Paleoclimate Pattern Effects and Revised Estimates of Modern-day Climate Sensitivity

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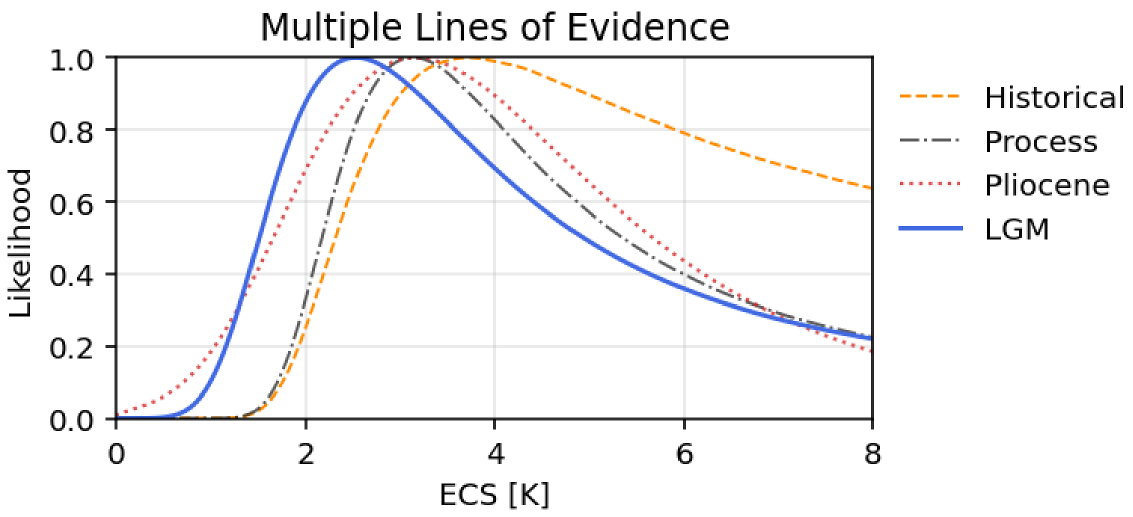
Motivation: Inference of modern-day ECS

$$ECS = \frac{-F_{2xCO_2}}{\lambda_{2xCO_2}}$$

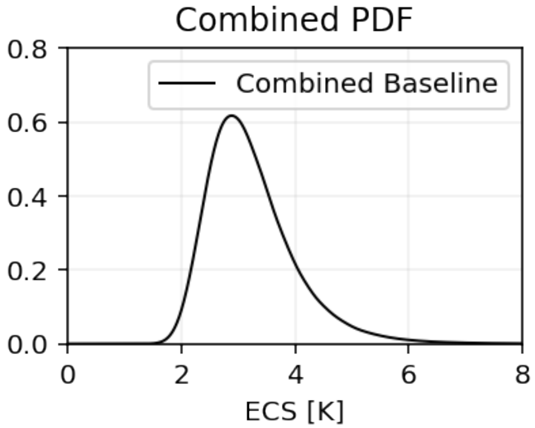
Sherwood et al. (2020), also IPCC AR6

Three lines of evidence for ECS:

1. Historical record (1870-present)
2. Process understanding
3. Paleoclimate
   - **Pliocene (~3 million years ago)**
   - **Last Glacial Maximum (~21 thousand years ago)**



Data from Sherwood, Webb et al. (2020)



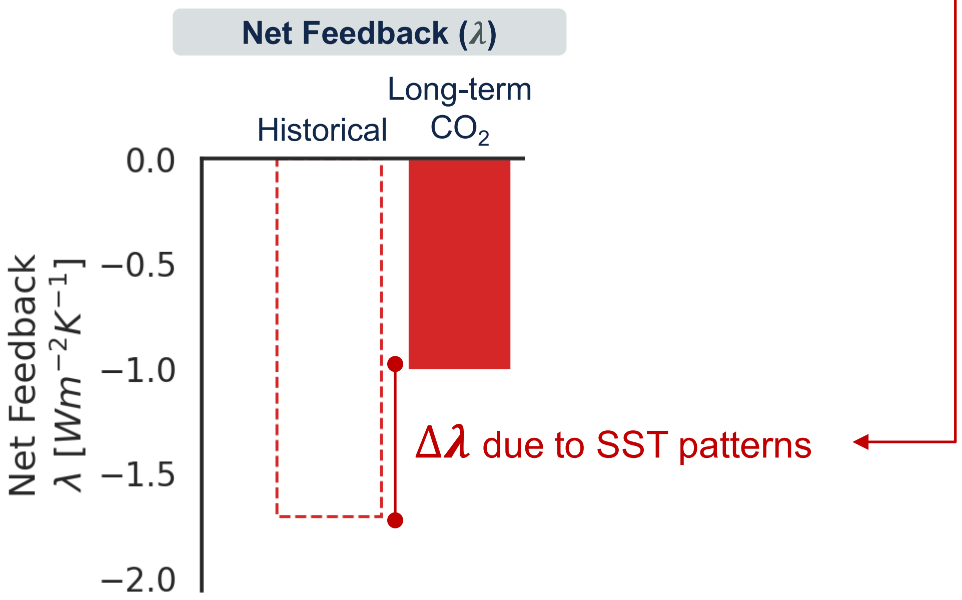
Combine lines of evidence: Median 3.1 K (5–95%: 2.0-5.7 K)

