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Response to Comment on "Climate Sensitivity Estimated from Temperature Reconstructions of the Last Glacial Maximum"

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The removal of data by Fyke and Eby is mostly unjustified, and their statistics are oversimplified, but the suggestion that structural model uncertainty— in particular, the atmospheric heat flux formulation— may have led to underestimation of equilibrium climate sensitivity for a doubling of atmospheric carbon dioxide concentrations in our 2011 paper may have merit and should be quantified in future studies.

Fyke and Eby (*1*) conclude that "exclusion of questionable comparison points and constructive changes to model design are both likely capable of altering the most probable value of equilibrium climate sensitivity" to a doubling of CO_2 (ECS_{2xC}) suggested in Schmittner *et al*. (*2*). Fyke and Eby modify the climate model used in (*2*) and remove data from the analysis. Together, this leads to a better fit [as indicated by the root mean square error (RMSE) of the zonally averaged difference between model and reconstructions] of their higher sensitivity (ECS_{2xC} = 3.6 K) model than that of the best fitting model of (*2*), which had a lower sensitivity (ECS_{2xC} = 2.4 K). Although the authors present tantalizing results, their conclusion is not fully substantiated by evidence, and we note that because they do not present probabilities, statements on the most probable value are inappropriate.

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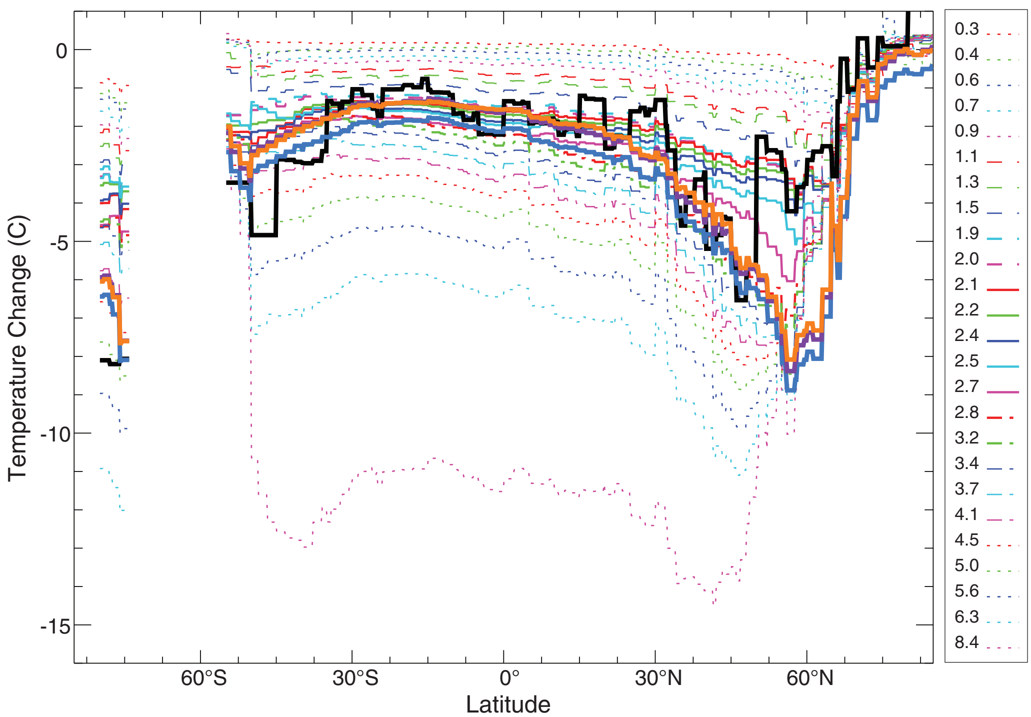
Fyke and Eby simulate the Last Glacial Maximum (LGM) with the same climate model—the University of Victoria (UVic) Earth System Climate Model—but with a different version (2.9 versus 2.8) from that used in (*2*). Two important changes in the model and experimental design are likely to be responsible for most of the differences in simulated LGM surface temperature anomalies compared with (*2*) [see figure 2 in (*1*)]. First, Fyke and Eby modified heat diffusion in the atmosphere, which reduces heat transport in their LGM simulation. This leads to warmer temperatures in the tropics and colder temperatures at high latitudes. Second, they ignore dust forcing in the experimental design of the LGM simulation, which leads to generally warmer temperatures.

The modified heat transport is an interesting sensitivity experiment exploring structural uncertainties of the simple atmospheric energy-moisture balance model component. Although it seems that this modification improves the agreement with the reconstructions and may lead to larger permissible ECS_{2xC} values than those estimated in (*2*), an unequivocal attribution and conclusion of its effect is hampered by the neglect of dust forcing in (*1*). Ample evidence from the paleo record shows elevated dust levels in the glacial atmosphere (*3*), and modeling studies have shown that dust radiative forcing influences climate (*4*) and estimates of climate sensitivity (*5*).

