Response to comments of reviewer #1

related to Köhler, P., de Boer, B., von der Heydt, A. S., Stap, L. B., and van de Wal, R. S. W.: On the state-dependency of the equilibrium climate sensitivity during the last 5 million years, Clim. Past Discuss., 11, 3019-3069, doi:10.5194/cpd-11-3019-2015, 2015.

September 29, 2015

We will in the following respond in detail to all comments of the reviewer #1. Thus, the full text of the review is also contained in this response letter, with our reply written in blue in-between.

Climate sensitivity is a key parameter in the understanding of the climate behaviour and therefore in the prediction/projection of our future climate. Such a paper dealing with this topic is therefore very welcome. This paper is in addition dealing with the climate sensitivity as a function of the background climate state, a research that started worldwide a few years ago and must be encouraged. Climate sensitivity must definitely be differentiated between warm and cold climates. Finally this paper couples data and models to show the state-dependency of climate sensitivity over a very long period (5 million years) which includes a large number of extreme climate situations. All these made the review favourable to the publication of such a paper, but with revisions of some points discussed here under.

General remarks

1.1 What is important for the future is to know whether the increase of temperature due to a doubling of the present-day (pre-industrial) CO2 concentration is equivalent or larger or smaller than a similar doubling during the previous interglacials (times when ice was similar as to-day). Such a climate sensitivity is different from the one used in this paper (K/(Wm-2)). For example, using a climate sensitivity restricted to the change of global temperature for a doubling of CO2, Yin and Berger (2012, Climate Dynamics) have stressed : "Within the range of the interglacial variability with the CO2eq concentration going from 234 to 300 ppmv, our climate sensitivity is shown to generally decrease with increasing temperature: MIS-9 has the lowest sensitivity and MIS-13 the highest. The sensitivity at MIS-5 is 10% lower than at Pre-Industrial time". The same results transferred in K/(Wm- 2) gives a decrease from 0.41 (MIS-13) to 0.37 (MIS-9) (if ΔT is divided by 5.35*ln(2), i.e. 3.71).

Our reply: We acknowledge the findings of Yin and Berger 2012, which we have not discussed so far. This will be revised. However, we here base our analysis mainly on the data compilation and we therefore can not directly answer the question of which temperature change an CO_2 doubling would provide (on a hundred years timescale), since such a thing has not happened so far and therefore has not been recorded in the paleo record. We are here interested in the generic Earth system response to radiative forcing changes that has been recorded in the paleo record. We believe such an analysis is important for a better understanding of climate change itself. In restricting their study to interglacials Yin and Berger 2012 kept ice sheets at present values and find climate sensitivity decreases with increasing temperature. At first glance this might seem contrary to our finding with larger climate sensitivity during late Pleistocene interglacials when compared to late Pleistocene full glacial conditions. We here include changes in land ice sheet as albedo forcing ($\Delta R_{[LI]}$) in our approach. When investigating over the whole range of climate states (e.g. including full glacial conditions with variable $\Delta R_{[LI]}$) we therefore probe a complete different regime, which is not directly comparable with the results from interglacials-only. Furthermore and most important, as written several times in our paper (introduction, discussion) the comparison of (paleo) data-based calculations of climate sensitivity with output from GCM not directly possible, since in the data-based approach the effect of all processes that have been active are contained in any reconstruction of global temperature, while in the model-based approach only those processes implemented in the model can lead to changes in calculated temperature. See also our replies on comments #1.2 and #1.8 with more details on interglacials.

Moreover, if the climate sensitivity (mainly to CO2) is indeed depending on the climate background, the results obtained from cold climates can hardly be used for improving the projection of our future climate (see page 3042 lines 17-19).

Our reply: This is certainly true. However, a lot of previous studies on paleo climate sensitivity focus on our knowledge of LGM climate, since (a) this can nowadays be reproduced reasonably well and (b) the climate anomaly is larger than the uncertainty in the data, so the signal-to-noise ratio is good enough to justify any analysis, something which is not always to case if only interglacial climates are investigated, since the anomalies with respect to pre-industrial conditions are close to zero, and specific climate sensitivity S, which we focus on here, calculated as the ratio of changes in temperature over the changes in radiative forcing produces for paleo data very often non-reliable results (the problem of calculating to ratio of two small numbers). Therefore, in former studies the interglacials were explicitly not considered (e.g. PALAEOSENS-Project Members, 2012; von der Heydt et al., 2014). We therefore believe one needs to investigate the state-dependency of S as systematic as possible by including also cold (LGM) and warm (Pliocene) climates in order to generate the best understanding possible. Also, we need to rely on (paleo)-data whenever possible in order to test our climate models against them and against the understanding which was derived from the data.

Previous works on climate sensitivity, Page 3022 lines 26 and mainly page 3023 line 4, conclusion page 3028 line : "during Pleistocene warm period S was about 45% larger than during the Pleistocene cold periods" and page 3041 lines 9-10 plead for Kohler et al. discussing such climate sensitivity considering only the interglacials/warm periods and only CO2 if possible(more detailed discussions than what is done in sections 2.3 and 3.3).

Our reply: We will extend the discussion of our findings with respect to other publications, especially concerning the interglacial periods (e.g. results of Yin and Berger (2012)).