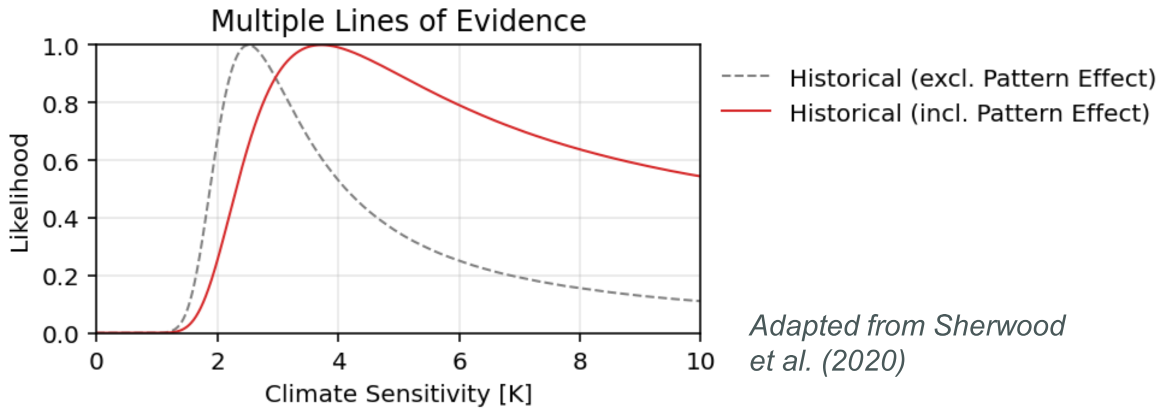
- **Paleoclimate is best constraint on high values of ECS**

Motivation: Inference of modern-day ECS

Why is the historical record so uninformative?

- Weak constraint because of ***SST pattern effect ($\Delta\lambda$)***
  (Andrews et al. 2018, 2022)





Adapted from Sherwood et al. (2020)

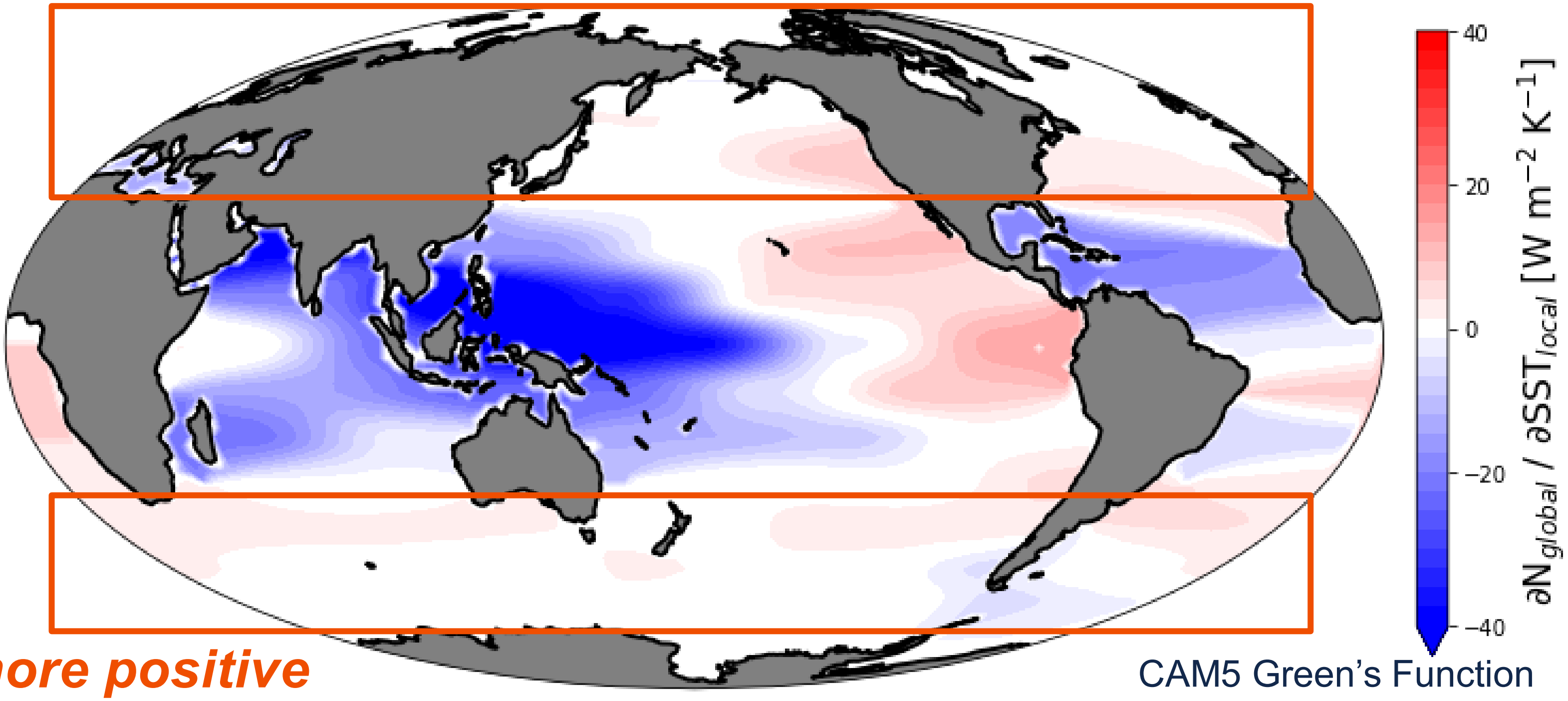
Pattern effect:
Net feedback (λ) depends on pattern of SST anomalies

