1 General Comments

This paper makes an important claim: the climate's sensitivity to combined CO_2 and land-ice sheet forcing ($S_{[CO2,LI]}$) appears to have been significantly larger during the warm phases of the Pleistocene than the cold phases. This claim runs counter to a recent Nature paper, "Plio-Pleistocene climate sensitivity evaluated using high-resolution CO2 records", Martínez-Botí et al. 2015, which claimed that $S_{[CO2,LI]}$ remained unchanged between the Pleistocene and the still warmer Pliocene. The present work claims that previous studies, such as Martínez-Botí et al., missed an important non-linearity by assuming that changes to sea-level recorded in $\delta^{18}O$ proxies were proportional to changes in land-ice induced radiative forcing. The authors use output from a three-dimensional ice sheet model to argue that this relationship is in fact not proportional, both due to the differential thickness of the ice sheets and their latidudinal placement (Figures 1 & 6).

To the extent $S_{[CO2,LI]}$ represents the sensitivity of the so-called "fast feedbacks" that determine the response to forcing on a centennial scale (which it does to the extent further Earth system forcings such as vegetative-albedo changes were negligble during the period studied), the present paper points towards an increase in sensitivity as global warming unfolds. The authors commendably caution against making this interpretation directly because of the uncertainty surrounding Earth system forcings, but their work helps point out an important subtlety that such an analysis must take into account.

For all of these reasons, I found that this paper made a significant point in a coherent fashion. There are, however, a few ways in which I feel that this paper could be improved. The first is to recalculate the polynomial fits used to analyze sensitivity state-dependence with the dependent and independent variables switched, which I would argue is more physical and more likely to give useful results. The second is to more clearly and fully explain the non-linearity found in their ice sheet model. The third is to more fully consider the comparison of Pleistocene and Pliocene results. The fourth is to clean up the grammatical issues discussed in the final section of this document.

2 Specific Comments

The paper uses proxy reconstructions of past CO_2 levels and changes to ice volume (the latter of which are converted to ice area and using a 3D model) to calculate past radiative forcings, and proxy reconstructions of benthic northern hemisphere ocean temperatures and various model-informed assumptions of the relation between high-latitude and global temperature change (polar amplification) to calculate past global temperature changes. The ratio of forcings to temperature changes gives the climate sensitivity. The state-dependence of this sensitivity is ascertained in two ways:

- by grouping data by background state ("cold" vs. "warm" Pleistocene, Figure 8 & 9; Pleistocene vs. Pliocene and Pleistocene vs. NH-ice-free Pliocene in Figure 10) and then calculating if the resulting distributions of sensitivity are significantly different.

- by applying polynomial fits of one, two, and three degrees to scatterplots of forcing vs. temperature change, and then seeing if the nonlinear fits are better than the linear ones (Figure 7)

The main point discussed above is made primarily with the first approach, e.g. grouping data by background state, and primarily for the comparison of the warm and cold Pleistocene. My first specific comment concerns the second approach, the polynomial fit. I would argue that the functional form at the heart of this fit ("$y(x) = a + bx + cx^2 + dx^3$", p. 3031, line 5, where x is ΔR and y is ΔT) switches the most useful choices for independent and dependent variable. This point requires explanation.

A radiative forcing is a change to the net top-of-atmosphere energy flux, which I will call N, caused by some change in something besides the temperature of the planet itself. In this case, the changes are to atmospheric CO2 and land ice sheets. In this sense, N is a function of CO_2 and LI, e.g. $N(CO_2, LI, ...)$. A positive radiative forcing indicates the change in CO_2 or LI has increased N, implying a net planetary gain of energy. This net gain of energy will cause the planet to begin warming, increasing T_g. As the planet warms, various physical process cause this warming to in turn change N, the most important being the increasing of blackbody radiation, which reduces N as T_g increases (e.g. acts as a negative feedback to the initial peturbation).

As this last point demonstrates, N is also a function of T_g, e.g. $N(CO_2, LI, T_g, ...)$, and it is the nature of the dependence of N on T_g that determines the warming response. The processes by which T_g changes N are called the climate feedbacks (e.g. the Planck feedback, water vapor feedabck, lapse rate feedback, etc.), and these are the physical process that determine the planet's sensitivity. Even though we are ostensibly looking for a function that converts radiative forcing into a surface temperature change, we find this temperature change by measuring the overall climate feedback, which can be expressed by taking the partial derivative of N with respect to surface temperature, $\lambda \equiv \partial N/\partial T_g$, and figuring out how much this feedback requires the planet to warm or cool until it undoes the initial forcing. Note that the climate feedback is simply the negative of the inverse of the sensitivity, $S_{[CO2,LI]} = -1/\lambda$.