This remark leads to the following recommendations. The authors say on purpose that their analysis is going beyond what has been done before. It would therefore be interesting to see the relative importance of each individual improvement to explain the differences from previous studies.

Our reply: This recommendation asks for the relative importance of the different improvements by which we go beyond what was done so far. We have to clarify that we understand these improvements especially with respect to the two most recent papers on this issue, namely (a) our own data interpretation of the ice core data (von der Heydt et al., 2014) and (b) the new Pliocene CO_2 data and their interpretation (Martínez-Botí et al., 2015). As stated in the introduction our study is going beyond previous studies in four ways:
(1) we increase the amount of data;
(2) we calculate the radiative forcing of the land ice albedo from a detailed spatial analysis of land ice distributions obtained with 3-D ice sheet models;
(3) we consider polar amplification to be a function of temperature;
(4) we consider whether a linear or a non-linear function best describes the relationship between changes in temperature and changes in radiative forcing.
The relative importance of these four improvements is the following:
(1: more data) Apart from the most recent paper of Martínez-Botí et al. (2015) all previous approaches in that direction focused mainly on the time window of the last 800 kyr of the late Pleistocene, for which ice core data exist. A few others (e.g. PALAEOSENS-Project Members, 2012) made some estimates on previous times, but we here compiled all available longer CO_2 time series of the last 5 Myr which are of good quality. In doing so we are able to extrapolate the state-dependency in climate sensitivity found in the ice core data of the last 800 kyr to the last 2.1 Myr.
(2: land ice albedo) While the state-dependency in $S_{[\mathrm{CO_2}]}$ depends on the chosen CO_2 data set, the state-dependency in $S_{[\mathrm{CO_2,LI}]}$ was mainly manifested by the analysis of the 3-D ice sheet output on land ice albedo changes. The difference in the strength of the state-dependency in $S_{[\mathrm{CO_2,LI}]}$ can been seen when comparing our results here with that of our previous study published in von der Heydt et al. (2014) for the ice core data of the last 800 kyr. In the other study the land ice albedo changes was

calculated based on simpler approaches. There, we already detected a state-dependency in $S_{[CO_2,LI]}$, but remarkably weaker than here (only different slopes in piece-wise linear regressions, but no non-linear relationship between ΔT_g and $\Delta R_{[CO_2,LI]}$).

(3: polar amplification) In our presented results we have no scenario, in which polar amplification was constant as assumed previously (e.g. van de Wal et al., 2011). We can however use our most simple approach, in which polar amplification varies as step function between a low value for times without large northern hemispheric land ice (before 2.82 Myr BP) and a high value thereafter. For times with land ice (after 2.82 Myr BP) the analysis of the ice core and Hönisch data sets lead for different assumptions on polar amplification to qualitatively similar results, e.g. a state-dependency in S (Table 1). We interpret this, that an improvement in polar amplification is important to be consistent with our state-of-the-art understanding of climate change, but not for the detection of a state-dependency in climate sensitivity.

(4: linear vs non-linear) Only by using statistics and checking if a non-linearity between ΔT and ΔR exists, we were able to quantify the state-dependency of $S_{[CO_2,LI]}$ as done here. So, this is the most important step that goes beyond the most recent paper of Martínez-Botí et al. (2015) on the same topic.

The importance of most of these different aspects have been discussed already in the previous version of the MS. However, in the revision we clearly highlight their importance as summarised here.

1.2 By introducing new data and calculations (see page 3023 bottom and page 3024 top), the authors introduce unintentionally also new hypotheses and sources of uncertainties. They discuss these uncertainties in section 2.5 and some other places in the paper, but what are the impact on the calculation of the climate sensitivity itself? Some conclusions are drawn in section 3.3 but it would be interesting to know, for example, which of the change of time series or resampling of CO2 data (page 3038 lines14-15) has the largest impact on S. This is very important for recommending in which direction studies must continue to be done to improve our knowledge.

Our reply: Following this comment we performed additional analyses of the data set based on ice core CO_2, in which one (or all) of the 3 times series $\Delta R_{[LI]}$, $\Delta R_{[CO_2]}$, and ΔT_g was (were) identical to the previous analysis of von der Heydt et al. (2014). However, since in von der Heydt et al. (2014) all data are resampled to 100 yr, but here to 2 kyr (the temporal resolution of the 3-D ice sheet models), we have to pre-process these data sets taken from the previous study as done here (resampling to 2 kyr). Furthermore, in von der Heydt et al. (2014) data are binned before any regression analysis, whose impact is finally also tested. In this additional analysis (Table 1 below) we find that even when all three data sets would be substituted with those used in von der Heydt et al. (2014) and resampled to 2 kyr we would find a non-linearity in the ΔT_g-$\Delta R_{[CO_2,LI]}$-scatter plot and therefore a state-dependency in $S_{[CO_2,LI]}$, but this time a 2nd order polynomial would be best to fit the data (not 3rd order polynomial as found here). However, if data are binned before analysis we find a state-dependency of $S_{[CO_2,LI]}$ only for the data sets used here, or when CO_2 is substituted by the previous time series, but not when the previous versions of $\Delta R_{[LI]}$, or ΔT_g are used. In these binned data (binned into bins of either $\Delta T_g = 0.2$ K or $\Delta R_{[CO_2,LI]} = 0.2$ W m^{-2}) both our new ΔT_g and $\Delta R_{[LI]}$ are important to generate this state-dependency in $S_{[CO_2,LI]}$. From the p-values of the F-tests to decide if 1st or 2nd-order polonium's best fit the data we find that ΔT_g seems actually to be even more important than $\Delta R_{[CO_2,LI]}$ to generate the non-linearity in the binned ΔT_g-$\Delta R_{[CO_2,LI]}$-scattered data. Please note, that for these tests we used our standard setup for polar amplification (f_{pa}) leading to a global temperature change ΔT_g=ΔT_{g1}. Also note, that here we tested if a non-linear polynomial might fit the data, while in von der Heydt et al. (2014) piece-wise linear regressions were performed for data sets, for which statistics indicated a break in the (linear) slope of the time series. So both methods are not directly comparable and our finding here, that the binned data which were based in all three variables on the old (previously used) data sets did not show any non-linearity is not per se in conflict with the previous paper. These findings will be included in the revised manuscript.

