# The Last Glacial Maximum Pattern Effect

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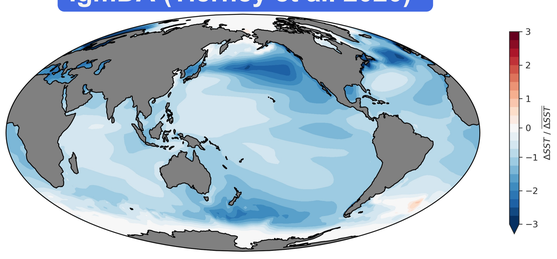
## MOTIVATION

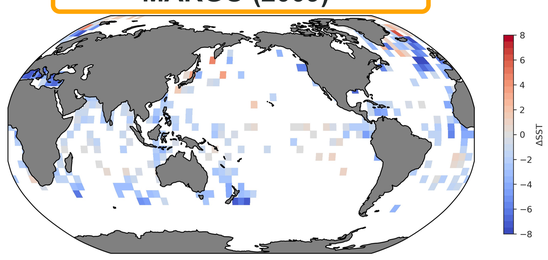
- The Last Glacial Maximum (LGM) has been proposed as a **strong constraint on modern-day equilibrium climate sensitivity** (ECS)[1], but SST pattern effects have not been accounted for
- Does the pattern effect in the LGM **increase or decrease ECS estimates?**
- How much do **uncertainty in SST pattern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

## LGM VS. 4xCO$_2$ SST PATTERNS

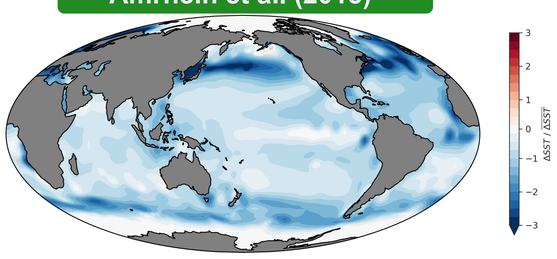
**IgmDA (Tierney et al. 2020)[2]**



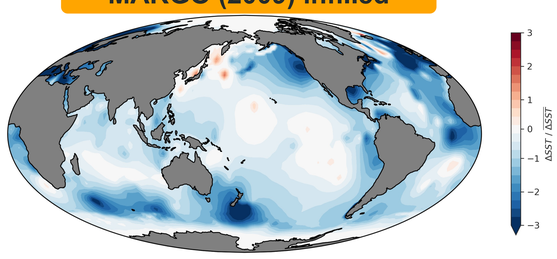

**MARGO (2009)[4]**



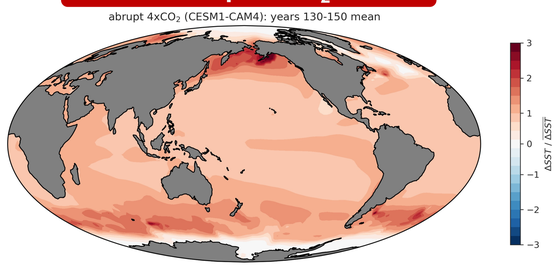

**Amrhein et al. (2018)[3]**




**MARGO (2009) infilled**




**abrupt4xCO$_2$**




- **Reconstructions differ** from 1) each other and 2) the 4xCO$_2$ warming pattern
- **Data assimilation** keeps reconstructions dynamically consistent, helps quantify uncertainty
- **More patterns still to test**: LGM Reanalysis (Osman et al. 2021)[5] and Annan et al. (2022, preprint), not shown

## METHODS: ATMOSPHERIC GCM EXPERIMENTS

- Run atmosphere-only GCMs (AGCMs) with prescribed SST/SIC boundary conditions (infilled to modern day sea level and ice sheets) for:
  - The **Last Glacial Maximum**, the **Late Holocene**, and **abrupt4xCO$_2$**
  - *Keep forcing constant in all 3 cases (use modern-day GHG, aerosol, etc.):*

