Response to Reviewers

"Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions" (Manuscript Number: esd-2014-26)

The authors would like to thank the referees for their careful and thorough review of our manuscript entitled "Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions", and for the comments and suggestions they provided to us in order to improve the manuscript. The following responses will follow a point-by-point style, and have been designed to address each of the referees' comments in order. Please note that page numbers refer to the revised version of the manuscript.

Response to Referee 1, David Archer:

General Comments

Comment: *"The carbon cycle responses are very interesting, but of course they are subject to uncertainties which could be pointed out more clearly. The glacial/interglacial pCO_2 cycle is a demonstration of something like this. Land uptake models are on difficult ground trying to predict the CO_2 fertilization effect, is my understanding, with widely diverging predictions from different models. This could be stated more clearly in the paper".*

Response: We agree that the land carbon uptake uncertainties could be stated more clearly. We have included references to recent model intercomparison studies showing the large spread in model responses and included a paragraph discussing the effects of including a coupled carbon-nitrogen cycle in the UVic model.

We have added the following text to the manuscript:

p. 14: **"**The land carbon cycle response to warming and elevated atmospheric CO_2 levels differs widely among models (Friedlingstein et al. 2006; Arora et al. 2013; Zickfeld et al. 2013)."

p. 15: "Another source of uncertainty in land carbon uptake is the coupling between the carbon and the nitrogen cycle. The land carbon cycle component of the UVic ESCM, like most land carbon cycle models, does not include a representation of the nitrogen cycle. In models that include coupled carbon and nitrogen cycles, the CO_2 fertilization effect under future CO_2 levels is reduced, since enhanced plant growth increases its need for mineralized nitrogen, and associated increases in litter inputs to the soil carbon pool can increase microbial demand for nitrogen (meaning there would be less available for plant use) (Thornton et al. 2007). This may suggest that the UVic ESCM could be overestimating the effects of CO_2 fertilization on land carbon uptake. Though plant and microbial nitrogen demand may increase in a warmer climate, the availability of usable nitrogen may also increase in a warmer climate (Rustad et al. 2001), which would reduce the negative effect that nitrogen limitation exerts on CO_2 fertilization."

Comment: *"In particular I wonder about frozen carbon in the Arctic; it doesn't seem to be represented in the model. It would be useful to note how much carbon is predicted to emerge from this source, and how that scales with the parts of the carbon cycle you are predicting."*

Response: True, the version of the UVic ESCM utilized in this study does not include permafrost carbon. We have included estimates of carbon released from permafrost in the future and included a discussion of the potential effect of considering permafrost carbon on our findings:

p. 10: "The version of the UVic ESCM used for this study does not include a permafrost carbon model. Consideration of permafrost carbon would affect the magnitude of warming and could potentially affect the linear relationship between warming and cumulative carbon emissions. As the permafrost thaw depth would increase with warming, it would expose more carbon to decomposition, driving further carbon release – a process known as permafrost carbon feedback (MacDougall et al. 2012). This feedback could affect the airborne fraction and hence the approximate constancy of the TCRE. McDougall (2014) shows that inclusion of the permafrost carbon feedback enhances the sensitivity of the TCRE to the rate of CO_2 emissions, with the TCRE declining more strongly with increasing rate of emissions. Overall, however, the permafrost carbon feedback does not appear to compromise the approximately linear relationship between global warming and cumulative carbon emissions (McDougall, 2014)."

p. 14: "The exclusion of permafrost carbon from this study could potentially affect land carbon uptake in a future climate. MacDougall et al. (2012) utilized a modified version of the UVic ESCM with a coupled permafrost carbon model and found that permafrost soils could release between 68 GtC and 508 GtC by 2100 under the RCP 2.6 – RCP 8.5 scenarios - on the same order of magnitude as the global land carbon uptake values found in this study. The addition of permafrost carbon could turn large portions of the high latitude regions into net sources of carbon (MacDougall et al., 2012), and the added warming, in addition to fueling further carbon release from permafrost regions through feedback loops, could exacerbate the declines in land carbon exhibited by tropical regions in this study. "

Response to Referee 2:

