Clim. Past Discuss.,
doi:10.5194/cp-2016-50-AC2, 2016

Climate of the Past Discussions
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Interactive comment on “Sensitivity of Pliocene climate simulations in MRI-CGCM2.3 to respective boundary conditions” *by* Youichi Kamae et al.

Youichi Kamae et al.

kamae.yoichi.fw@u.tsukuba.ac.jp

Received and published: 28 June 2016

> Based on several experiments performed with the model MRI-CGCM2.3, the authors have analyzed the climate response to the updated boundary conditions of PlioMP2, including the CO2 concentration, the orography+vegetation+lake (OVL) as a whole, and the ice sheets. They have also compared their results with those obtained during PlioMP1 by the same model and with proxy data. This work is helpful for understanding better the origin of the Pliocene warm climate and the individual contributions of CO2, OVL and ice sheets. The manuscript is well organized and the introduction and method are well explained. The research topic is quite suitable for publication in Climate of the Past. However, this manuscript is lack of depth due to insufficient explanation on mechanisms. I would recommend to reinforce the analysis and discussion on physical mechanisms before publication by taking into account my following comments.

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Thank you for your careful reading and many constructive suggestions. Firstly ice sheet effect is estimated by changing (1) land cover and (2) topography. There are no overlaps between estimated OVL and Ice Sheet effects, so one of the reviewer's concerns (comments #5 and #6) is not true in this case.

According to reviewer's comments, we add discussions on physical processes responsible for the derived climate anomalies in Eoi400 (Pliocene) run and sensitivity runs. In revised version of our manuscript, we clarify physical meaning of "nonlinear" residual term estimated in this study. Responses to individual comments are listed below.

> 1. The authors have described the impact of OVL and ice sheets on sea surface temperature, sea ice, AMOC and the Hadley circulation, but almost no explanation is given on the physical mechanisms. I would recommend to add explanations on how the changes in OVL and ice sheets cause the changes in these climatic variables.

We agree to the comment. In our original manuscript, we only introduced general characteristics and individual roles of boundary forcings in climate responses to the Pliocene boundary conditions.

In response to the ice sheet reduction, land surface warms up locally (Fig. 5a) due to lower albedo (Fig. 7d) and lower orography (Fig. 3). The regional warming may result in sea ice reduction and sea surface warming over the surrounding regions (Figs. 5h, 6b, f). Here secondary changes in atmospheric and ocean circulations are generally smaller than the responses to other forcings (Figs. 6d, g, h, 9d, 10d). The change in atmospheric northward heat transport (Fig. 6g) may be related to mid-latitude atmospheric eddy (due to orography change and/or change in meridional temperature gradient in the troposphere and/or other processes), but more detailed analyses are needed to examine quantitatively physical processes contributing to the meridional heat transport.

OVL effect contains variety of forcing-feedback processes: direct influences of altered orography, vegetation, lakes and secondary influences/feedbacks initiated by them.

For vegetation, previous studies pointed out that vegetation cover change can result in local and global climate through biogeophysical (albedo and evapotranspiration; Davin and de Noblet-Ducoudré 2010; Willeit et al. 2013; Zhang and Jiang 2014) effect (and biogeochemistry effect; but this is not considered in this study because the model does not treat carbon cycle). Generally, large-scale vegetation change over the high latitude has substantial impact on temperature through change in albedo (Fig. 1; Davin and de Noblet-Ducoudré 2010). Decrease in albedo over the Northern Hemisphere high latitude due to northward shift of boreal forest (Fig. 1) can be a trigger for climate feedback (e.g. ice albedo feedback including sea ice reduction; Fig. 6f) and Arctic warming amplification (Fig. 6a), similar to previous studies (e.g. Zhang and Jiang 2014). The resultant meridional warming gradient induced by OVL effect (discussed in Sect. 4) can influence on global atmospheric circulation including strength and position of the mean meridional circulation including Hadley circulation (Figs. 6d, 9c), mid-latitude synoptic eddies, and associated atmospheric heat transport (Fig. 6g; see response to comment #3), precipitation pattern (Figs. 6c, 8c; see response to comment #4). Change in sea water density flux over the North Atlantic, a driving factor for the AMOC, can be drastically changed in response to OVL forcing via surface latent and sensible heat flux, radiative (longwave and shortwave) flux, and salinity budget (see response to comment #2). Physical processes responsible for the AMOC change simulated in Eoi400 and Eo400 are examined in detail in a separated paper.

In revised version of our manuscript, we add explanations and discussions on the derived climate responses to the boundary forcings to the main text.

> 2. The OVL is the major contributor for a stronger AMOC. What is the mechanism?

