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A new estimate of climate sensitivity using Last Glacial Maximum model-data constraints that includes parametric, feedback, and proxy uncertainties

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Introduction

As the most recent period of large climate change, the Last Glacial Maximum (LGM) has been a useful target for analysis by model-data comparison[1]. In addition, significant changes in greenhouse gas forcing across the last deglaciation[2] and the relative wealth of LGM temperature reconstructions by proxy data[3-5] provide a potentially useful opportunity to quantify equilibrium climate sensitivity (ECS), the change in global mean surface air temperature due to a doubling of atmospheric CO_2. ECS is in part defined by the radiative forcing of CO_2, but the amplifying (dampening) nature of positive (negative) feedbacks in the climate system play a large role in how global mean temperature will respond to a change in forcing. Uncertainties in both the proxy data and climate feedbacks must be considered in a LGM-based assessment of ECS. Here, we present a new LGM-based assessment of ECS using the latter approach along with a simple linear parameterization of the longwave and shortwave cloud feedbacks derived from the CMIP5/PMIP3 results applied to the University of Victoria Earth System intermediate complexity model (UVIC)[6,7].

A cloud feedback emulator

UVIC does not explicitly capture the effects of cloud cover on the climate system. Therefore, we have developed a simple linear parameterization for the shortwave and longwave cloud feedbacks, as assessed from the CMIP5/PMIP3 results from the $4xCO_2$ and LGM simulations[7]. Our control simulations with these cloud feedbacks generally capture the top of the atmosphere (TOA) fluxes and temperature change from the original CMIP5/PMIP3 results.

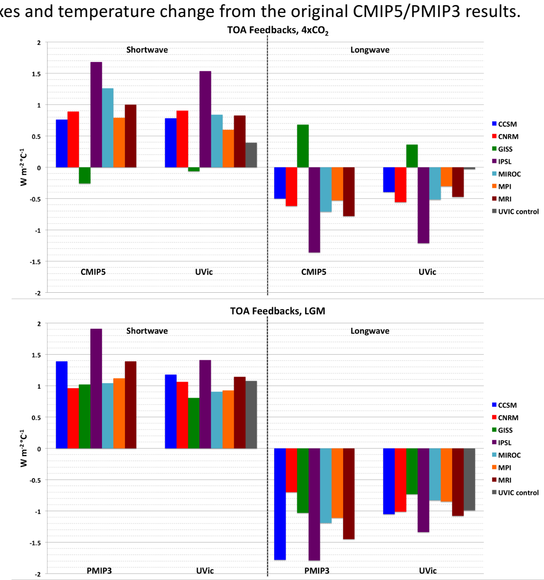


Fig. 1. Shortwave and longwave top-of-the-atmosphere (TOA) feedbacks, comparing the CMIP5/PMIP3 results with our cloud feedback emulator (UVIC). Top panel shows results from $4xCO_2$ simulations; bottom panel shows LGM results (ref. 7).

LGM:$2xCO_2$ ensemble

We conducted 280 paired simulations of the LGM and a doubling of CO_2 ($2xCO_2$) in which we adjust model ECS across a range of possibilities[8]. The LGM simulations are used to compare with proxy data, while the $2xCO_2$ simulations are used to estimate ECS. In addition, we have sampled the range of uncertainty in other model parameters that potentially impact global mean temperature:

Ensemble Member	Values	Description
Climate Sensitivity	0.5 - 7.5 °C	Adjustment made to the slope of the outgoing longwave parameterization. Effectively changes ECS.
GCM Forcings	from 7 models in the CMIP5/PMIP3 archive*	Cloud feedback parameterizations and surface wind stress[9] are derived using output from models with both LGM and 4xCO2 runs
Anomalous Diffusion Factor	0 - 0.09 $°C^{-1}$	Adjusts atmospheric heat diffusion as a function of global mean temperature. Following ref. 10.
Global Dust Forcing	0.0 - 2.0 W m^{-2}	2-D longwave/shortwave dust forcing[11] scaled to global forcing.
Snow Albedo	0.7 - 0.8	Global average snow albedo, range assessed from CMIP5/PMIP3.