<u>**General Comments**</u>

Comment: *"The authors have already done a great job in citing and framing their results. However this connection could be even better. For instance, while the authors cite many studies which suggest that global temperature remains approximately constant for centuries to millennia after CO_2 emissions cease, there is also a recent study which indicates this should not necessarily be the case (Frölicher et al, 2014). It would be good to cite this study, and discuss possible implications. This is related to the other connection which I would like to see being more elaborated. While the text already mentions the study by Krasting et al (2014), and highlights that they find different results, it would [be] really helpful to discuss why the authors think this is the case. It appears that both studies cited above use a much more detailed ocean representation. A few lines which discuss this would be welcome."*

Response: **We included a brief discussion of the Frölicher et al (2014) paper:**

p. 7: "A study by Frölicher et al. (2014) tested an instantaneous pulse scenario with cumulative carbon emissions of 1800 GtC and found that surface air temperature increases for several centuries after an initial decrease following emission cessation. They suggest that this is due to the warming associated with a decrease in ocean heat uptake together with feedback effects arising in response to the geographic structure of ocean heat uptake overcompensating the cooling associated with a decline in radiative forcing."

The implications of the results of Frölicher et al. for our study are not immediately clear. However, Krasting et al (2014), using the same model as Frölicher et al. (GFDL EMS2), find an approximately linear relationship between global mean temperature and cumulative emissions, suggesting that the GFDL model response is not fundamentally different from that of the UVic ESCM used in our study.

We agree that the differences compared to the study by Krasting et al. (2014) should be discussed in more detail. It is true that the models used by Frölicher et al (2014) and Krasting et al. (2014) have a more detailed ocean model than the UVic ESCM. That being said, however, Lowe et al (2009), Frölicher and Joos (2010), and Zickfeld et al (2012) also used more complex models, but similarly to our study, they find that global temperature remains

approximately constant for centuries after CO_2 emissions cease, so the disagreement may not simply be due to reduced model complexity. Rather, we suggest that the differences are due different representations of ocean mixing, and different equilibrium climate sensitivities.

p. 10: "In a study with the GFDL model using scenarios with a range of linear emission increase rates, Krasting et al. (2014) found the TCRE to increase with increasing emission rates (for emission rates of 5-25 GtC yr^{-1}), which is the opposite tendency from that found in this study. The TCRE is determined by the effect of the CO_2 emission rate on carbon and ocean heat uptake (Krasting et al, 2014): a higher CO_2 emission rate results in a larger airborne fraction and hence higher atmospheric CO_2 levels and radiative forcing. On the other hand, the climate system is less equilibrated with the radiative forcing, such that a lower fraction of the equilibrium warming is realized compared to scenarios with slower emission rates. Whether the TCRE increases or decrease with higher emission rates depends on the balance between these two processes. Ocean heat and carbon uptake are determined by ocean mixing, and the equilibration timescale is a function of equilibrium climate sensitivity, quantities that differ widely among models. It is therefore conceivable that such differences cause the opposite dependence of TCRE on emission rate in our study compared to that of Krasting et al. (2014)."

Comment: *"It is a pity that the lowest cumulative emission budget used in this study already brings temperatures to above 2^oC relative to preindustrial levels. If computation time permits, I would therefore be strongly in favor of adding a case with, for example, 775 GtC cumulative emissions."*

Response: We don't expect the addition of simulations with 775 GtC cumulative emissions to provide new insight. The cumulative emission groups were chosen to reflect a wide range of cumulative carbon emissions, especially those which had not thoroughly been explored in the literature (cumulative emissions >2500 GtC). Previous studies by Matthews et al. (2009), Zickfeld et al. (2009), Zickfeld et al. (2012), Gillett et al. (2013) and Nohara et al. (2013) all explored scenarios with cumulative emissions up to 2500 GtC, and all found evidence of an approximately linear relationship between global warming and cumulative emissions. In our study, the surface air temperature (SAT) vs. cumulative emissions (CE) relationship is quite linear for CE < 1500 GtC (Figure 8). Also, the long term temperature response in the UVic ESCM is independent of emission pathway for CE < 1000 GtC (Zickfeld et al. 2009). Thus, we do not expect to gain any significant new insights by adding simulations with cumulative emissions of 775 GtC.