When the world is linear (when sensitivity is not state-dependent), the warming response to a forcing $R_{[CO2,LI]}$ is just $\Delta T_g = R_{[CO2,LI]} S_{[CO2,LI]} = -R_{[CO2,LI]}/\lambda$. However, when sensitivity (and therefore the climate feedback) is temperature-dependent, we must account for changes in the sensitivity as the planet warms. Since sensitivity itself is caused by climate feedbacks, we would expect changes in sensitivity to be caused by changes in the strength of feedbacks (for example, the Planck effect getting stronger under warming due to the σT^4 dependence), and so the simplest non-linearity is *a linear change in the strength of the overall feedback*

with temperature, not a linear change in the strength of sensitivity. See, for example, "Non-linear climate feedback analysis in an atmospheric general circulation model", Colman et al. 1997; "How sensitivity is climate sensitivity?", Roe and Armour, 2011; ''Climate Feedbacks in CCSM3 under Changing CO2 Forcing. Part II: Variation of Climate Feedbacks and Sensitivity with Forcing', Jonko et al. 2013; and "Feedback temperature dependence determines the risk of high warming", Bloch-Johnson et al., 2015.

Therefore, in determining whether sensitivity was state-dependent under past forcings, it is perhaps more useful to first calculate a polynomial fit of ΔR as a function of ΔT, since the curve of ΔR can also be interpreted as the negative of the curve of $N(\Delta T)$ (assuming that climate feedbacks are primarily affected by T_g as opposed to $CO2$ and LI directly. The skill of the fits can once more be compared to see whether linear or nonlinear polynomials do a better job. You can then invert this curve to get a sense of changing sensiviity. One can get a crude sense of the utility of this switch by turning figure 7 on its side. Data that seems impossible to fit when upright, like subplot "g", becomes an almost horizontal line indicative of a barely negative overall feedback, and thus high sensitivity, when sideways. The polynomial fits in subplot "a" have a kink which, if interpreted literally, imply that a radiative forcing that moves you from -2.5 to -2 W/m^2 (i.e., a radiative forcing of 0.5 W/m^2) would result in cooling, a nonsensical result. If we perform the fit the other way, we would get part of a parabola implying a growing sensitivity under warming during Pleistocene, consistent with the results from the first approach. Generally, I predict the fits of almost all the figures would likely improve if the independent/dependent variables were switched.

The second specific comment concerns the non-linear relationship of sea level rise and land ice radiative forcing. Given the central importance of this non-linearty to the paper, it would be useful to have a more direct explanation of the workings of the ANICE model rather than only relying on a citation to previous work. The de Boer et al. 2014 paper can still be referenced, but some of its most relevant points could be brought over, and specifically which elements of the three-dimensional picture are most important for creating the non-linearity. This would help readers judge the robustness of this result. It would also be good to have a brief explanation of what ICE-5G is.

The third specific comment concerns arguments about the difference in sensitivity between the Pliocene and Pleistocene using the sensitivities gleaned from the Hönisch and Foster datasets. Figures 9 and 10 strike me as suggesting that both the present paper and Martínez-Botí et al. are right that the cold Pleistocene and the Pliocene have similar sensitivities, while the sensitivity in the warm Pliestocene was significantly higher than either (compare the peaks of the Hönisch ^{11}B cold Pleistocene, warm Pleistocene, and the Martinez-Boti ^{11}B Pliocene sensitivity distributions in Figure 9; the first and third are close together, while the second is much higher.) Note that this sort of "third-order" sensitivity (two changes in strength) is not uncommon seen in models ("Climate feedbacks under a very broad range of forcing", Colman and McAvaney, 2009; "Fast atmosphere-ocean model runs with large changes in CO2", Russell et al., 2013), though typically the other way around (the present is relatively insensitive, e.g.,

Russell et al., 2013, surrounded on either side by a growing ice albedo feedback and a growing water vapor feedback). Some discussion on this point might be warranted.

A few other smaller comments:

- Part of the above discussion of the ice sheet model should also note how deep ocean temperatures are used to estimate ΔT_{NH}, and if this relationship contributes to the nonlinearity derived in this paper in any way.
- As someone relatively unfamiliar with the proxy literature, I found Section 2.3 particularly useful in understanding the various CO_2 proxies available.
- I was a bit confused as to the units of the colorbar in Figure 1c. Are the colors representative of the globally-normalized forcing of the entire global ice sheet (in which case color would be independent of the y-axis) or are they supposed to represent the impact of the 5° latitudinal bins, in which case the units should be something like "W/m^2 per 5°"?

3 Technical Corrections

This paper has some grammar mistakes:

- (p. 3020, l. 1) "A still open question is how equilibrium warming in response to increasing radiative forcing – the specific equilibrium climate sensitivity S – is depending on background climate." should be "It is a still open question how equilibrium warming in response to increasing radiative forcing – the specific equilibrium climate sensitivity S – depends on background climate."
- (p. 3020, l. 10) "Important for the non-linearity between land-ice albedo and sea level is a latitudinal dependency in ice sheet area changes." should be "The latitudinal dependency of ice sheet area changes is important for the non-linearity between land-ice albedo and sea level.'
- (p. 3020, l. 13) "state-dependency" should be "state-dependence"
- (p. 3020, l. 15) "...interglacial periods $S_{[CO2,LI]}$ is..." should be "...interglacial periods, $S_{[CO2,LI]}$ is..."
- (p. 3020, l. 17) "...the CO2 data uncertainties prevents a well-supported..." should be "...the CO2 data uncertainties prevent a well-supported..."
- (p. 3021, l. 14) "for ECS e.g. of " should be "for ECS, e.g. of "