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

- Prescribe the change in SST and sea-ice concentration, compute change in top-of-atmosphere radiative imbalance ($\Delta \boldsymbol{N}$)
  - **The result: estimate of feedback $\boldsymbol{\lambda}$ actuated by SST changes[6,7]**
- Schematic of model experiments (3 configurations run in **CAM4** and **CAM5**):

| **LGM** | **Late Holocene (baseline)** | **abrupt4xCO$_2$** |
|---|---|---|
| Prescribed SST/SIC: *3 datasets (see above)* | Prescribed SST/SIC: Tierney et al. 2020 | Prescribed SST/SIC: From CESM1-CAM4 (mean of yrs. 130-150) |
| $\lambda_{\mathrm{LGM}} = \frac{N_{LGM} - N_{LH}}{T_{LGM} - T_{LH}}$ | Compute baseline $N_{LH}$ and $T_{LH}$ | $\lambda_{4\mathrm{xCO_2}} = \frac{N_{4\mathrm{xCO_2}} - N_{LH}}{T_{4\mathrm{xCO_2}} - T_{LH}}$ |


### References

[1] Sherwood, S. C., et al. (2020). An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. In *Reviews of Geophysics* (Vol. 58, Issue 4).

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[5] Osman, M. B., Tierney, J. E., Zhu, J., Tardif, R., Hakim, G. J., King, J., & Poulsen, C. J. (2021). Globally resolved surface temperatures since the Last Glacial Maximum. *Nature 2021 599:7884*, *599*(7884), 239–244.

[6] Andrews, T., Gregory, J. M., Paynter, D., Silvers, L. G., Zhou, C., Mauritsen, T., Webb, M. J., Armour, K. C., Forster, P. M., & Titchner, H. (2018). Accounting for Changing Temperature Patterns Increases Historical Estimates of Climate Sensitivity. *GRL*, *45*(16), 8490–8499.

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[8] 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*, *9*(5), 2174–2189.


# RESULTS

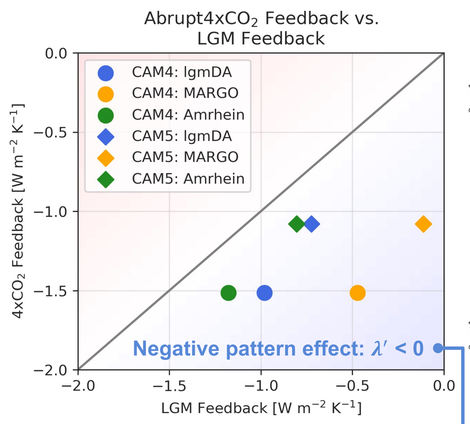
## PATTERN EFFECT IN THE LGM

**Figures:** Comparison of feedback (λ) from 4xCO$_2$ vs. LGM SST changes, diagnosed in AGCM experiments

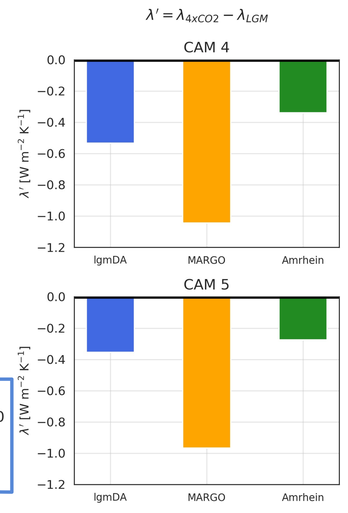
- Pattern effect $\lambda'$ quantified as:

$$\lambda' = \lambda_{4\mathrm{xCO_2}} - \lambda_{\mathrm{LGM}}$$

- Uncertainty in $\lambda'$ from:
  - Different SST reconstructions
  - Different model physics




LGM feedback is weaker (less negative) than 4xCO$_2$ feedback



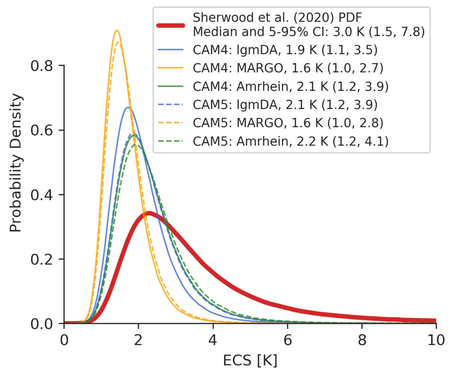

## IMPACT ON CLIMATE SENSITIVITY

- Adjust $\lambda$ for pattern effect $\lambda'$ when using LGM for ECS:

