The Last Glacial Maximum Sea Surface Temperature Pattern Effect

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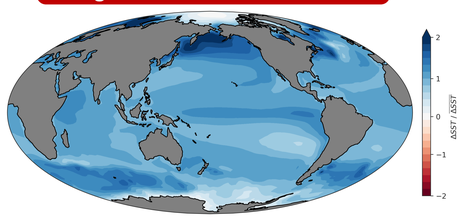
MOTIVATION

- The Last Glacial Maximum (LGM) has been proposed as a **strong constraint on modern-day equilibrium climate sensitivity** (ECS)[1], but radiative **feedbacks that determine ECS depend on spatial patterns of sea surface temperature (SST)**
  - SST "pattern effects" have not been accounted for in estimates of ECS based on the LGM
- Does accounting for the SST pattern effect in the LGM **increase or decrease ECS estimates?**
- How much do **uncertainty in SST pattern reconstructions** and **uncertainty in atmospheric physics** contribute to uncertainty in ECS derived from the LGM?

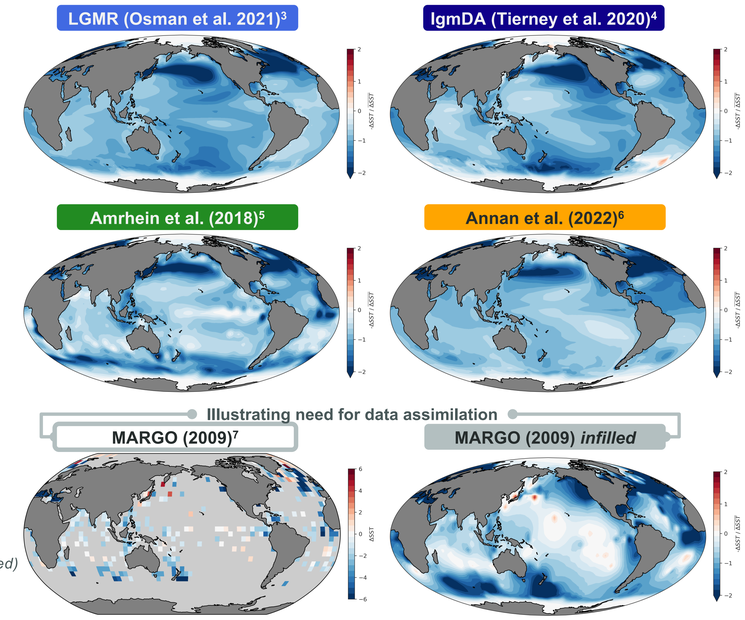
LGM VS. 2xCO$_2$ SST PATTERNS

- **Reconstructed SST anomalies** for the LGM differ from 1) each other and 2) the expected long-term 2xCO$_2$ warming pattern
- **Data assimilation** keeps reconstructions dynamically consistent (compared to infilling) and helps quantify uncertainty

Equilibrium 2xCO$_2$ LongRunMIP[2] Multi-model Mean



Mean near-equilibrium SST warming pattern (with colorbar reversed) from 2xCO2 experiments in 6 models: CESM1.0.4, HadCM3L, CNRM-CM6.1, MIROC3.2, MPI-ESM1.2, and GFDL ESM2M



METHODS: ATMOSPHERIC GCM EXPERIMENTS

- Run atmosphere-only GCMs (AGCMs) with **prescribed SST/SIC boundary conditions** (infilled to modern sea level and ice sheets):
  - SST patterns for each of the **Last Glacial Maximum**, the **Late Holocene**, and equilibrium **2xCO$_2$**
  - *Keep forcing constant in all 3 cases (use modern-day GHG, aerosol, etc.):*

$$\Delta N = \lambda \Delta T + \Delta F, \qquad \text{constant } \Delta F = 0, \qquad \text{yields } \lambda = \frac{\Delta N}{\Delta T}$$

- Prescribe the change in SST and sea-ice concentration, compute change in top-of-atmosphere radiative imbalance (ΔN)
  - **The result: estimate of feedback λ actuated by SST changes[8,9]**
- Schematic of model experiments (3 configurations run in **CAM4** and **CAM5**):

LGM
Prescribed SST/SIC:
4 datasets (see above)

Late Holocene (baseline)
Prescribed SST/SIC:
LGMR (Osman et al. 2021)

Equilibrium 2xCO$_2$
Prescribed SST/SIC:
LongRunMIP multi-model mean (final 200 years)

$$\lambda_{\mathrm{LGM}} = \frac{N_{LGM} - N_{LH}}{T_{LGM} - T_{LH}}$$

Compute baseline N_{LH} and T_{LH}

$$\lambda_{2\mathrm{xCO_2}} = \frac{N_{2\mathrm{xCO_2}} - N_{LH}}{T_{2\mathrm{xCO_2}} - T_{LH}}$$

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[3] Osman, M. et al. (2021). Globally resolved surface temperatures since the Last Glacial Maximum. *Nature.*
[4] Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J., & Poulsen, C. J. (2020). Glacial cooling and climate sensitivity revisited. *Nature.*
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[8] Andrews, T., et al. (2018). Accounting for Changing Temperature Patterns Increases Historical Estimates of Climate Sensitivity. *Geophysical Research Letters..*
[9] Rugenstein, M., & Armour, K. (2021). Three Flavors of Radiative Feedbacks and Their Implications for Estimating Equilibrium Climate Sensitivity. *Geophysical Research Letters.*
[10] Zhou, C., Zelinka, M. D., & Klein, S. A. (2017). Analyzing the dependence of global cloud feedback on the spatial pattern of sea surface temperature change with a Green's function approach. *JAMES.*