***Eos* article,** *October 2023*: "Patterns of Surface Warming Matter for Climate Sensitivity" (Rugenstein et al. 2023)

Response of **global-mean TOA radiation** to **local SST anomalies**

Blue = negative feedback

Red = positive feedback



Feedbacks are ***more positive*** *at high latitudes*

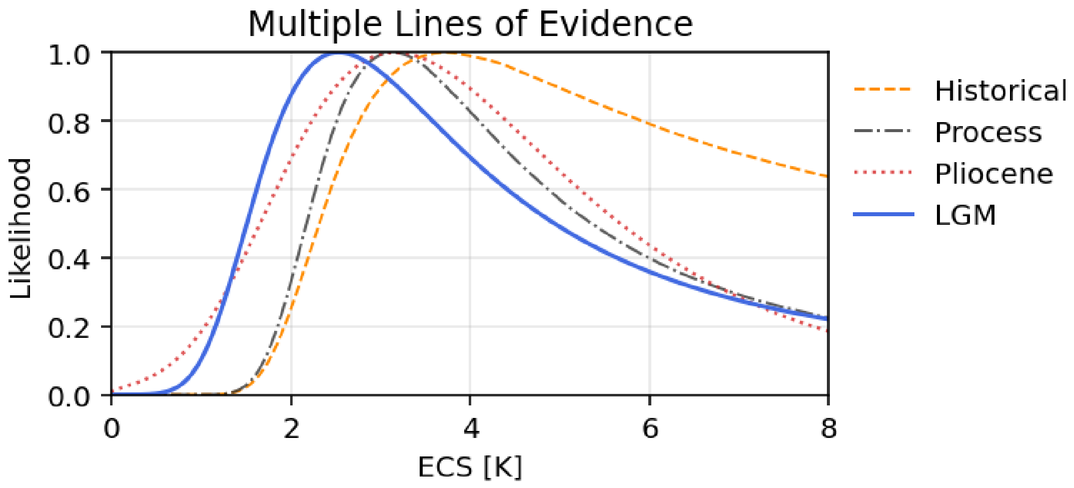
CAM5 Green's Function (Zhou et al. 2017)

Motivation: Inference of modern-day ECS

Key question:

- Are there **paleo pattern effects** that have not been accounted for?
  - Last Glacial Maximum and **Pliocene**

    Cooper et al., in revision



$$\lambda_{\mathrm{LGM}} = -\frac{\Delta F_{\mathrm{ice}} + \Delta \mathrm{F}_{\mathrm{CO_2}} + \Delta \mathrm{F}_{\mathrm{CH_4,N_2O}} + \Delta \mathrm{F}_{\mathrm{dust}} + \Delta \mathrm{F}_{\mathrm{veg}}}{\Delta T}$$

Does λ_{LGM} need an adjustment for pattern effects $(\Delta\lambda)$?