In a much-appreciated collaboration with Fyke and Eby, we have estimated the effect of dust forcing by calculating temperature anomalies from simulations in (*2*) with a model with similar ECS_{2xC} (3.4 K) as that used in (*1*). Adding these anomalies to the model results in (*1*) (thick blue line in Fig. 1) results in too-cold temperatures over most of the tropics. The tropics are highly influential in the ECS_{2xC} estimates in (*2*) because

Fig. 1. As figure 2 in (*1*), but including the effects of dust forcing (thick blue line) and without excluding data. The thick purple line, which is mostly obscured by the orange line, shows the dust forcing effects without the global mean. [Figure courtesy of M. Eby]



of the large surface area covered with data [figure 1 in (*2*)]. This suggests that a model with smaller ECS_{2xC} than that used in (*1*) would be in better agreement with the observations. However, tropical temperatures in the model in (*1*) (with dust forcing considered) are significantly warmer than the models in (*2*) with similar ECS_{2xC} and are more similar to the models in (*2*) with lower ECS_{2xC} by about 0.8 K. This tentatively supports the conclusion in (*1*) that structural model uncertainties (in particular, formulations of atmospheric heat transport) may have led to systematic underestimation of ECS_{2xC} in (*2*). Further study with new ensemble model experiments, including the modified heat flux formulation and LGM dust forcing, are necessary to quantify the effect of heat flux uncertainties on the best ECS_2xC estimate.

Fyke and Eby also remove various data from the analysis. This is warranted in the few cases where the reconstructed ice sheet used in the LGM simulations incorrectly puts ice over areas where pollen records exist, because fair comparison with the model is not possible there. However, most data removed in (*1*), such as from the northern North Atlantic and Beringia, is based on more subjective criteria, such as model misfit. Differences between various sea surface temperature reconstructions in the North Atlantic were extensively discussed by the Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface (MARGO) group (*6*). Grid points for which different proxies do not agree have been assigned larger error bars. In the statistical method used in (*2*), these data points are given a lower weight and have little influence on the ECS_{2xC} estimate. Thus, proxy uncertainty was appropriately considered in (*2*). Fyke and Eby argue that dinocyst reconstructions from the North Atlantic should be discarded because they are warmer than those estimated from foraminifera species, but they do not discard dinocyst reconstructions from the North Pacific (*7*), which are anomalously cold relative to estimates based on Mg/Ca and foraminifera (*8*, *9*). They also exclude data from Alaska, arguing that the UVic climate model cannot reproduce large spatial temperature gradients. Schmittner *et al*. (*2*) estimated model error objectively without removing data subjectively from the analysis. It is not surprising that removing data based on model misfit results in apparently improved model performance [as shown in the RMSE plots in the figure 2 insets in (*1*)]. We prefer the procedure recommended in the original MARGO data compilation (*6*), where all the data are retained and their uncertainties are rigorously accounted for when compared to models.

Finally, the simple metric (RMSE) used by Fyke and Eby does not permit probabilistic inferences. In particular, zonal averaging is problematic for statistical reasons (e.g., proper consideration of the reconstruction errors) and may obscure model error, and the RMSE does not consider spatial autocorrelation of the residuals, spatial error distribution of the reconstructions, or quantitative model error estimates. One feasible way forward would be to repeat the more complex study of (*2*) with model heat flux formulation uncertainties properly considered.

References

1. J. Fyke, M. Eby, *Science* **337**, 1294 (2012); www.sciencemag.org/cgi/content/full/337/6100/1294-b.
2. A. Schmittner *et al*., *Science* **334**, 1385 (2011).
3. B. A. Maher *et al*., *Earth Sci. Rev.* **99**, 61 (2010).
4. N. M. Mahowald *et al*., *J. Geophys. Res.-Atmos.* **111**, D10202 (2006).
5. T. Schneider von Deimling, H. Held, A. Ganopolski, S. Rahmstorf, *Clim. Dyn.* **27**, 149 (2006).
6. MARGO Project Members, *Nat. Geosci.* **2**, 127 (2009).
7. A. de Vernal, T. Pedersen, *Paleoceanography* **12**, 821 (1997).
8. T. Kiefer, M. Sarnthein, H. Erlenkeuser, P. M. Grootes, A. P. Roberts, *Paleoceanography* **16**, 179 (2001).
9. H. Gebhardt *et al*., *Paleoceanography* **23**, PA4212 (2008).

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