***CMIP5/PMIP3 forcings assessed using results from CCSM4, CNRM-CM5, GISS-E2-R, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-P, and MRI-CGCM3**

Simulation Results

The ensemble resulted in a large variety of LGM and $2xCO_2$ climate states. However, 77 of the ensemble members led to a runaway ice-albedo feedback during the LGM simulation, mostly under high climate sensitivity ensemble states. Such a "snowball earth" scenario is inconsistent with the geologic record for the LGM; therefore such failed simulations were discarded from subsequent analysis.

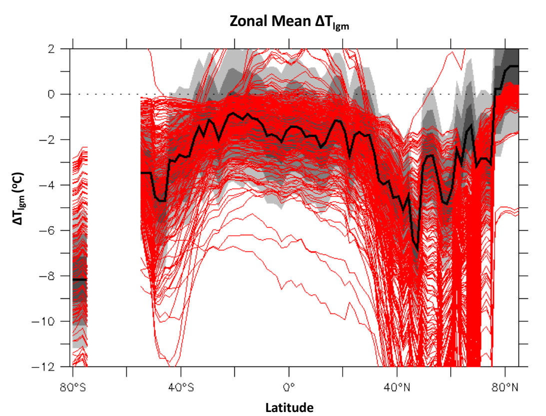
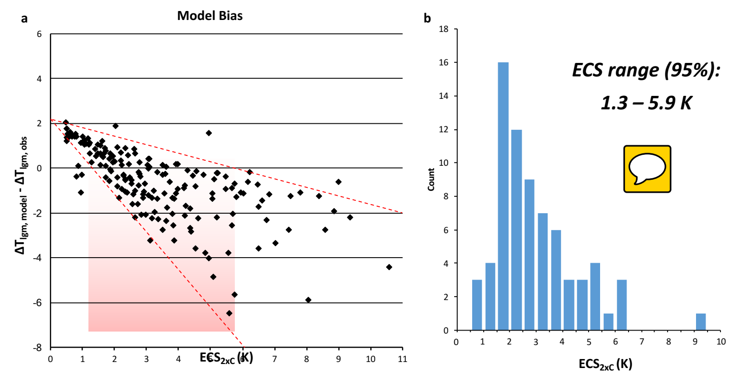


Fig. 2. Zonally averaged LGM temperature anomalies from proxy data[3-5,8] (black line with ±1-3 K uncertainty grey shading) and results from all successful individual ensemble simulations (red lines).

Estimating Climate Sensitivity



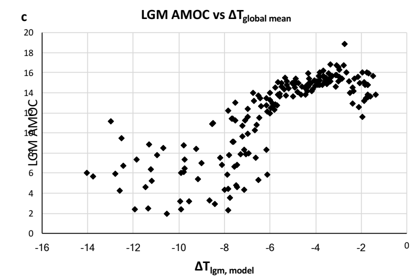


Fig. 3. (a) LGM temperature anomaly model bias (model minus proxy data[3-5,8]) as a function of simulation ECS. (b) Histogram of ECS_{2xC} for those simulations with corresponding LGM model bias that is within 0.8 K of zero (cutoff of 0.8 K was selected based on estimated uncertainty in LGM global temperature anomaly from ref. 12). The 95% confidence interval for this distribution is listed in the upper right corner (mean = 3.0 K, median = 2.5 K). (c) Modeled LGM maximum Atlantic Meridional Overturning Circulation (AMOC) as a function of LGM temperature anomaly.

Conclusions

- New parameterization of cloud feedbacks applied in UVIC generally captures the relative range of CMIP5/PMIP3 top-of-the-atmosphere feedbacks, although absolute magnitude of feedbacks may be slightly diminished.
- Ensemble of LGM and $2xCO_2$ simulations with different ECS leads to a large variety of climate states, some of which do not match proxy data synthesis.
- Ensemble results indicate an ECS range of 1.3 - 5.9 K (95% confidence), suggesting the incorporation of cloud feedback model spread from CMIP5/PMIP3 greatly increases the uncertainty from the IPCC[13] estimate of 1.5 - 4.5 K. Higher ECS values cannot be ruled out.
- There may be a possible threshold in LGM AMOC for global temperature anomalies lower than -6 °C, below which the model shows a large reduction in AMOC, consistent with other models[14].

References

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