Different spatial patterns of **forcing** in modern-day 2xCO_2 vs. Paleoclimates

Effective Radiative Forcing **(ERF)** in AGCMs,
Normalized by global mean

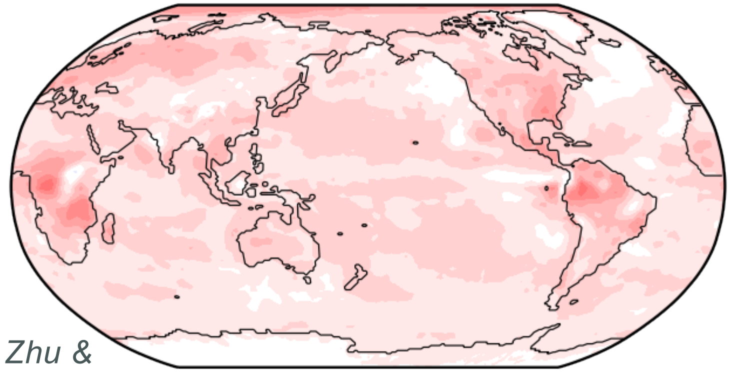
IPCC AR6: $\Delta T = -6.0 \pm 1.0\ °C$

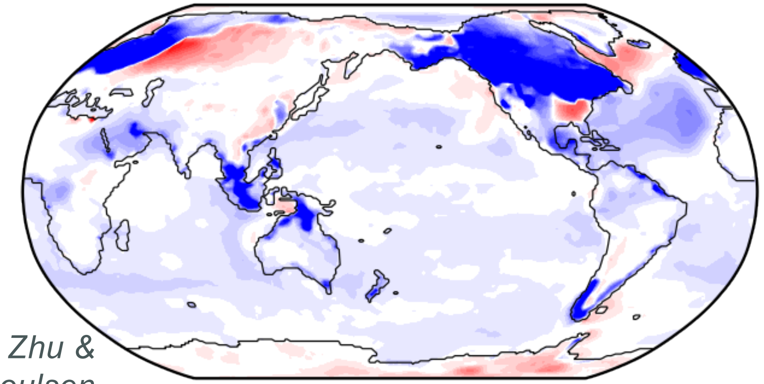
IPCC AR6: ΔT range $2.5–4.0\ °C$

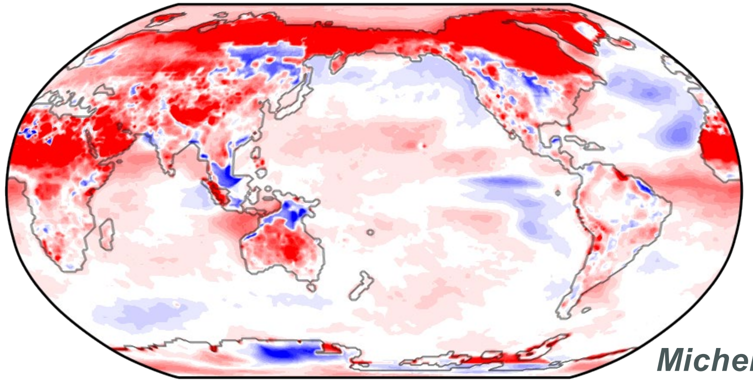
Modern-day 2xCO_2

Last Glacial Maximum
(19–23 kya)

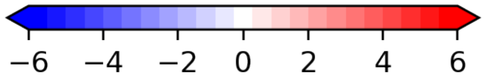
Pliocene
("mid-Pliocene warm period" ~3 million ya)







Zhu & Poulsen (2021), CESM1.2



ΔERF / |$\overline{\Delta ERF}$|

[Wm^{-2} / Wm^{-2}]

Zhu & Poulsen (2021), CESM1.2

GHG forcing +

Localized forcing:

- **Ice sheets** + sea level
- *Not shown: vegetation, dust/aerosols*

Michelle Dvorak *et al. (in prep), CESM2.1*

GHG forcing +

Localized forcing:

- **Ice sheets** + sea level
- **Vegetation**
- *Not shown: dust/aerosols*

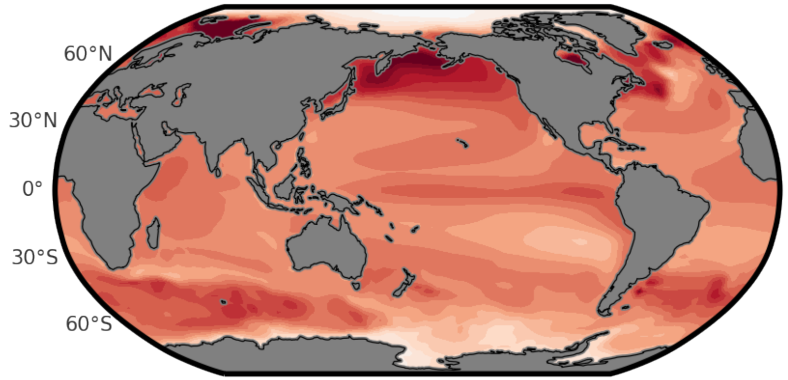
Different forcings produce different **SST patterns**

SST anomalies,
Normalized by global mean

Reconstructions from ***Paleoclimate Data Assimilation***

Modern-day $2xCO_2$

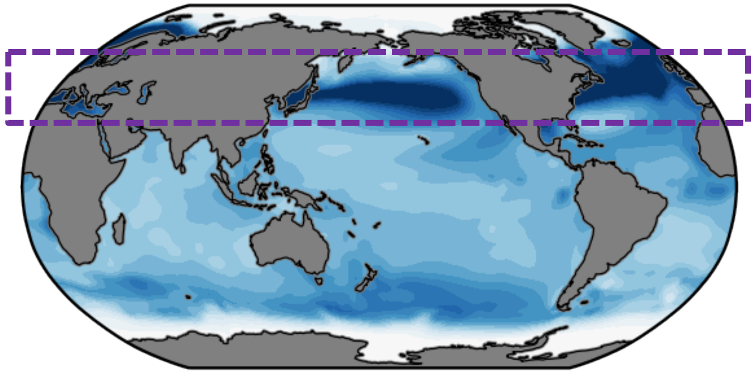
Rugenstein et al. (2019)