- (p. 3021, l. 18) "some understanding on model-based differences" should be "some understanding of model-based differences"

- (p. 3023, l. 16) "this analysis was, that average" should be "this analysis was that average"

- (p. 3023, l. 23) "First, we increase the amount and spread of the underlying data which then offers the possibility to calculate $S_{[CO2,LI]}$ based on paleo-data including most of the Pleistocene and the Pliocene, the latter is the rather warm epoch between 2.6 and 5.3 Myr BP that has been suggested as paleo-analogue for the future (Haywood et al., 2010)." should be something like "First, we increase the amount and spread of the underlying data, which offers the possibility to calculate $S_{[CO2,LI]}$ based on paleo-data covering most of the Pleistocene and the Pliocene. The latter is the rather warm epoch between 2.6 and 5.3 Myr BP that has been suggested as a paleo-analogue for the future (Haywood et al., 2010)."

- (p. 3024, l. 1) "Third, previously (e.g. van de Wal et al., 2011) polar amplification was assumed to be constant over time." should be something like "Third, polar amplification was previously assumed to be constant over time (e.g. van de Wal et al., 2011)."

- (p. 3024, l. 15) "This approach uses CO2 data from ice cores and based on different proxies from three different labs" should be something like "This approach uses CO2 data from ice cores, as well as from proxies from three different labs"

- (p. 3024, l. 17) "zonal averaged changes" should be "zonally-averaged changes"

- (p. 3024, l. 18) "simulations (de Boer et al., 2014), that" should be "simulations (de Boer et al., 2014) that"

- (p. 3024, l. 25) "ANICE (de Boer et al., 2014) the benthic" should be "ANICE (de Boer et al., 2014), the benthic"

- (p. 3025, l. 3) "Antarctic, Eurasian and North American" should be "Antarctic, Eurasian, and North American"

- (p. 3028, l. 10) "...in the simulation results and in all SST records, so is the strong glacial-interglacial (100kyr) variability thereafter." should be "...in the simulation results and in all SST records, and so is the strong glacial-interglacial (100kyr) variability thereafter."

- (p. 3032, l. 21) "For R[LI] changes in surface albedo are assumed to have a 1σ-uncertainty of 0.1, simulated changes in land-ice-area have in the various simulation scenarios performed in de Boer et al. (2014) a relative uncertainty of 10%." should be "For R[LI], changes in surface albedo are assumed to have a 1σ-uncertainty of 0.1.

Simulated changes in land-ice-area have a relative uncertainty of 10% in the various simulation scenarios performed in de Boer et al. (2014)."

- (p. 3034, l. 4) "agrees resonable well" should be "agrees resonably well"
- (p. 3034, l. 20) "This implies, that a" should be "This implies that a "
- (p. 3036, l. 16) "has in our simulation results" should be "in our simulation results has"
- (p. 3036, l. 18) "when not 3-D ice-sheet models (de Boer et al., 2014) as used here, but simpler approaches to calculate R[LI] are applied, e.g. based on 1-D ice-sheet models" should be "when overly simplified approaches to calculate R[LI] are applied, e.g. based on 1-D ice-sheet models, as opposed to the 3-D ice-sheet models (de Boer et al., 2014) used here"
- (p. 3037, l. 1) "land-ice distribution affect" should be "land-ice distribution affects"
- (p. 3037, l. 11) "calculate $S_{[CO2,LI]}$, however" should be "calculate $S_{[CO2,LI]}$. However"
- (p. 3037, l. 14) "Note, that" should be "Note that"
- (p. 3037, l. 17) "generated, when dividing" should be "generated when dividing"
- (p. 3037, l. 20) "falls rarely" should be "rarely falls"
- (p. 3039, l. 2) "which has be" should be "which has been"
- (p. 3039, l. 3) "Note, that" should be "Note that"
- (p. 3040, l. 19) "information, which are relevant" should be "information which is relevant"
- (p. 3041, l. 12) "data sets, which are" should be "data sets which are"
- (p. 3041, l. 19) "A support of our findings by other modelling approaches is in the light of the existing uncertainties nevertheless necessary to come to firm conclusions." should be something like "In the light of the existing uncertainties, our findings must be supported by other modelling approaches to come to firm conclusions."
- (p. 3041, l. 23) "filtering out data points, in which temperature changed abruptely, led to similar results" should be "filtering out data points in which temperature changed abruptely led to similar results"
- (p. 3042, l. 7) "is especially for those data not straight forward" could be something like "is not straightforward, especially for these data."

- (p. 3044, l. 1) "In the Pliocene S[CO2,LI]" should be "In the Pliocene, S[CO2,LI]"
- (p. 3064) "that varies linear" should be "that varies linearly"