Table 1: Sensitivity analysis 1: Investigating the importance of the three variables ΔT_g, CO_2, ΔR_{LI} with respect to the previous analysis of the ice-core based CO_2 data of von der Heydt et al. (2014) (cited here as vdH2014). Here, all data are resampled to 2kyr while in vdH2014 data are resampled to 100 yrs and binned ΔT_g before any regression analysis. Fitting a linear or a non-linear function to the data. 5000 Monte-Carlo-generated realisations of the scattered ΔT_g–$\Delta R_{[CO_2,LI]}$ were analysed. The data are randomly picked from the entire Gaussian distribution described by the 1σ of the given uncertainties in both ΔT_g and $\Delta R_{[CO_2,LI]}$. The parameter values of fitted polynomials are given as mean $\pm 1\sigma$ uncertainty from the different Monte-Carlo realisations. In all scenarios summarised here ΔT_g vs. $\Delta R_{[CO_2,LI]}$ with $\Delta T_g = \Delta T_{g1}$ was investigated.

Data set	n	χ^2 1st	χ^2 2nd	F	p	L	r^2 %	a	b	c	d
Investigating the importance of ΔT_g, CO_2, ΔR_{LI} with respect to the vdH2014:											
ice cores[a]	394	1219	1176	14.3	< 0.001	$**$	72	-0.43 ± 0.07	2.16 ± 0.10	0.36 ± 0.04	0.02 ± 0.00
ice cores, binned in $\Delta R_{[CO_2,LI]}$	31	56	37	14.4	< 0.001	$**$	81	-0.66 ± 0.37	1.61 ± 0.26	0.14 ± 0.04	0
ice cores, binned in ΔT_g	32	203	148	10.8	0.003	$*$	87	-0.20 ± 0.18	1.70 ± 0.20	0.14 ± 0.04	0
ice cores, CO_2 as in vdH2014[a]	390	1283	1235	15.0	< 0.001	$**$	70	-0.42 ± 0.06	2.17 ± 0.10	0.37 ± 0.04	0.02 ± 0.00
ice cores, CO_2 as in vdH2014, binned in $\Delta R_{[CO_2,LI]}$ [a]	31	60	42	12.0	0.002	$*$	80	-0.68 ± 0.36	1.56 ± 0.25	0.14 ± 0.04	0
ice cores, CO_2 as in vdH2014, binned in ΔT_g[a]	32	213	160	9.6	0.004	$*$	85	-0.20 ± 0.19	1.67 ± 0.21	0.13 ± 0.04	0
ice cores, ΔR_{LI} as in vdH2014	390	1684	1373	87.7	< 0.001	$**$	67	-0.49 ± 0.08	1.70 ± 0.06	0.16 ± 0.01	0
ice cores, ΔR_{LI} as in vdH2014, binned in $\Delta R_{[CO_2,LI]}$	27	43	32	8.3	0.008	$*$	79	-0.41 ± 0.43	1.75 ± 0.34	0.16 ± 0.06	0
ice cores, ΔR_{LI} as in vdH2014, binned in ΔT_g	32	193	164	5.1	0.031	/	82	-0.39 ± 0.16	1.08 ± 0.08	0	0
ice cores, ΔT_g as in vdH2014	390	742	658	49.4	< 0.001	$**$	66	0.13 ± 0.12	1.13 ± 0.08	0.08 ± 0.01	0
ice cores, ΔT_g as in vdH2014, binned in $\Delta R_{[CO_2,LI]}$	31	42	35	5.6	0.025	/	73	-0.34 ± 0.23	0.63 ± 0.08	0	0
ice cores, ΔT_g as in vdH2014, binned in ΔT_g	24	40	34	3.7	0.068	/	77	-0.05 ± 0.25	0.70 ± 0.09	0	0
ice cores, ΔT_g, CO_2, ΔR_{LI} as in vdH2014	390	788	744	22.9	< 0.001	$**$	62	0.25 ± 0.14	1.12 ± 0.10	0.07 ± 0.01	0
ice cores, ΔT_g, CO_2, ΔR_{LI} as in vdH2014, binned in $\Delta R_{[CO_2,LI]}$	28	35	32	2.3	0.138	/	74	-0.07 ± 0.26	0.72 ± 0.09	0	0
ice cores, ΔT_g, CO_2, ΔR_{LI} as in vdH2014, binned in ΔT_g	24	42	39	1.6	0.218	/	76	0.23 ± 0.30	0.80 ± 0.11	0	0