LongRunMIP: Multi-model mean 1000+ years after $2xCO_2$

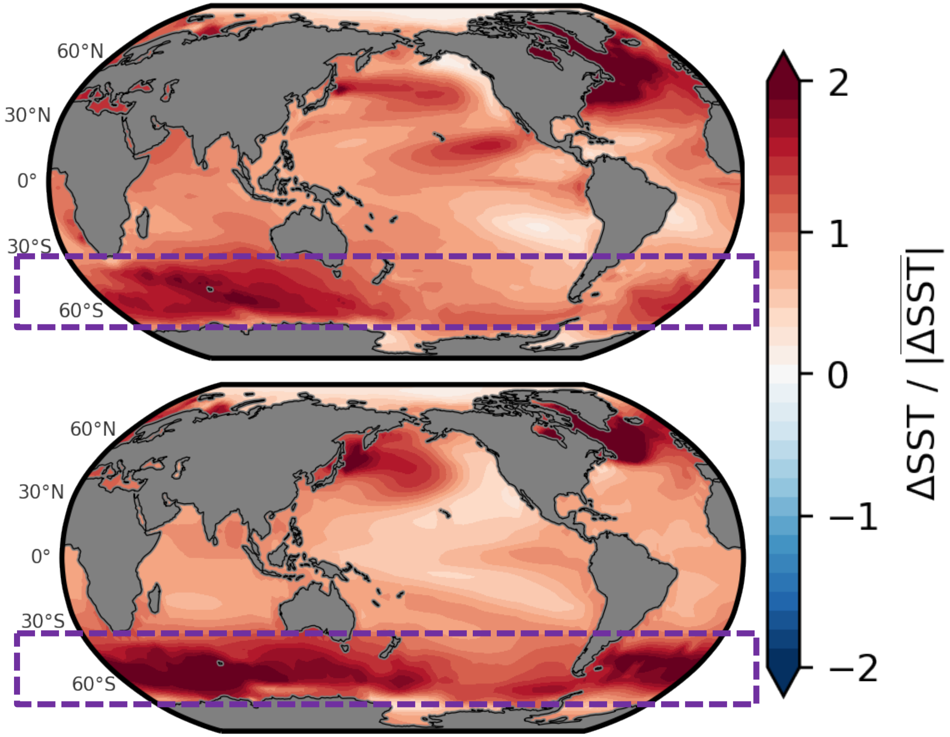
Last Glacial Maximum
(19–23 kya)

Mean of 4 reconstructions



Pliocene
(“mid-Pliocene warm period” ~3 million ya)

Tierney et al. (in prep)



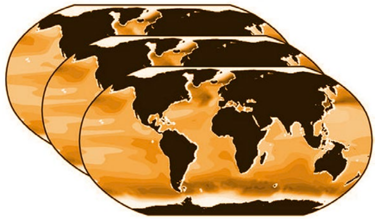
Annan et al. (submitted)

SST patterns from **paleoclimate data assimilation:** Combination of model covariance and proxy data

Hakim et al. (2016)
Tierney et al. (2020)
Osman et al. (2021)

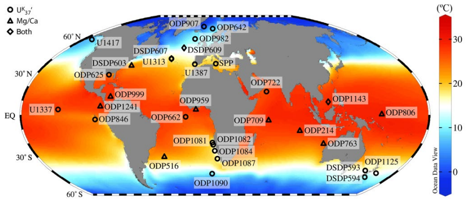
$$\mathbf{x}_{prior} + \mathbf{K}(y_{observation} - \hat{y}) = \mathbf{x}_{posterior}$$

Prior State: Model Ensemble



(e.g., iCESM)

Proxy data

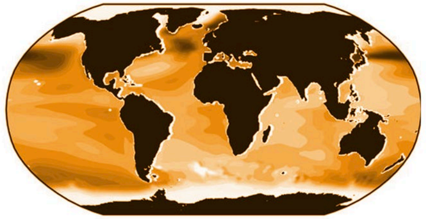


(e.g., ocean sediments)

McClymont et al. 2020 for Pliocene

Estimate of data from prior

Posterior Mean



And uncertainty

$$\mathbf{K} = \text{covariance}(\mathbf{x}_{prior}, \hat{y})[\text{var}(\hat{y}) + R_{obs}]^{-1}$$

- Proxy information is **spread across state estimate**
- Update is **weighted by uncertainty** in model prior and proxies

Schematic adapted from Tierney et al. (2020)

Methods: Feedbacks in atmosphere models (AGCMs)

Goal: calculate feedbacks from global energy budget

$$\Delta N = \cancel{\Delta F} + \lambda \Delta T$$

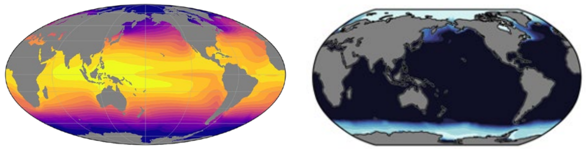
$$\lambda = \Delta N / \Delta T$$

λ_{2xCO_2}

λ_{LGM} and $\lambda_{Pliocene}$

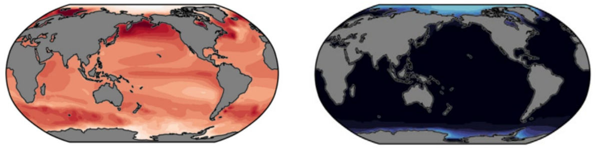
3 required simulations: SST/sea ice prescribed in AGCMs ("AMIP" style with *constant forcing*)

1 **Pre-industrial baseline**



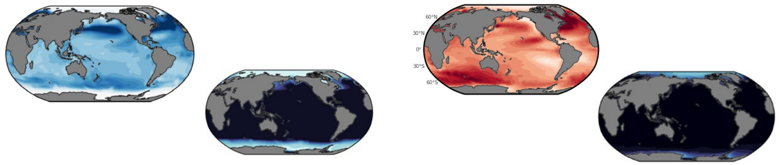
(Late Holocene 0–4 kya, Osman et al. 2021)

