Response to Referee Comments on the Manuscript

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

Dear Editor:

The authors would like to thank the referees for their careful and thorough review of our manuscript entitled "Path dependence 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.

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.

One 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.

In addition, even between dynamic global vegetation models without a nitrogen cycle, the land carbon cycle responses to warming and elevated levels of CO_2 differ widely. Friedlingstein et al. (2006) note that in the Coupled Model Intercomparison Project 4 (C^4MIP) study, the year 2100 cumulative global land carbon responses to the Special Report on Emissions Scenario (SRES) A2 scenarios ranged from ~100 GtC to nearly 1100 GtC. The cumulative land uptake in the UVic ESCM was ~700 GtC – approximately in the middle of the range. Similarly, land carbon responses from the Coupled Model Intercomparison Project 5 (CMIP5) also showed large variations. Arora et al. (2013) note that under a 1% CO_2 increase experiment, the cumulative land uptake at year 140 (the time of quadrupling of the pre-industrial CO_2 concentration) in the CMIP5 models ranged from ~150 GtC to ~800 GtC. The year 2100 uptake by the land in the UVic ESCM is approximately in the middle of the range, at about 500 GtC.

We will add a discussion of land carbon cycle uncertainties with reference to the C^4MIP and CMIP5 intercomparison projects, and indicate where the UVic model is situated in the range of model responses.

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. 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 (rather than regions of net carbon uptake as they are in this study) (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.

Release of carbon emissions from permafrost could be a self-sustaining process, as the permafrost thaw depth would increase with warming, thereby exposing more carbon to decomposition, driving further carbon release – a process known as permafrost carbon feedback (MacDougall et al. 2012). By releasing large amounts of carbon into the atmosphere, this feedback could potentially affect the linear relationship between surface air

temperature and cumulative carbon emissions. McDougall (2014) shows that that consideration 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).

We will add a paragraph outlining the potential effects of permafrost carbon on our findings.

Response to Referee 2:

General Comments

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: It is true that the Frölicher et al (2014) and Krasting et al (2014) models 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 similar to our study, they also find that global temperature remains approximately constant for centuries after CO_2 emissions cease, so the disagreement may not simply be due to limitations caused by a less detailed ocean model.

Frölicher et al (2014) test an instantaneous pulse scenario with cumulative carbon emissions of 1800 GtC, and find that surface air temperature increases for several centuries after an initial decrease following emission cessation. They note 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.

In our simulations, surface air temperature decreases following emission cessation for cumulative emissions in the range 1275-2275 GtC and increases for cumulative emissions of 4275-5275 GtC. The reason is that for larger cumulative emissions the system takes longer to equilibrate with the radiative forcing, i.e. the decline in ocean heat uptake is smaller, leading to larger warming.

The implications of the results of Frölicher et al. for our study are not immediately clear. Krasting et al (2014), however, 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.

One discrepancy between the two models regards the dependence of the Transient Climate Response to carbon Emissions (TCRE) on the rate of CO_2 emissions. Krasting et al. find that the TCRE increases with increasing emission rates, for emission rates of 5 to 25 GtC/yr. In contrast, the TCRE decreases with increasing emission rates in our study. The sensitivity of the TCRE to the emission rate is determined by the subtle balance between atmospheric CO_2 levels (and hence radiative forcing) and ocean heat uptake (Krasting et al, 2014). These two processes differ largely between models, and it is conceivable that this difference causes the opposite dependence of TCRE on emission rate.

We will include a reference to Frölicher et al (2014) and strengthen the discussion of the difference between our results and those of Krasting et al.

Comment: “It is a pity that the lowest cumulative emission budget used on this study already brings temperatures to above 2^{o}C 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 would 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 will amend this. Our study finds that the year 3000 sea level rise is approximately independent of emission pathway. Convergence of the sea level response for simulations with different emission rates takes much longer than for air temperature – owing to the ocean's slow response timescale. The decadal to century timescale response therefore varies with emission pathway – with the largest increases for emission pathways with the highest emission rates – a finding qualitatively similar to Bouttes et al. (2013).

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