n: number of data points in data set.
χ^2: weighted sum of squares following either a linear fit (1st order) or a non-linear fit (2nd order polynomial), for some data sets (labelled: [a]) also of 2nd or 3rd order polynomials.
F: F ratio for F test to determine, if the higher order fit describes the data better than the lower order fit (1st vs. 2nd order polynomial or 2nd vs. 3rd order polynomial).
p: p value of the F test.
L: significance level of F test (/: not significant ($p > 0.01$); $*$: significant at 1 % level ($0.001 < p \leq 0.01$); $**$: significant at 0.1 % level ($p \leq 0.001$)).
r^2: correlation coefficient of the fit.
a, b, c, d: derived coefficients of fitted polynomial $y(x) = a + bx + cx^2 + dx^3$.

Along the same lines:

1.3 What is the impact of the uncertainties of the reconstruction of paleoclimate data of the last 5 million years (in particular of ΔT_g)?

Our reply: Our analysis to find any non-linearity in S or of which order of a polynomial fits the data best is based on a Monte-Carlo approach, in which the uncertainties of all data points in both x (ΔR) and y (ΔT_g) direction are considered. The uncertainties in the data, therefore have a direction impact on the calculated regressions. However, when we estimate the impact of the uncertainties by artificially reducing the uncertainties in $\Delta T_g (\sigma_{\Delta T_g})$ and $\Delta R_{[CO_2,LI]}$ $(\sigma_{\Delta R})$ by a factor of 2 or 10 we find statistically the same non-linearity in the ΔT_g-$\Delta R_{[CO_2,LI]}$-scattered data than with the original uncertainties in all four CO_2 data sets, so ice core and Hönisch stay non-linear, Foster and Pagani stay linear (Table 2 below). So we can conclude, that our proposed state-dependency of $S_{[CO_2,LI]}$ is robust and independent of the uncertainties. However, any calculated value of S depends in detail on σ in the underlying data. This finding will be included in the manuscript.

Table 2: Sensitivity analysis 2: Investigating the importance of the uncertainties on the regression results by artificially reducing both $\sigma_{\Delta T_g}$ and $\sigma_{\Delta R}$ by a factor of 2 or 10. Fitting a linear or a non-linear function to the data. 5000 Monte-Carlo-generated realisations of the scattered ΔT_{g}–$\Delta R_{[\mathrm{CO_2,LI}]}$ were analysed. The data are randomly picked from the entire Gaussian distribution described by the 1σ of the given uncertainties in both ΔT_{g} and $\Delta R_{[\mathrm{CO_2,LI}]}$. The parameter values of fitted polynomials are given as mean $\pm 1\sigma$ uncertainty from the different Monte-Carlo realisations. In all scenarios summarised here ΔT_{g} vs. $\Delta R_{[\mathrm{CO_2,LI}]}$ with $\Delta T_{\mathrm{g}} = \Delta T_{\mathrm{g1}}$ was investigated.

Data set	n	χ^2 1st	χ^2 2nd	F	p	L	r^2 %	a	b	c	d
Investigating the importance of the uncertainties:											
ice cores[a], original uncertainties	394	1219	1176	14.3	<0.001	$**$	72	-0.43 ± 0.07	2.16 ± 0.10	0.36 ± 0.04	0.02 ± 0.00
ice cores[a], uncertainties $\times 1/2$	394	3268	3105	210.6	<0.001	$**$	80	-0.36 ± 0.04	2.23 ± 0.06	0.41 ± 0.03	0.03 ± 0.00
ice cores[a], uncertainties $\times 1/10$	394	83489	77553	30.0	<0.001	$**$	83	-0.31 ± 0.01	2.34 ± 0.01	0.47 ± 0.01	0.04 ± 0.00
Hönisch, original uncertainties	52	327	256	13.6	<0.001	$**$	79	-1.15 ± 0.14	1.27 ± 0.12	0.10 ± 0.02	0
Hönisch, uncertainties $\times 1/2$	52	850	598	20.7	<0.001	$**$	87	-1.01 ± 0.08	1.37 ± 0.07	0.10 ± 0.01	0
Hönisch, uncertainties $\times 1/10$	52	16235	10712	25.3	<0.001	$**$	89	-0.97 ± 0.02	1.40 ± 0.01	0.11 ± 0.00	0
Foster, original uncertainties	105	2589	2569	0.8	0.38	/	61	-1.53 ± 0.05	0.63 ± 0.03	0	0
Foster, uncertainties $\times 1/2$	105	8972	8954	0.2	0.65	/	61	-1.53 ± 0.03	0.67 ± 0.02	0	0
Foster, uncertainties $\times 1/10$	105	306105	306079	0.1	0.93	/	61	-1.53 ± 0.00	0.69 ± 0.00	0	0
Pagani, original uncertainties	153	5125	5040	2.5	0.11	/	45	-2.19 ± 0.07	0.82 ± 0.04	0	0
Pagani, uncertainties $\times 1/2$	153	15283	14795	5.0	0.03	/	56	-2.23 ± 0.04	1.00 ± 0.03	0	0
Pagani, uncertainties $\times 1/10$	153	343134	329292	6.3	0.01	/	60	-2.24 ± 0.01	1.07 ± 0.01	0	0

