Climate Sensitivity from Paleoclimate Simulations

Esther Brady
Bette Otto-Bliesner
Nan Rosenbloom
NCAR NESL
Outline

- Motivation
- CCSM4 Paleoclimate CMIP5/PMIP3 Simulations
- CCSM4 LGM vs. Proxy Reconstructions
- Climate Sensitivity
- Polar Amplification
- Conclusions
Motivation

- Evaluate CCSM4 response to Ice-age boundary conditions and forcings as compared to the latest glacial climate reconstructions.

- Establish a constraint on Climate Sensitivity using CCSM4 paleoclimate CMIP5/PMIP3 simulations.
Motivation

Why use the LGM (21ka)?

- Long stable climate
- Large Proxy Reconstructions
- Large TOA Radiative Perturbation

LGM Radiative Forcings:

- ghg \( \sim -2.8 \text{ W m}^{-2} \) (IPCC AR4)
- Ice Sheets/Sea Level \( \sim -3.2 \text{ W m}^{-2} \) (IPCC AR4)
- Aerosols* \( \sim -1 \text{ W m}^{-2} \) (not included here)
- Vegetation* \( \sim -1 \text{ W m}^{-2} \) (not explicitly included)

Total ghg+Ice Sheet Forcing [ -5.5 to -7 W m\(^2\)] as found in Literature...
### CCSM4 Paleoclimate Simulations

**CCSM4: CAM4 FV1.25x.9_gx1v6**

<table>
<thead>
<tr>
<th>Case-name</th>
<th>GHG forcing</th>
<th>Ice Sheets</th>
<th>Orbital Year/SCON</th>
<th>Veg/Aerosols</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI (1850 Control)</td>
<td>CO2=284.7ppm</td>
<td>Modern Greenland and Antarctica</td>
<td>1990CE SCON=1360.89W/m²</td>
<td>Pre-industrial</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>CH4=791.6ppb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2O=275.68ppb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LGM</td>
<td>CO2=185ppm</td>
<td>PMIP3 LGM</td>
<td>21,000yrs before 1950CE SCON=PI</td>
<td>PI</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>CH4=350ppb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2O=200ppb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LGMCO2</td>
<td>CO2=185ppm</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>1100</td>
</tr>
<tr>
<td>4xCO2</td>
<td>CO2=1138.8ppm</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>255*</td>
</tr>
</tbody>
</table>
Last Glacial Maximum (LGM) 21ka

Ice Sheet Elevation change from Present day - a new ‘blended’ ice sheet product
(ICE-6G v2.0, Argus and Peltier 2010; MOCA, Tarasov and Peltier 2004; ANU, Lambeck et al. 2010)
LGM vs. Glacial Proxy Reconstructions

[Annual Mean LGM-PI ΔTS]
Terrestrial pollen-based (Bartlein et al. 2011)
Marine-based multi-proxy (MARGO 2009)

Modeled ΔTS over open ocean and land compares well in magnitude and pattern to latest Proxy Reconstructions
LGM vs. Proxy Data

Simulated LGM reproduces well the large scale spatial pattern in the proxy reconstructions.
Proxy warming over North Atlantic Near(Under?) Seaice has high uncertainty.
LGM vs. Proxy Data

Model is colder near Boundaries in North Atlantic
LGM vs. Proxy Data

Model is colder over high latitude Eurasia.
LGM vs. Proxy Data

CCSM4 LGM doesn’t show terrestrial warming as in proxies
LGM vs. Proxy Data

Model shows more uniform cooling across tropical oceans.
LGM compares reasonably well to available Proxy Reconstructions (within $\sim1.2^\circ$C).