RESULTS

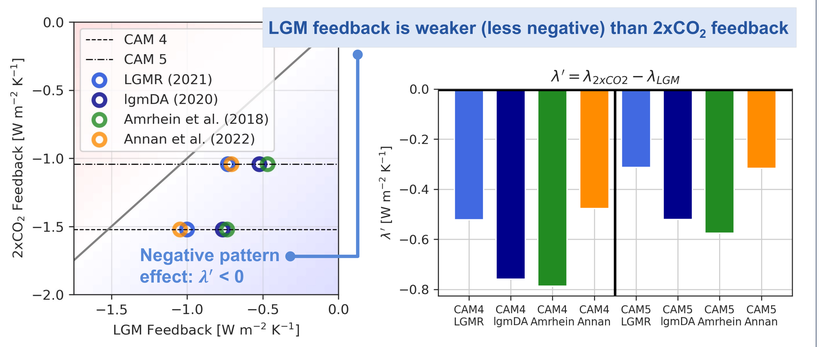
PATTERN EFFECT IN THE LGM

Figures: Comparison of radiative feedback (λ) from 2xCO$_2$ vs. LGM SST changes, diagnosed in AGCM experiments

- Pattern effect λ' quantified as:

$$\lambda' = \lambda_{2\mathrm{xCO_2}} - \lambda_{\mathrm{LGM}}$$

- Uncertainty in λ' from:
  - Different SST reconstructions
  - Different model physics



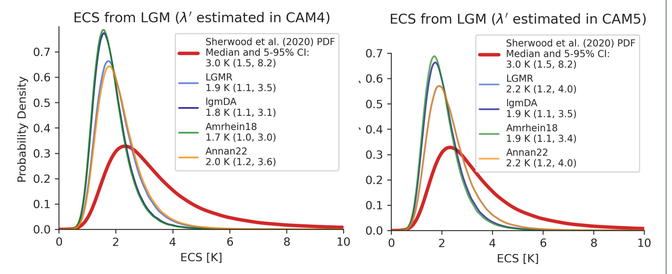
IMPACT ON CLIMATE SENSITIVITY

- Adjust λ in ECS from LGM for pattern effect λ':

$$ECS_{\mathrm{LGM}} = \frac{\Delta F_{2\mathrm{xCO2}}}{\lambda_{\mathrm{LGM}} + \lambda'}$$

Figure: PDF of ECS from LGM following Sherwood et al. (2020), including pattern adjustments to λ_{LGM}

- LGM feedback weaker (less negative) than 2xCO$_2$ feedback in all reconstructions and both AGCMs
  - Implies negative pattern effect ($\lambda' < 0$): **reduces modern-day ECS** when pattern effect is accounted for



DISCUSSION

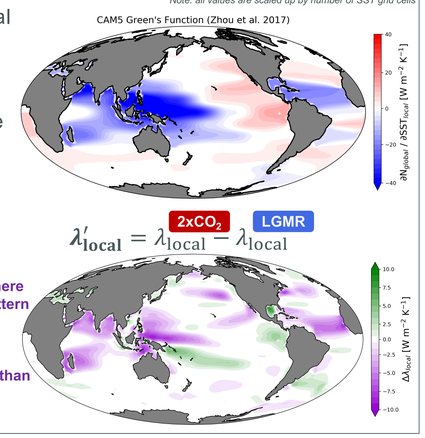
GREEN'S FUNCTIONS AND PALEO SST PATTERNS

Define $\boldsymbol{\lambda_{\mathrm{local}}} = \Delta \mathrm{N}_{\mathrm{local}} / \overline{\Delta \mathrm{T}_{\mathrm{global}}}$, at each SST grid point, where $\Delta \mathrm{N}_{\mathrm{local}}$ is the global TOA response from a local SST change, and the global integral of $\boldsymbol{\lambda_{\mathrm{local}}} = \boldsymbol{\lambda}$.

Figures (using CAM5 Green's Function[10]):

- (top right) CAM5 Green's Function for change in global TOA radiative imbalance (ΔN) per local SST increase
- (lower left) λ_{local} from 2xCO$_2$
- (lower middle) λ_{local} from LGM based on LGMR dataset
- (bottom right) $\lambda'_{\mathrm{local}} = \lambda^{2\mathrm{xCO2}}_{\mathrm{local}} - \lambda^{LGM}_{\mathrm{local}}$
  - *Note: global integral of λ'_{local} equals pattern effect λ'*

Note: all values are scaled up by number of SST grid cells



CONCLUSIONS AND NEXT STEPS

- **LGM SST pattern produces weaker radiative feedbacks (i.e., less negative) than 2xCO$_2$**, yielding a negative pattern effect: $\lambda_{2\mathrm{xCO_2}} - \lambda_{\mathrm{LGM}} < 0$
  - **Significant uncertainty in LGM pattern effect** from 1) differences in SST reconstructions and 2) differences in atmospheric model physics
  - Ensemble members from data assimilation will be used to quantify uncertainty in SST reconstructions
  - Additional AGCMs will be used to further quantify uncertainty from differences in model physics
- Accounting for the negative **pattern effect reduces ECS estimates derived from the LGM**
- Future experiments normalizing global $\Delta \boldsymbol{T}$ will separate pattern-based changes in $\boldsymbol{\lambda}$ from **state-dependence** on $\Delta \boldsymbol{T}$

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