n: number of data points in data set.
χ^2: weighted sum of squares following either a linear fit (1st order) or a non-linear fit (2nd order polynomial), for some data sets (labelled: [a]) also of 2nd or 3rd order polynomials.
F: F ratio for F test to determine, if the higher order fit describes the data better than the lower order fit (1st vs. 2nd order polynomial or 2nd vs. 3rd order polynomial).
p: p value of the F test.
L: significance level of F test: (/: not significant ($p > 0.01$); $*$: significant at 1 % level ($0.001 < p \leq 0.01$); $**$: significant at 0.1 % level ($p \leq 0.001$)).
r^2: correlation coefficient of the fit.
a, b, c, d: derived coefficients of fitted polynomial $y(x) = a + bx + cx^2 + dx^3$.

1.4 What is the impact on the calculated radiative forcing of the land ice albedo from a 3-D ice sheet model uncoupled (?) to the rest of the climate system? Can the authors be a little bit more explicit on how they calculate $\Delta R_{[\mathrm{LI}]}$? What else more than surface albedo, TOA and changes in ice-sheet area is needed to "estimate" $\Delta R_{[\mathrm{LI}]}$? What is the relative impact of this "technique" on climate sensitivity?

Our reply: The 3-D ice sheet models from which we obtain our land ice albedo estimates are included in a modelling framework, that in a simplified form also considers changes in the climate system (see for more details de Boer et al., 2014). However, in the applied 3-D ice sheet modelling framework there is no direct effect of any calculated radiative forcing to the climate system. Further details on the importance and role of coupling these 3-D ice sheet models to more sophisticated climate models was investigated in detail by others (e.g. citations above or Ganopolski et al., 2010; Ganopolski and Calov, 2011) and is not the main focus of our paper here. We will nevertheless briefly extend the methods section on specific details here.

How is $\Delta R_{[\mathrm{LI}]}$ calculated in detail? This was described in detail in Köhler et al. (2010), but will be briefly repeated here: The main input is a change in ice sheet area (ΔA_{LI}) (in m^2) from the 3-D ice sheet simulation output of de Boer et al. (2014). We then calculate the insolation at the surface I_{S} (in W m^{-2}) as a function of insolation at top of the atmosphere I_{TOA} (in W m^{-2}, taken from (Laskar et al., 2004)), albedo of the atmosphere α_{A} (unitless), and absorption ratio a within the atmosphere (unitless) for every 5° latitudinal band i:

$$I_{\mathrm{S}}(i) = I_{\mathrm{TOA}}(i) \times (1 - (\alpha_{\mathrm{A}} + a))$$

Changes in land ice sheet-based radiative forcing $\Delta R_{[\mathrm{LI}]}$ per latitudinal band are then given by

$$\Delta R_{[\mathrm{LI}]}(i) = -I_{\mathrm{S}}(i) \times \Delta A_{\mathrm{LI}}(i) \times (\Delta\alpha)/A_{\mathrm{Earth}}$$

with $\Delta\alpha = \alpha_{\mathrm{LI}} - \alpha_{\mathrm{land}}$ being the difference in albedo between land ice (α_{LI}) and ice-free land (α_{land}). $\Delta R_{[\mathrm{LI}]}(i)$, if integrated over all latitudinal bands i leads to the total global number $\Delta R_{[\mathrm{LI}]}$.

The following parameter values derived for present day and shown in Köhler et al. (2010) are used here: $\alpha_{\mathsf{A}} = 0.212$, $a = 0.20$, $\alpha_{\mathsf{LI}} = 0.75$; $\alpha_{\mathsf{land}} = 0.2$, $A_{\mathsf{Earth}} = 510 \times 10^{12}$ m^2.

1.5 What is the impact of fixing the value of a polar amplification factor as a function of the climate state itself (page 3026 line 6; to which extend is it not a circular reasoning by claiming finally that the climate sensitivity — which depends on polar amplification — is climate state-dependent). What is the importance of such polar amplification factor on the climate sensitivity? There are finally few figures showing the influence of different parameters on S (only Figures 8 b and e).The importance/meaning of the linearity or non-linearity of the relationship between $\Delta T_{\rm g}$ and ΔR must be better explained.

Our reply: So far, the importance of polar amplification $f_{\rm pa}$ being a function of climate state itself has been tested by calculating results for 3 different assumptions on $f_{\rm pa}$. The results on these choices are only visualised in Table 1 of the manuscript. We came to the conclusion, that the detailed choice of $f_{\rm pa}$ is not important for our claim on state-dependent climate sensitivity. For example, $\Delta T_{\rm g2}$, in which $f_{\rm pa}$ follows a step function and is constant for the last 2.82 Myr (and therefore constant for all times, for which the ice core and Hönisch CO_2 data exist) still leads to qualitatively the same non-linearity (state-dependencies) than other choices for polar amplification. See also our reply to comment #1.1 on the polar amplification. For the quantification of the impact of the climate-dependency of $f_{\rm pa}$ on climate sensitivity we replot and analyse Figure 9 (PDF of $S_{[\rm CO_2,LI]}$) based on the other two global temperature change records $\Delta T_{\rm g2}$ and $\Delta T_{\rm g3}$, see Figure 1 below. We find that changes both alternative temperature change records $\Delta T_{\rm g2}$ and $\Delta T_{\rm g3}$ lead to maxima in the PDF for slightly smaller values $S_{[\rm CO_2,LI]}$. However, we like to clarify that our standard choice of $\Delta T_{\rm g}$=$\Delta T_{\rm g1}$ is in best agreement with our understanding of climate change. The results based on $\Delta T_{\rm g2}$ (dotted lines) are comparable to our earlier study in which polar amplification was kept constant (van de Wal et al., 2011).

