that reference to and discussion of the Foster and Rohling paper can be cut, so we have done so in the interests of limiting paper length.

**Line 491:** Yes, there was a typographical error upon inserting a late change to that sentence, which has now been corrected.

**Line 634:** Yes, the correct reference is to Hansen et al. (2000). Thanks for catching that!

**Lines 643-658:** Reviewer #2 suggests that these two paragraphs are tangential. We have removed them.

**Lines 698-700:** BP reference has been added. (This topic has been moved to Appendix A9).

**Figure 9:** Reviewer #2 notes that Fe, MPTGs and OTGs are not defined. They are defined earlier in the text and in the caption of Figure 4, so we now add direction to the latter caption in Fig. 9.

**Equation 1:** Reviewer #2 (thankfully) continues to badger us about this equation. Programming of the two terms was correct, but the representation in equation (1) was not.

The first term is the contribution of the forcing increment of each preceding year multiplied by the appropriate portion of the equilibrium response,  $R(t - t')$ , with integration up to time  $t$ .

The second term is an approximation of the small warming due to recovery from volcanoes that occurred prior to 1850. Those unknown volcanoes are approximated as a constant forcing of  $-0.3 \text{ W/m}^2$ . Resulting warming increases in proportion to  $R(t - 1850)$ . This second term is not a constant, it grows in time. At  $t = \text{infinity}$ , the second term is  $0.3 \text{ W/m}^2 \times 0.75^\circ\text{C per W/m}^2 = 0.225^\circ\text{C}$ . This warming is countered by volcanic cooling of identified volcanoes in the period 1850-present, so that on average volcanoes do not cause a long term warming or cooling.

**L761:** We have incorporated the footnote into the text, as suggested.

**L765-782:** Reviewer #2 suggests that these three paragraphs are tangential and can be removed, thus improving clarity. We largely adopt his suggestion. We need to retain the final sentence of the 3<sup>rd</sup> paragraph to define our simulations, so we add this sentence to the end of the paragraph that preceded these three paragraphs. We also retain the first of the three paragraphs, but we move it to the appendix on non-CO<sub>2</sub> GHGs, using it as the introductory paragraph.

**L881-888:** Reviewer #2 says this paragraph is an example of an unnecessary digression. Because of the importance to our climate stabilization scenario of the CO<sub>2</sub> drawdown from “improved agricultural and forestry practices” we would like to keep this clarification about what we mean. It is set off at the end of a section as a “comment”.

**L959-961:** Reviewer #2 suggests that this sentence could be omitted. There may be some confusion here. This sentence does not refer to the “alternative scenario,” for which, as mentioned above, we decided to drop the discussion (L643-658). Instead the sentence here refers to the 6%/year emission reduction scenario defined in the 2013 Plos One paper that served as the scientific basis for Alec L versus United States lawsuit filed in 2012, which was finally lost by Alec L in the United States DC District Court (the court just below the Supreme Court from which Supreme Court justices are commonly selected). That case was lost largely because

a sufficient Constitutional basis for the claims was not demonstrated, and the Alec L decision is now cited by the U.S. government as a reason to dismiss the new case (Juliana et al versus United States). The important point is that while in 2012 it only required extraction of 100 GtC from the air to get back to 350 ppm CO<sub>2</sub> by 2100, an amount that seemed feasible with reasonably natural improvements in agricultural and forestry practices including extensive reforestation, continued high emissions qualitatively change the prospects. This is a fairly important conclusion of the paper, which helps illustrate how young people are being impacted by continuing high emissions, and it only requires one sentence here.

**L962-965:** Reviewer #2 suggests that we can save some sentences here, as there is some repetition from an earlier part. We agree and have made this change.

**L962-970:** Reviewer #2 suggests that these details should have been given in the earlier section where extraction scenarios were first defined. Now that we have minimized the size of this paragraph by omitting the first three sentences (see comment above), and considering that what remains relates to the cost discussion to follow immediately, it seems better to keep the remaining sentences here.

**L971:** Reviewer #2 feels that this statement is confusing. We agree that it can be stated more clearly. We have revised this along the lines suggested by Reviewer #2.

**L1048:** misspelling corrected.

### **Reviewer #3 Minor Comments**

**L56:** Thanks – typo corrected.

**L85:** Reviewer #3 suggests that we should clarify whether we refer to annual or cumulative emissions from China. We have fixed that in the course of shortening the paragraph.

**L111-112:** Yes, we used a less appropriate reference – we have switched to the one suggested.

**L135:** CMIP acronym spelled out; as noted, we don't need the integrated assessment reference

**L189:** We added an indication of the super El Niños in the figure.

**L200-201:** We added reference to the Huber and Knutti paper.

**L490-492:** Garbled statement has been fixed.

**L654:** That line was eliminated in cutting of tangential material.

**L675:** Negative growth now defined parenthetically.

**L769:** “annually” has been inserted before “added”

**L852:** We added the terminology “carbon dioxide removal (CDR)”

**L932:** These sentences were eliminated in removing tangential discussion.



**L1048:** spelling corrected

**L1065:** Agreed, it was not clear – we have simplified the sentence

**L1096:** Word “to” added for clarity.

**L1100:** This paragraph was removed in distilling the paper.

**L1142:** We added the specific terminology “solar radiation management (SRM)”

**L1201:** Good point – we don’t mean to downplay the implications of 0.5-1 meter sea level rise, so we changed “consequences” to “dire consequences”

**L1252-1253:** We have expanded the sentence to expand on the potential for developed countries to contribute to a slowdown of climate forcing growth.

**L1277:** We have expanded that sentence to clarify extraction and reduction requirements.