Specific Comment

Comment: *"Page 755, line 7: I'm puzzled by the statement 'the finding of path independence of thermosteric sea level rise over century timescales is similar to the findings of other studies' with a reference to Bouttes et al. (2013). The abstract of that paper reads: 'Whereas surface temperature depends on cumulative CO_2 emissions, sea level rise, due to thermal expansion depends on the time profile of emissions'. To me this reads like sea-level rise is actually dependent on the path that is followed. Please clarify. "*

Response: Agreed. We have amended the paragraph to read:

p. 7: "The finding of path dependence of thermosteric sea level rise on century timescales is similar to the finding of Zickfeld et al. (2012) and Bouttes et al. (2013) and results from the proportionality of thermosteric sea level rise to the time integrated radiative forcing on those timescales (Bouttes et al. 2013). Convergence of the sea level response at the end of the 1200-year long simulation for all cumulative emission groups, however, indicates that on longer timescales sea level rise is determined primarily by cumulative emissions."

In addition to the changes implemented in response to reviewers comments we have:

- Ammended the title to read "Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions" to highlight the finding that climate and carbon cycle response after cessation of emissions to be approximately independent of emission pathway for all cumulative emission levels considered.

- Clarified that CO_2 emissions from land use change are both generated internally from imposed land-cover changes and externally prescribed to the UVic ESCM:

  p. 4: The model was also forced with historical land-cover changes. Since CO_2 emissions from land-use change (LUC) generated by the UVic ESCM are small, these emissions were complemented by externally prescribed LUC emissions to match the observations-based estimate of Houghton (2008).

  "The emission scenarios include a cumulative 1000–5000 GtC of fossil fuel emissions as well as a cumulative 275 GtC of externally prescribed LUC emissions. Prescribed LUC emissions follow the historical LUC emissions to 2008 and then decline linearly, reaching zero by 2100. In addition, the emission scenarios include ~50 GtC of internally calculated LUC emissions from imposed land use changes. Note that scenarios are labeled according to the total externally prescribed fossil fuel and LUC emissions (1275 GtC, 2275 GtC, 3275 GtC, 4275 GtC, and 5275 GtC)."

References:

1. Arora VK, Boer GJ, Friedlingstein P, Eby M, Jones CD, Christian JR, Bonan G, Bopp L, Brovkin V, Cadule P, Hajima T, Ilyina T, Lindsay K, Tjiputra JF, Wu T (2013). Carbon-Concentration and Carbon-Climate Feedbacks in CMIP5 Earth System Models. J. Clim. 26: 5289-5314.

2. Bouttes N, Gregory JM, Lowe JA (2013) The Reversibility of Sea Level Rise. J.Clim. 26: 2502-2513.

3. Gillett NP, Arora VK, Matthews HD, Allen MR (2013) Constraining the ratio of global warming to cumulative CO2 emissions using CMIP5 simulations. J. Clim. 26:6844-6858.

4. Friedlingstein P, Cox P, Betts R, Bopp L, Von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I (2006) Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. J.Clim. 19: 3337-3353.

5. Frölicher T, Joos F (2010) Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with a comprehensive climate-carbon model. Clim. Dyn. 35:1439-1459.

6. Lowe JA, Huntingford C, Raper SCB, Jones CD, Liddicoat SK, Gohar LK (2009) How difficult is it to recover from dangerous levels of global warming? Environ. Res. Lett. 4:014012.

7. MacDougall AH, Avis CA, Weaver AJ (2012) Significant contribution to climate warming from the permafrost carbon feedback. Nature Geoscience 5: 719-721.

8. MacDougall AH (2014), A modelling study of the permafrost carbon cycle feedback to climate change: feedback strength, timing, and carbon cycle consequences, PhD thesis, University of Victoria, BC, Canada, 118 p.

9. Matthews HD, Gillett NP, Stott PA, Zickfeld K (2009) The proportionality of global warming to cumulative carbon emissions. Nature 459: 829-832.

10. Nohara D, Yoshida Y, Misumi K, Ohba M (2013) Dependency of climate change and carbon cycle on CO2 emission pathways. Environmental Research Letters 8: 014047.

11. Rustad L, Campbell J, Marion G, Norby R, Mitchell M, Hartley A, Cornelissen J, Gurevitch J (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia 126: 543-562.

12. Thornton PE, Lamarque J, Rosenbloom NA, Mahowald NM (2007) Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability. Global Biogeochem.Cycles 21: GB4018.

13. Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009, Setting cumulative emissions targets to reduce the risk of dangerous climate change, Proceedings of the National Academy of Science, 106(38): 16129-16134.

14. Zickfeld K, Arora VK, Gillett NP (2012) Is the climate response to CO2 emissions path dependent? Geophys.Res.Lett. 39: L05703.