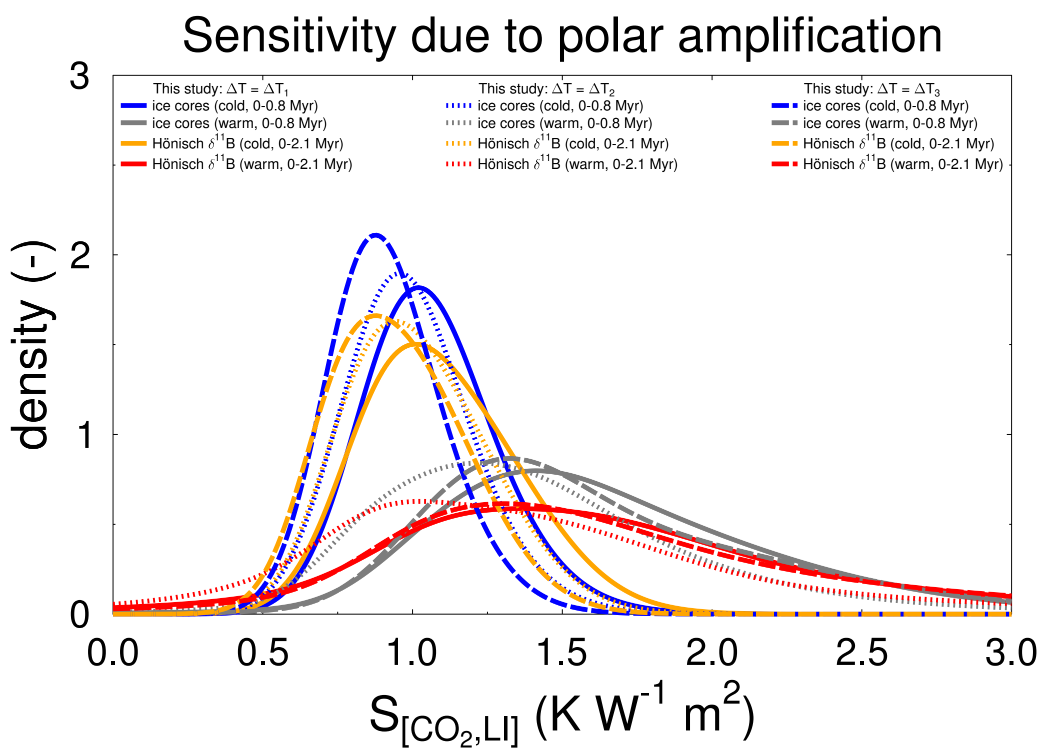

Figure 1: *Replotting the probability density functions (PDF) of $S_{[\rm CO_2,LI]}$ based on our results for ice cores or Hönisch CO_2 as a function of different polar amplifications leading to different global temperature changes (similar to previous Figure 9).*

1.6 Does the fact that "if the fit follows a linear function, its value might be determined from the slope of the regression line..." (page 3031 line 8) imply that a state-dependency is absolutely requesting a non-linear relationship between ΔT and ΔR as the authors seem to let it assume page 3024 line 7 , page 3031 lines 1 and 2 and page 3035 line 5.

Our reply: Yes, this is indeed the case: According to our understanding a state-dependency in $S_{[\mathsf{X}]}$ is absolutely requesting a non-linear relationship between ΔT_{g} and $\Delta R_{[\mathsf{X}]}$. We emphasise on that in the text to make this absolutely clear.

1.7 I think that what is missing the most in the paper is a figure with $S_{[\mathrm{CO_2}]}$, $S_{[\mathsf{LI}]}$ and $S_{[\mathrm{CO_2},\mathsf{LI}]}$ as a function of ΔT_{g} showing clearly (?) the state-dependency of S which is the purpose of the paper.

Our reply: In our approach we investigate the response of the climate system to the radiative forcing ΔR, which drives all changes, so it also it seems straightforward to put ΔR on the x-axis. Furthermore, we believe the state-dependency can also be investigated from the figures, in which S is shown as function of ΔR (Figures 8b,e). When preparing the figures and final analysis of the paper we made the strategic decision to show in Figures 8,b,e S as a function of ΔR, not ΔT_{g}, because of the non-linearity in the relationship of both variables. As can be seen from Fig 7b,d the flatness of the relationship between both variables for cold conditions lead to the fact, that a range in ΔR is corresponding to a much smaller range in ΔT_{g}. This implies that the splitting of the data in "cold " and "warm" periods as done here (in order to be able to compare results with the previous study of von der Heydt et al. (2014)) is not so easily done when data are plotted as S being a function of ΔT_{g}. Furthermore, in von der Heydt et al. (2014) binned data are split in cold and warm while here much more diverse data are contained. This leads to less defined relationships of S as a function of ΔT_{g}. Clearly, this is a shortcoming which urgently needs improvements. We furthermore like to emphasise that before a clear formulation of S as a function of temperature change can be given (in more detail than the PDF of S for two sub-groups of the data representing "cold" or "warm" conditions) still more theoretical work seems necessary. This might be achieved during future work, e.g. we are preparing some discussion in that directions for a workshop on that issue.