2 **$2xCO_2$**



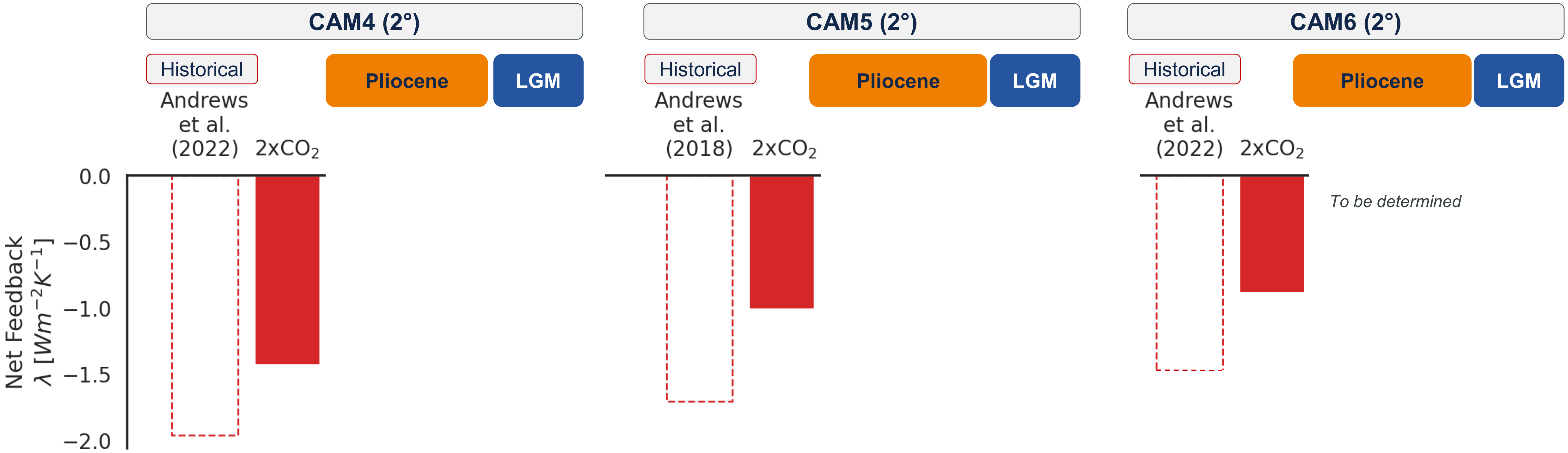
- 1 multi-model mean pattern
  - LongRunMIP (Rugenstein et al. 2019)

3 **LGM and Pliocene**



- **LGM (4 reconstructions):**
  - Amrhein et al. (2018), Tierney et al. (2020), Osman et al. (2021), Annan et al. (2022)
- **Pliocene (2 reconstructions):**
  - Tierney et al. (*in prep*) and Annan et al. (*submitted*)

***Preliminary* Results:** Feedbacks in AGCMs



Paleo Pattern Effect: $\Delta\lambda = \lambda_{2xCO_2} - \lambda_{Paleo}$

Mean LGM $\Delta\lambda = -0.37$ W/m² K⁻¹

Mean Pliocene $\Delta\lambda = -0.24$ W/m² K⁻¹

Negative pattern effect ($\Delta\lambda$) means **stronger constraints on modern-day ECS**

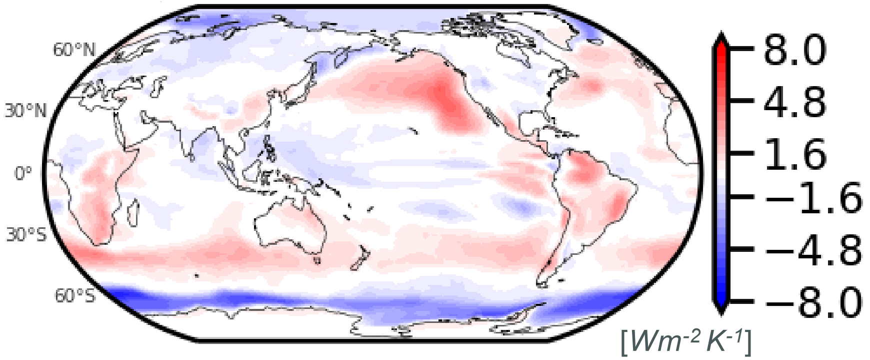
Note: consistent results found in ***GFDL AM4*** *and* ***HadGEM3***

Mechanism: Positive SW cloud feedbacks caused by non-CO_2 forcings

Cloud Radiative Effect: $\lambda_{CRE} = \frac{\Delta N_{local}}{\Delta \overline{T}_{global}}$