Change in sea surface density flux can be one of the controlling factors for the change in AMOC (Speer and Tziperman, 1992). Warmer surface air and sea surface water, changes in humidity and cloud cover can influence on surface sensible flux, latent heat flux, and longwave and shortwave radiation at sea surface over the North Atlantic. In addition, changes in river runoff, sea ice melt, and precipitation minus evaporation can affect sea surface salinity over this region. Such heat and salinity forcings can result in stronger/weaker AMOC in a perturbed climate (Speer and Tziperman, 1992). More detailed analyses will be conducted and reported in a separated paper, as described in the original manuscript. In revised version of our manuscript, we add possible factors for the AMOC change due to OVL forcing to the main text.

> 3. Page 8, line 29: how do the ice sheet and OVL enhance northward heat transport?

The anomalous atmospheric northward heat transport in Ice Sheet effect and OVL effect are found over 50N-70N. Here these anomalous transports are not attributed to zonal-mean meridional circulation because their changes are quite small (Fig. 6d). Here the mid-latitude eddy transport may play an important role in this anomalous heat transport. Ulbrich et al. (2009) summarized physical processes responsible for change in mid-latitude eddy activity in projected future climate. They revealed that changes in meridional temperature gradient in the middle-upper troposphere and near the surface can result in changes in jet stream and the mid-latitude eddies. Li et al. (2015) showed substantial changes in meridional temperature gradient in the troposphere in selected PlioMIP1 models. Actually, tropospheric meridional temperature gradient shows a similar anomalous pattern to Li et al. (2015). Such changes in meridional temperature gradient (Fig. 6a) can be one of factors for the anomalous meridional heat transport due to the atmosphere. In addition, anomalous orography over Greenland as a part of Ice Sheet effect may also contribute to changes in jet stream and mid-latitude heat transport. We add discussion on the physical processes associated with the enhanced heat transport.

> 4. The OVL causes significant change in the tropical precipitation. Any idea about which factor contributes the most, orography, vegetation or lake?

Willeit et al. (2013) and Zhang and Jiang (2014) also showed that change in vegetation cover from pre-industrial to Pliocene condition can result in significant change in tropical precipitation. Albedo reduction over the Northern Hemisphere high latitude due to vegetation change (e.g. northward shift of boreal forest; Figs. 1, 6e, 7c) contributes to the Arctic warming amplification (Figs. 5c, 6a). Associated feedback processes (e.g. snow and sea ice) amplify the high latitude warming, leading to the substantial change in meridional warming gradient (discussed in Sect. 4). Resultant warming gradient between the Northern/Southern Hemispheres (found in OVL effect; Fig. 6a) can lead to change in strength and position of the intertropical convergence zone (ITCZ)-related precipitation (e.g. Zhang and Delworth 2006; Braconnot et al. 2007) including the increase in tropical North Atlantic-North African precipitation (Fig. 8c). Other processes (evaporation change over tropical and subtropical land due to changes in vegetation and lake, orography-induced atmospheric circulation changes) may also play roles in the tropical precipitation change. We add discussion on the physical processes above to the main text.

From a regional perspective, tropical precipitation changes in the Pliocene run may strongly be related to changes in individual monsoon systems. In the PlioMIP2, systematic investigations of regional monsoon behaviors during the late Pliocene are planned to conduct. Detailed physical processes (e.g. Zhang R. et al. 2013) will be examined in future studies.

> 5. In the ice sheet experiment, how is the ice sheet defined? By changes in albedo and topography? In the lake experiment, how is the lake defined in the model? These should be explicitly explained in the paper.

> 6. The effect of ice sheets should include the effect of its topography. In the OVL experiment, the effect of the ice sheet topography seems to be also included. In this case, there should be an overlap of the effect of ice sheet topography in these two experiments. Is it true?

In this study, we estimated the ice sheet effect by comparing results of simulations with and without the ice sheet over the part of Greenland and Antarctic Continent (Figs. 1, 3). Here the anomalous ice sheet was prescribed as anomalous orography and land

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cover, so the resultant ice sheet effect contains both orography and land cover effects. The derived ice sheet effect is not overlapped with OVL effect because "orography effect" in OVL does not include the ice sheet orography.

In our original manuscript, details of the prescribed boundary conditions were not sufficiently explained. We revise the explanations on the experimental setups.

The lakes are treated in land surface model as inland water in grid boxes with a drainage basin unconnected to oceans (Yukimoto et al. 2006). The subgrid lake parameterization included in land surface model predicts water budget, but the lake surface temperature is predicted by the heat budget at the water surface, assuming a slab with a thickness of 50m, as described in Sect. 2.1. In the control run, five lakes were modeled as inland waters (Fig. 2a, Yukimoto et al. 2006). In the Pliocene run, additional lakes are implemented to land surface (Fig. 2b). We add explanations of the treatment of lakes to Sect. 2.1.