More specific remarks:

1.8 1. P 3021 line 23: What the authors mean by "These details" when speaking about the astronomical forcing? Is that statement not opposed to what they say page 3025 line 20. There the authors claim that they use the long term variations of the solar radiation input. It is true that these variations can hardly be visible on figure 1a. Is it due to a lack of resolution or are these variations negligible? The second possibility is probably true as the authors use annual mean isolation which variations are indeed very small (their figure 4c, black curve). This raises a real problem because the insolation forcing is not totally negligible for calculating the temperature changes, but provided the seasonal variations are used in the response of the climate system. (see the relative contribution of insolation and CO2 in Yin and Berger, 2012)

Our reply: What is meant by "These details" is the latitudinal and seasonal change in orbital-induced incoming solar radiation. On page 3025, line 20 the uncertainty in total solar energy output (in the solar constant) is mentioned, which refers to global incoming radiation input. Changes in annual mean insolation as a function of latitude (Fig 1a) are small and not really visible in the figure due to resolution. For example, the annual mean insolation in the band 40-80°N has a peak-to-peak amplitude on the order of a few W m^{-2} on obliquity time scales (41 kyr), on which the effects of longer (eccentricity-based) variations are superimposed. The approach of calculating climate sensitivity from data always refers to global and annual values of ΔT_{g} and ΔR. This is based on the intrinsic definition of climate sensitivity. Truly, seasonal variations in insolation play a role for climate, but their impact can yet not be analysed with this approach. We have to acknowledge, that the approach here comes to its limits. See also the review on paleo-climate sensitivity for more details on this issue (PALAEOSENS-Project Members, 2012). We checked the content of Yin and Berger (2012) for this issue. They found that for most of the interglacials of the last 800 kyr the effect of the greenhouse gases on global temperature change is larger than the effect of insolation. We therefore think following only CO_2 changes here and neglecting these details of insolation is for first order effects a valid assumption. Also note, that in this data-based analysis S which is the ratio of the two numbers ΔT_g, ΔR, is for interglacial climates not computable for single-points since both ΔT_g and ΔR are close to zero (discussed already in PALAEOSENS-Project Members (2012)). For interglacials S can only be determined from the overall analysis of the scatter-plots of ΔT_g-ΔR. In such a setting, different interglacials can not be distinguished (as done in Yin and Berger (2012)), but only the overall mean response of climate can be calculated. But be aware that in Yin and Berger (2012) ice sheets were kept constant and therefore $\Delta R_{[LI]} = 0$ W m^{-2}, which also makes a direct comparison of both studies difficult. Nevertheless, we will include these limitations and the findings of Yin and Berger (2012) in a wider discussion.

1.9 2. Page 3022 line 26: Is the linear combination of $\Delta R_{[LI]}$ and $\Delta R_{[CO_2]}$ giving the same weight for the two? At least this is what can be deduced from the numerical values given page 3034. Would it not be better to give them a weight depending on their relative uncertainty.

Our reply: When combining both $\Delta R_{[LI]}$ and $\Delta R_{[CO_2]}$ their average values are added and the overall uncertainty of the sum is calculated from the individual uncertainties of both variables following standard error propagation methods. We believe, this approach is sufficient to account for the uncertainties.

1.10 3. Page 3025 line 1: what is the exact meaning of eustatic here (is it total sea level variations both mass and steric components?)

Our reply: Eustatic here means the global mean change in sea level due to changes in ice volume alone. We revise for clarity.

1.11 4. Page 3026 section 2.2: what is the impact of neglecting changes of temperature in the SH?

Our reply: The inverse approach of de Boer et al. (2014) is based in the first place on the stack of marine benthic δ^{18}O, which contains the mixed signal of global deep ocean temperature and global ice volume (sea level) change. The approach of de Boer et al. (2014) tries to deconvolve the changes in ice sheets by 3-D ice sheet models as good as possible. Since most of the modelled ice sheets are situated in the high northern hemisphere, the model is good at predicting also surface air temperature changes in these regions. In the history of the model development various tests of the relation of temperature change in the ocean and in the high northern latitudes have been performed, and the assumed relation used here was verified with transient model simulations with more complex climate models. In the model, the temperature anomaly calculated out of the benthic δ^{18}O stack, ΔT of the deep ocean, is forwarded to two model routines, the 3-D ice-sheet model and the deep-water to surface-air temperature coupling. To calculate the deep-water temperature anomaly, we used a parameterisation that linearly relates the deep-water temperature to the 3-kyr mean NH temperature ΔT_{NH} (Bintanja et al., 2005b). According to Bintanja et al. (2005a), glacial-interglacial variations in deep-water and surface temperatures show sufficient coherence to justify the use of this relationship. The coupling coefficient between deep ocean and northern hemisphere temperature change was determined using a simplified atmosphere–ocean climate model (Bintanja and Oerlemans, 1996) by correlating atmosphere to deep-water temperatures in a series of transient climate runs. A more extensive analysis of this parameterisation is presented in de Boer et al. (2010). We derive global temperature changes from these high northern hemisphere temperature changes by some assumptions on polar amplification, which we support with GCM output (own models, two PMIP contributions to the LGM and the Pliocene). Temperature of the SH is thus not implicitly included in this calculation, but is contained in the global temperature change via the polar amplification factor, into which global temperature field from GCMs contribute to.