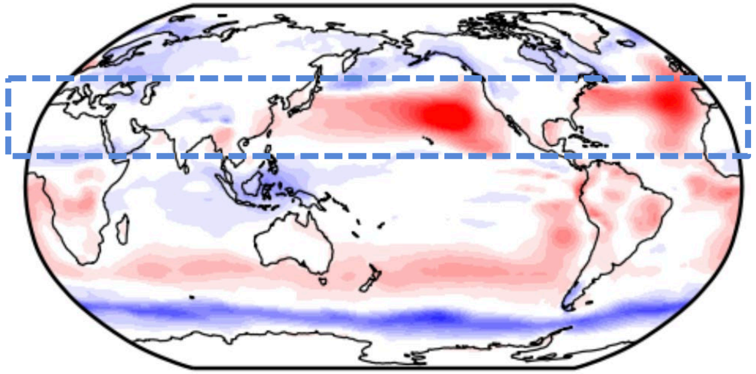
$2xCO_2$

LongRunMIP



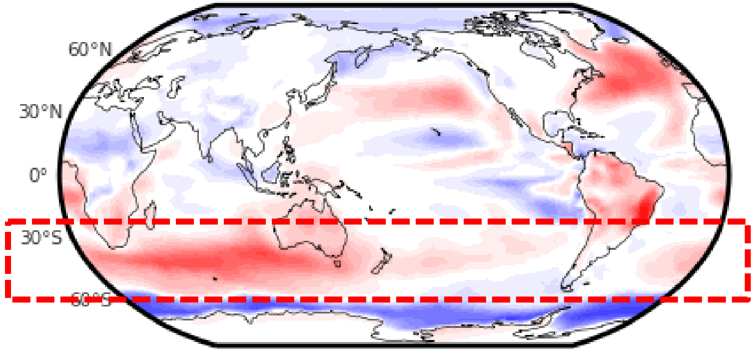
LGM

Mean across patterns

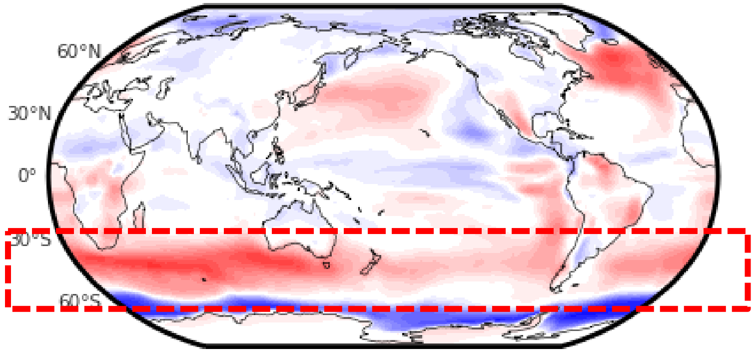


Pliocene

Tierney et al. *(in prep)*

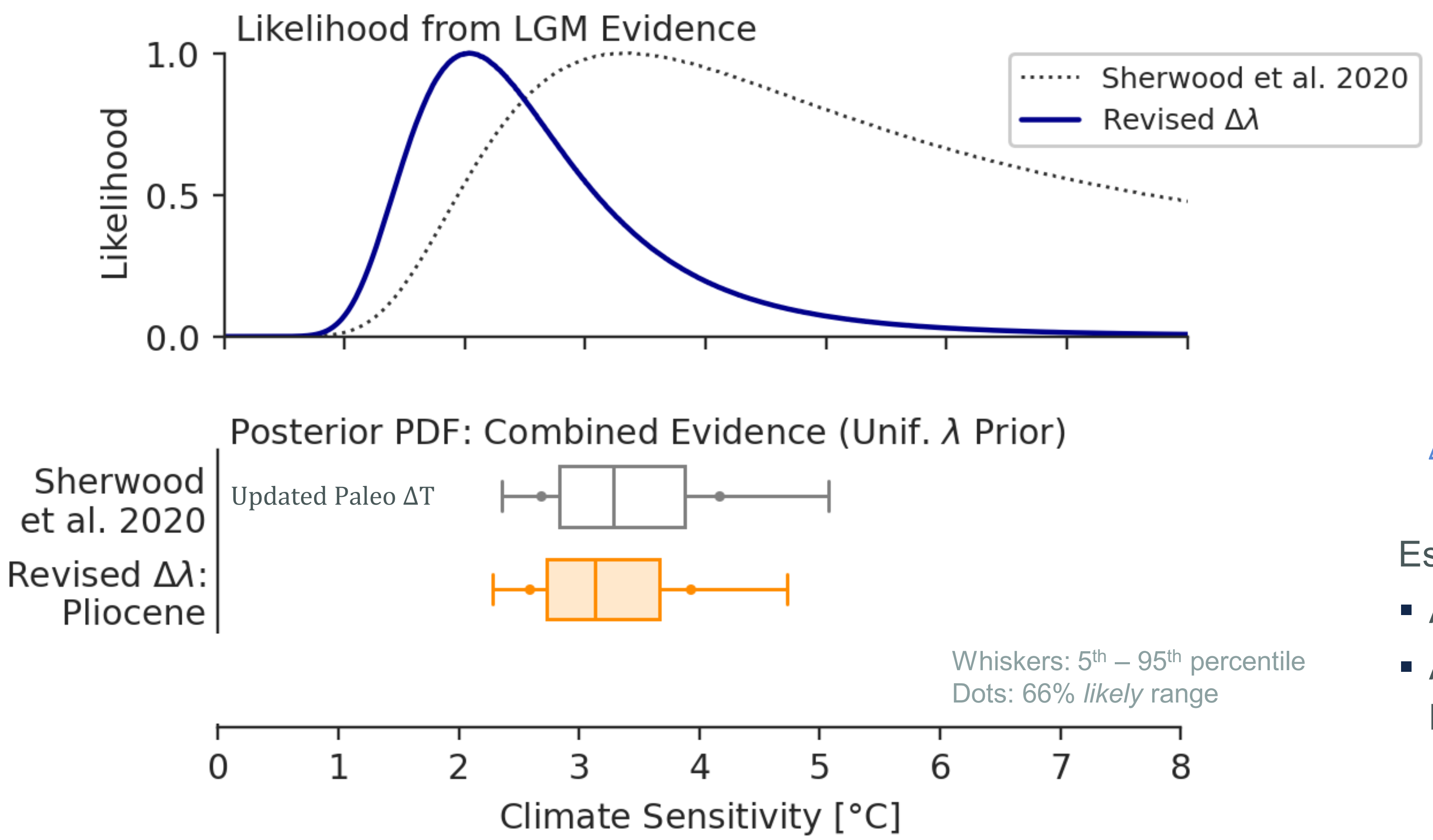


Annan et al. *(submitted)*



- Zhu & Poulsen (2021) and Amaya et al. (2021) in CESM1.2: **LGM pattern** caused by *non-CO_2* forcing
- Dvorak et al. *(in prep)* CESM2: **Pliocene pattern** caused by *non-CO_2* forcing
  - Also Feng et al. (2022), focused on hydroclimate

***Preliminary* Results:**
Paleoclimates provide stronger constraints on modern-day ECS



$$ECS = \frac{-F_{2xCO_2}}{\lambda_{Plio} + \Delta\lambda}$$

from Sherwood et al. (2020)

$\Delta\lambda \sim N(\mu = -0.2, \sigma = 0.2)$ W m^{-2} K^{-1}

