Incorporating feedback uncertainties in a model-based assessment of equilibrium climate sensitivity using Last Glacial Maximum temperature reconstructions

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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.

Background

Past model-data comparisons have attempted to estimate ECS using the LGM climate in two ways: (1) scaling of proxy data with results from general circulation model intercomparisons[6-8], and (2) comparing data with results from an ensemble of ECS-tuned simulations using a single intermediate complexity model[9,10]. While the first approach includes the complexity of climate feedbacks, the sample size of the ECS-space may be insufficiently large to assess climate sensitivity. However, the second approach may be model dependent by not adequately incorporating uncertainty in climate feedbacks. 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)[11].

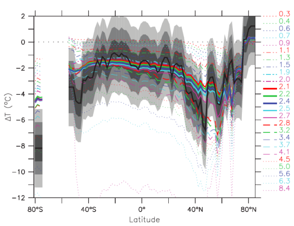

Fig. 1 (From Ref. 10). Zonally averaged LGM temperature anomalies. Black line and grey shading indicate proxy data[3-5] and ±1-3 K uncertainty. Colored lines indicate various model simulations with differing ECS. However, this approach does not consider uncertainty in climate feedbacks as expressed in the spread of other general circulation models.

CMIP5 Feedbacks

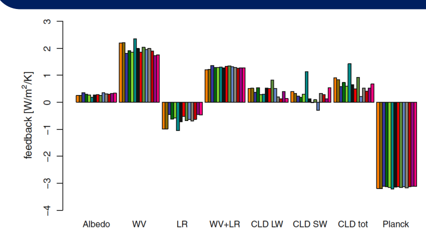

Fig. 2 (From Ref. 12). Comparison of various feedbacks from a sampling of the CMIP5 model results.

- Spread among CMIP5 models dominated by cloud feedbacks
- Both longwave and shortwave effects contribute to inter-model spread

UVIC as an CMIP5/PMIP3 emulator

As an intermediate complexity model with an energy balance atmosphere, UVIC does not explicitly capture the effects of cloud cover on the climate system. Therefore, we have developed a linear parameterization for the shortwave and longwave cloud feedbacks, as assessed from the CMIP5/PMIP3 results. The shortwave cloud feedback perturbs the atmospheric (AtmAlb) as a function of surface temperature (SAT) change, while the longwave cloud feedback directly adjusts the outgoing longwave radiation (OLW).

$$m_{atmalb}(i,j) = \frac{\Delta AtmAlb}{\Delta SAT} \qquad \text{From CMIP/PMIP} \qquad m_{OLW,cld}(i,j) = \frac{\Delta(RLUT - RLUTcs)}{\Delta SAT}$$

To UVIC

$$\Delta AtmAlb(i,j) = m_{ATMALB} \times (SAT - SAT_{control}) \qquad OLW_{cloud}(i,j) = m_{OLW,cld} \times (SAT - SAT_{control})$$

When applied in UVIC, this new parameterization generally captures the inter-model variability in the top-of-the atmosphere feedbacks.

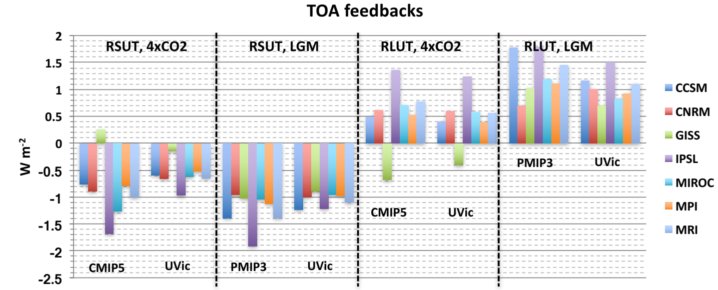

Fig. 4. Comparison of top-of-the-atmosphere feedbacks from each of the models in the CMIP5/PMIP3 and the resulting feedbacks in UVic simulations with the new cloud feedback parameterization.

An Ensemble for Climate Sensitivity

We are estimating ECS using paired simulations of the LGM and a quadrupling of CO_2 ($4xCO_2$). The LGM simulations are used to compare with proxy data, while the $4xCO_2$ simulations are used to estimate effective ECS[13]. In addition, we have sampled the range of uncertainty in other model parameters that potentially impact global mean temperature with a ensemble of 70 simulations.

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[14] are derived using output from models with both LGM and 4xCO2 runs
Anomolous Diffusion Factor	0 - 0.09 °C^{-1}	Adjusts atmospheric heat diffusion as a function of global mean temperature. Following ref. 15.
Global Dust Forcing	0.0 - 2.0 W m^{-2}	2-D longwave/shortwave dust forcing[16] 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**

Results

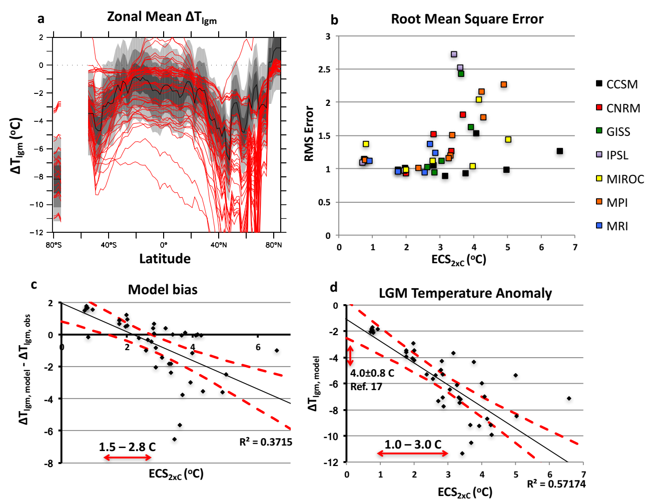

Fig. 5. (a) Zonally averaged LGM temperature anomalies from proxy data[3-5,10] (black line with ±1-3 K uncertainty grey shading) and results from individual ensemble simulations (red lines). (b) Root mean square error calculated between LGM temperature and ensemble results as a function of simulation ECS. (c) LGM temperature anomaly model bias (model minus data) as a function of simulation ECS. Red dashed lines indicate 95% confidence interval around the regression line (black). (d) LGM temperature anomaly for each ensemble member as a function of simulation ECS. Vertical red arrows indicate range from alternative model-data synthesis of LGM global mean temperature anomalies[17].

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 $4xCO_2$ simulations with different effective ECS leads to a large variety of climate states, some of which do not match proxy data synthesis.
- Preliminary ensemble results suggest ECS range of approximately 1-3 °C, on the low end of most estimate ranges.
- Future simulations will further sample ensemble space, which may revise our LGM-based estimate of ECS.

References

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