1.12 5. Page 3027 line 4: what are the two choices mentioned: are they -4.6±0.8 and -5.7±0.6 or -5.7-0.6 and -5.7+0.6?

Our reply: The two choices of f_{pa} mentioned here are f_{pa} being a linear function of ΔT_{NH}, or f_{pa} following a step function, as illustrated in Fig 2a. We revise for clarity.

1.13 6. All the reconstructed CO2 values are far from being homogeneous (see pages 3029 and 3030). This discussion is very welcome but what is the final impact on the climate sensitivity?

Our reply: The final impact of the reconstructed CO_2 values on climate sensitivity is, that CO_2 data beyond 2.1 Myr are (a) too sparse, (b) still dependent on the chosen approach, and (c) have too large uncertainties to come to final conclusions on the state-dependency of S for the Pliocene. We summarise this briefly in the revision.

1.14 7. Section 3.2 is discussing the relationship between ΔT and ΔR looking for non-linearity. This is an excellent point, but I have difficulties with figure 7, namely to understand the fitting lines of figure 7e and 7g. In particular I do not see the inverse slope in the points of Fig 7e. If the black line is a fit I do not see how it can be obtained.

Our reply: We tested the fit in Figures 7e and 7g with a second statistical toolbox, now without considering the uncertainties in the data and without the Monte-Carlo (MC) approach. We again find the inverse slope and a similar gradient in Fig 7g, so we can exclude any fitting errors here (see Figure 2 below). Note, that the software for analysis used throughout the draft (black lines in figure) was based on numerical recipes (NR), but modified by us, while the second statistical toolbox (blue lines in figure) is the one implemented in the software Graphics Layout Engine (GLE, see http://glx.sourceforge.net/index.html). In details the fits differ because of (a) uncertainties and (b) Monte-Carlo, but the general picture is the same. We therefore exclude an error here.

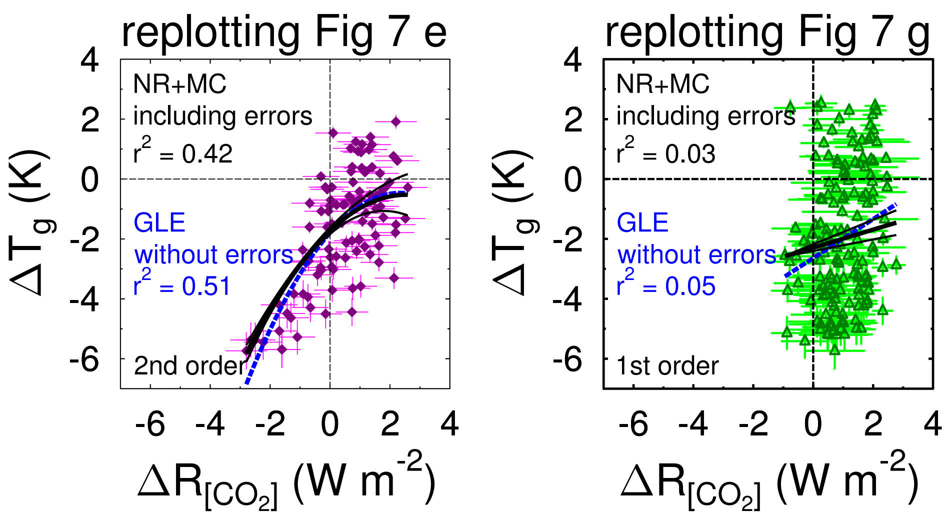

Figure 2: *Replotting Figures 7 e,g with two different softwares to calculate the (non)-linear regression functions. Black and solid lines: Numerical Recipes (NR) combined with Monte Carlo (MC) statistics, including errors as done in the paper. Blue and broken lines: GLE only based on mean values (not considering errors).*

1.15 8. Page 3044 line 3: another earlier and still valid reference is Berger and Loutre (2002, Science) who were the firsts to come with such a result.

Our reply: Page 3044 line 3 is the start of the acknowledgements. We therefore believe there is a typo in the stated line (or page) number and we are not sure where this comment refers to. However, from given reference to Berger and Loutre (2002) it probably relates to the beginning of page 3043, where we discuss the disappearance of the Greenland ice sheet. We extend this discussion on the content of an additional reference of the work of Berger and Loutre, however, we believe that the more interesting paper in this context was Loutre and Berger (2000), a paper in Climatic Change, in which the Greenland ice sheet melted away for scenarios with CO_2 between 200 and 300 ppmv.

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