> 7. Page 9, line 19: Please explain what the “nonlinear residual” means in terms of physics.

The nonlinear residual term defined as Eq. 6 in this study means a departure from ’linear additivity of forcing-response relationships’ (e.g. Shiogama et al. 2013). If external forcing A and B were added to system separately or together, climate response to "A+B" forcing is not necessarily identical to sum of climate responses in A forcing run and B forcing run. In case for discussion in Page 9 line 19, sea ice reduction and surface warming are larger in Sum than All (Fig. 6f). Over the regions with Arctic sea ice edge, climatological sea ice concentration is limited. Sum of sea ice reductions due to strong forcings A and B (for example, 12% and 8%) can be larger than climatological sea ice concentration (for example, 15%), resulting in nonlinear forcing-sea ice reduction relationship (-20% is larger reduction than -15%) because sea ice concentration is always larger than or equal to 0%. We add explanation on possible physical processes responsible for the nonlinear residual term discussed here.

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> 8. Page 5, line 10: would there be any difference between with and without the addition of deep ocean temperature to the initial condition?

The anomalous deep ocean temperature imposed in PlioMIP1 run may play some roles, but general ocean warming pattern and AMOC change are generally similar between PlioMIP2 and PlioMIP1 (Figs. 5e, 6h in this paper, and Fig. 8e in Kamae and Ueda 2012), suggesting that the imposed deep ocean temperature is not the dominant contributor for the simulated Pliocene climate anomaly, at least after the long-term integrations (500 years). We add a note on influence of the imposed deep ocean temperature as an initial condition.

> 9. Page 5, line 26: what does the "nonlinear" mean exactly?

The "nonlinear" effect stated here means nonlinear forcing-feedback relationship. Please see response to comment #7. We add meaning of "nonlinear" effect to Sect. 2.3.

> 10. Page 5, line 29: does it suggest no interactive effect of the CO2, OVL and ice sheets?

The interactive effect suggested by Residual term is minor to All, but the residual term is not negligible for regional climate anomalies. We revise this part to clarify that Residual can be found in regional scale.

> 11. Page 8, line 12: isn’t better to change "suggesting" to "resulting from"?

We revise as "resulting from" according to your comment.

> 12. Fig11: how was the confidence level (medium, high, very high) defined?

The confidence level shown here was derived from Dowsett et al. (2013). In their paper, confidence level of proxy-suggested climate anomaly was defined by chronology, sampling density, sampling quality and performance of quantitative method. Details of confidence scheme used in the PRISM SST reconstruction can be found in Dowsett et al. (2013). We add “defined by chronology, sampling density, sampling quality and performance of quantitative method” to the caption.

> 13. Page 10: lines 2-3: PlioMP2 is cooler than PlioMP1 over N. Atlantic, so the underestimation of the warming there is actually increased but not reduced as written by the authors. And why A.Atlantic is cooler in PlioMP2 than PlioMP1?

We guess this is a reviewer’s misunderstanding on the meaning of Fig. 11. SST in PlioMIP2 run is warmer than PlioMIP1 run (Figs. 6b, 11a), so the underestimation of the warming is reduced (Fig. 11b). Generally PlioMIP2 run shows larger warming than PlioMIP1 run (Table 3). Both underestimation of warming over the North and South Atlantic middle and high latitude (Fig. 11a) are reduced in the PlioMIP2 run (Fig. 11b). We revise main text in section 5 to avoid confusing.

> 14. Page 10, line 15: the linear additivity of the Pliocene climate simulation is not necessarily obvious at regional scale (see fig6).

We agree to your comment. Global-mean response shows good linear additivity (Table 3), but the linear additivity is limited for the regional climate responses. We add a note to this section as follows: "However, linear additivity does not hold so well for regional climate responses including sea ice reduction over the high latitude oceans."

> 15. Page 10, line 21: Please comment what are the possible reasons that the model fails to reproduce the extremely warm condition over the Arctic to high-latitude North Atlantic region.

This underestimation of the high latitude North Atlantic warming was also found in PlioMIP1 multiple climate models. Haywood et al. (2013) pointed out that almost all the PlioMIP1 AOGCMs underestimated this extreme warming. Possible reasons why the model cannot reproduce the extremely warm condition over the high latitude North Atlantic may be associated with (1) AMOC biases in models, (2) sea ice biases in models, and/or (3) uncertainty in SST estimate based on proxy records (Robinson 2009;

Haywood et al. 2013). Haywood et al. (2013) noted that this large model/data discord was highly dependent on geochemically-based proxy mean annual temperature estimate and was not derived from faunal based estimates of cold/warm month means. They suggested that we should not rely on this model/data discord too much until more variety of proxy records is available from more locations in the high latitude North Atlantic and the Arctic. We add discussion on this issue to section 5.

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