Using idealized GCM simulations to reconstruct (and interpret) past climate change

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Past climate has been driven by multiple concurrent forcings (orbital, greenhouse gas, ice sheets, etc.). Isolating the exact roles of each forcing in causing paleoclimate change can be difficult.

To help interpret paleoclimate records, we propose a use of idealized GCM simulations (in which climate forcings are applied individually) – By scaling and combining these idealized simulations, linear reconstructions of past climate can be made.

Research questions:

• To what degree are idealized sensitivity experiments adequate to understand climate response to combined forcings?

• Is the model’s climate sensitivity supported by proxy data?
Idealized “fingerprint” simulations isolate the climate response to individual forcings.

We use **GFDL CM2.1**, a coupled atmosphere-ocean general circulation model.

**Idealized equilibrium simulations**

- **Obliquity (tilt):** Obliquity set to low (~22°) and high (~24.5°) values of the past 600 kyr (Berger and Loutre 1991).

- **Precession and eccentricity:** Perihelion set to four times during precession cycle, with increased eccentricity. One additional simulation has zero eccentricity.

- **Greenhouse gases:** CO₂ set to half its preindustrial value.

- **Ice sheets:** Ice sheets set to LGM sizes.

All other forcings are set to preindustrial.
Low – high obliquity (tilt)

Perihelion at NH winter solstice – summer solstice

Climate fingerprints

$\Delta T$ of annual-mean 2m air (°C) in the idealized experiments.

Additional perihelion simulations (perihelion at NH autumnal and vernal equinoxes, and zero eccentricity) are not shown.
Climate fingerprints

Annual-mean $\Delta T$ of 2m air ($^\circ$C) in the idealized experiments.

Next: By properly scaling and combining climate “fingerprints”, linear reconstructions of past climate can be made.
Reconstructing past climate: mid-Holocene

Annual-mean $\Delta T$ (°C), mid-Holocene - preind

Time-slice

Linear reconstruction

Correlation = 0.85
RMSE = 0.22°C
The mid-Holocene linear reconstruction can be separated into its two components: changes due to obliquity and changes due to precession.

**Effects of obliquity at mid-Holocene**
- Warming at high latitudes.
- More zonally-consistent changes.
- Small changes in seasonal cycle (not shown).

**Effects of precession at mid-Holocene**
- Monsoons: stronger in NH, weaker in SH.
- Cooling over oceans.
- Large changes in seasonal cycle (not shown).
Reconstructing past climate: LGM

Annual-mean $\Delta T$ ($^\circ\text{C}$), LGM - preind

Linear reconstruction

Time-slice $\Delta T$

Correlation = 0.99
RMSE = 1.26$^\circ\text{C}$
Mid-Holocene and LGM precipitation

Annual-mean *precipitation* (mm/day)
Time-slice (x) vs. linear reconstruction (y)

Mid-Holocene - preind

Correlation = 0.88
RMSE = 0.14 mm/day

LGM - preind

Correlation = 0.93
RMSE = 0.32 mm/day
To reconstruct time-series, the climate “fingerprints” are scaled by the records of *time-varying* forcings:

- Orbital calculations (Berger and Loutre 1991)
- CO₂ and CH₄ from Vostok (Petit et al. 1999)
- Sea level as a proxy for ice sheet volume (Lea 2002)

Records are aligned to the LR04 benthic stack using Match software (Lisiecki and Lisiecki 2002).
Core TR163-19 (Lea 2004)

G. Ruber; Eastern equatorial Pacific, 2.26°N, 90.95°W, 2348m.

SST a function of Mg/Ca (Dekens et al. 2002).
Cocos Ridge ΔSST (°C) from proxy (black) and annual-mean reconstruction (blue).

Proxy (x) vs. reconstruction (y).
Correlation = 0.75
RMSE = 1.04°C

Contribution of ΔSST due to:
- obliquity (red)
- precession (red dashed)
- ice sheets (purple)
- greenhouse gases (green)
How would scaling factors change with a more ideal fit? A Markov Chain Monte Carlo is performed to select scaling factors for the orbital, GHG, and ice sheet terms, as well as a vertical offset term.

Cocos Ridge ΔSST (K) from proxy (black) and fitted reconstruction (blue):

a) Using annual-mean values:
   - GHG scaling > 1
   - Ice sheet scaling < 1

b) Allowing a seasonal bias:
   - GHG scaling > 1
   - Ice sheet scaling < 1
   - Slightly improved fit
   - Seasonal bias toward ~DJF
Conclusions

• Many aspects of mid-Holocene and LGM simulations are replicated by linear reconstructions of idealized simulations. Idealized simulations may help identify forcing/response relationships and possible non-linearities.

• For Cocos Ridge, broad features are captured, but some details are not well replicated.

• Bayesian analysis suggests a higher sensitivity to greenhouse gases and a smaller sensitivity to ice sheets than found in the model at Cocos Ridge. Allowing a seasonal bias (centered on ~DJF) improves the fit, suggesting a possible seasonal influence on the proxy.

• Possible sources of error: using simulations from only one GCM, lack of additional forcings (aerosols, vegetation), choice of forcing records, other design limitations. However, results are promising and analysis is ongoing.


Figure sources:

Thank you.

Questions?