<table>
<thead>
<tr>
<th></th>
<th>PROXY</th>
<th>LGM</th>
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<tbody>
<tr>
<td>GLOBAL $\Delta$SST</td>
<td>-2.0</td>
<td>-2.9</td>
</tr>
<tr>
<td>$\Delta$MAT</td>
<td>-6.1</td>
<td>-7.3</td>
</tr>
<tr>
<td>TROPICS $\Delta$SST (+/-30°)</td>
<td>-1.5(+/-1.2)</td>
<td>-2.2</td>
</tr>
<tr>
<td>$\Delta$MAT</td>
<td>-3.2</td>
<td>-3.5</td>
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but with a consistent cold bias.
Gregory et al. (2004) method to diagnose Climate Response Parameter $\lambda$

$$\Delta Q = \Delta F - \lambda \Delta TS$$

Net TOA Imbalance = Forcing – (Climate Response)

At Equilibrium: $\lambda = \Delta F/\Delta TS$

<table>
<thead>
<tr>
<th>Case</th>
<th>$\Delta F$ W m$^{-2}$</th>
<th>$\Delta T_{Seq}$ °C</th>
<th>$\lambda_c$ W m$^{-2}$/°C</th>
<th>ECS °C</th>
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<tbody>
<tr>
<td>LGMCO2</td>
<td>-2.3</td>
<td>-2.6</td>
<td>0.9</td>
<td>4.2</td>
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<tr>
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LGM $\Delta F$ estimated by regression over first 20 years; Other cases by IPCC formula.
Use Gregory et al. (2004) method to diagnose Climate Response Parameter $\lambda$:

$$\Delta Q = \Delta F - \lambda \Delta TS$$

Net TOA Imbalance = Forcing – (Climate Response)

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$\Delta T_{Seq}$ estimated as $\Delta TS$-intercept ($\Delta Q=0$)

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$$\Delta Q = \Delta F - \lambda \Delta T_S$$

Net TOA Imbalance = Forcing – (Climate Response)

$$\lambda_c = \frac{\Delta F}{\Delta T_{Seq}}$$

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$\text{ECS} = 3.7 \text{Wm}^2/\lambda_c$

Equilibrium Climate Sensitivity ($\Delta TS$ for 2xCO2 forcing)

Bitz et al. 2011 CCCM4; $\text{ECS} = 3.2^\circ$C.
Use Gregory et al. (2004) method to diagnose Climate Response Parameter $\lambda$:

$$\Delta Q = \Delta F - \lambda \Delta T_S$$

Net TOA Imbalance = Forcing – (Climate Response)

IPCC AR4: ECS = 2-4.5°C (to 2xCO2 forcing) with 3°C as best estimate.

Schmittner et al. (2011)
ECS = 1.7-2.6°C, with 2.3°C as best estimate. (Statistical approach using Proxy Reconstructions combined with EMIC simulations of LGM)

Bitz et al. (2011) CCSM4-SOM
ECS = 3.2°C

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<tr>
<th>Case</th>
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ECS = 3.7 W m⁻²/λ_c
Equilibrium Climate Sensitivity ($\Delta T_S$ for 2xCO2 forcing)
Polar Amplification =

$$\frac{\Delta TS(y)}{\Delta TS_{glob}}$$

$$\frac{\Delta TS(y)}{(\Delta F - \Delta Q)}$$
NH Sea Ice Concentration

LGM

LGMCO2

PI

4xCO2
Atlantic Meridional Overturning Circulation

Both LGMCO2 and 4xCO2 show a weakening in AMOC (and northward ocean heat transport).

LGM simulation shows a strengthening of AMOC (and northward ocean heat transport) in response to stronger wind stresses.
Conclusions

1. The LGM simulation compares well to available proxy temperature reconstructions, however, there is a consistent cold bias with no simulated warming as in the proxy reconstructions.

2. CCSM4 LGM simulation predicts an ECS = ~3.3°C comparable to Bitz et al. 2011 CCSM4-SOM ECS.

3. CCSM4 shows a greater climate sensitivity (and a greater polar amplification in NH) to a lowering to glacial CO2 levels than either a 4-fold increase or the full glacial forcing including the ice sheets.

4. Weakening AMOC response in LGMCO2 may act as a positive feedback to increased sea ice growth in North Atlantic, enhancing the positive ice/snow albedo feedback.
\[ \lambda_{\text{eff}} = \frac{\Delta Q - \Delta F}{\Delta TS} \]

\[ \text{ECS} = 3.7 \text{Wm}^{-2}/\lambda_{\text{eff}} \]