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

**Figure:** PDF of ECS from the LGM following Sherwood et al. (2020), including pattern adjustments to $\lambda_{\mathrm{LGM}}$

- LGM feedback is weaker (less negative) than 4xCO$_2$ feedback in all reconstructions and AGCM simulations:
  - Implies negative pattern effect ($\lambda' < 0$), which **reduces modern-day ECS** when pattern effects are accounted for



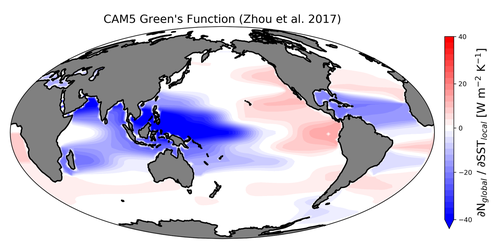

# DISCUSSION

## GREEN'S FUNCTIONS AND PALEO SST PATTERNS

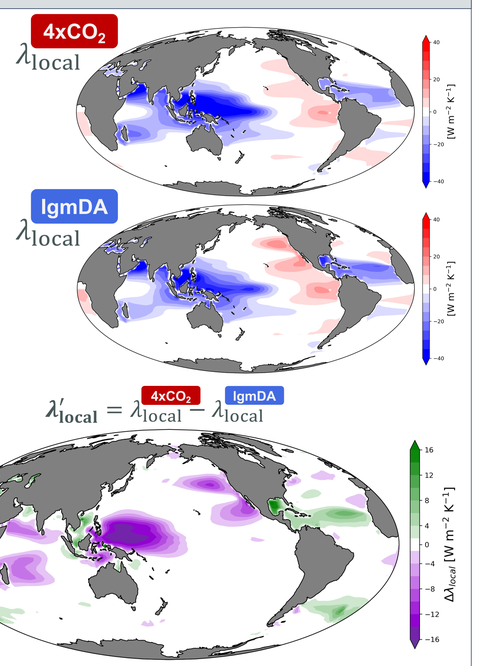
Define $\boldsymbol{\lambda_{\mathrm{local}}} = \Delta \mathrm{N}_{\mathrm{local}} / \overline{\Delta \mathrm{T}_{\mathrm{global}}}$, at each SST grid point, where $\Delta \mathrm{N}_{\mathrm{local}}$ is the global TOA response from a local SST change, and the global integral of $\boldsymbol{\lambda_{\mathrm{local}}}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

**Figures** (all computed using CAM5 Green's Function "GF"):

- (top right) $\lambda_{\mathrm{local}}$ from 4xCO$_2$
- (middle right) $\lambda_{\mathrm{local}}$ from LGM based on IgmDA dataset
- (bottom right) $\lambda'_{\mathrm{local}} = \lambda^{4\mathrm{xCO2}}_{\mathrm{local}} - \lambda^{LGM}_{\mathrm{local}}$
  - *Note: global integral of $\lambda'_{local}$ equals pattern effect $\lambda'$*
- (bottom left) CAM5 GF[8] for change in global TOA radiative imbalance (ΔN) per local SST increase




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




Purple where 4xCO$_2$ pattern yields stronger negative feedback than LGM

# CONCLUSIONS AND NEXT STEPS

- **LGM SST pattern produces weaker feedback (i.e., less negative) than 4xCO$_2$**, yielding negative pattern effect: $\lambda' < 0$
  - *Need to test sensitivity to 4xCO$_2$ pattern (e.g., run experiment with extrapolated equilibrium pattern)*
- **Significant uncertainty in LGM pattern effect** from 1) different SST reconstructions and 2) different model physics
- Negative **pattern effect reduces ECS estimates based on LGM,** but substantial spread comes from pattern effect uncertainty
- Future experiments with normalized global mean $\Delta \boldsymbol{T}$ will separate pattern-based changes in $\boldsymbol{\lambda}$ from **state-dependence** on $\Delta \boldsymbol{T}$

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