$$ECS = \frac{-F_{2xCO_2}}{\lambda_{LGM} + \Delta\lambda}$$

$\Delta\lambda \sim N(\mu = -0.37, \sigma = 0.23)$ W m^{-2} K^{-1}

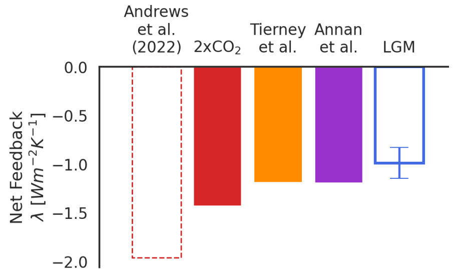
Estimate of $\Delta\lambda$ samples uncertainty:

- Across **models**
- Across **reconstructed SST patterns**

Preliminary **Conclusions:**
Paleo pattern effects *help* constrain ECS

Contact: **Vince Cooper**, vcooper@uw.edu

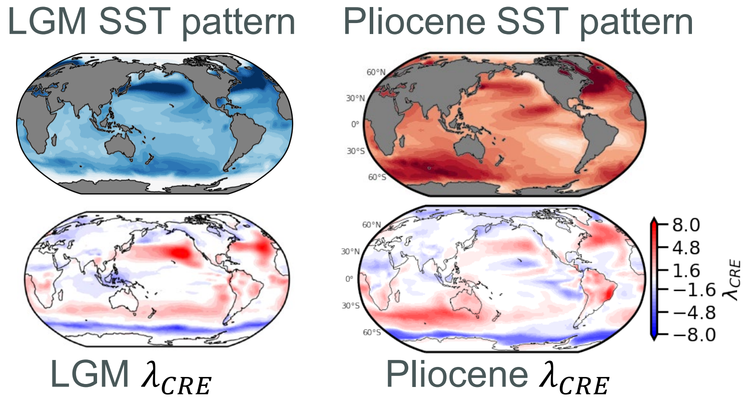
"Last Glacial Maximum pattern effects…" preprint: https://doi.org/10.31223/X5VD56



- Feedback is ***more negative*** in $2xCO_2$ than LGM & Pliocene:

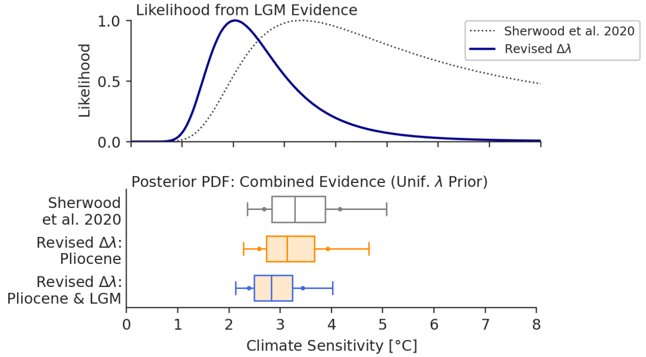
$$\text{Pattern effect: } \Delta\lambda = \lambda_{2xCO_2} - \lambda_{\text{Paleo}}$$

- $\Delta\lambda$ driven by differences in **cloud feedbacks**
  - Caused by non-CO_2 paleo forcings



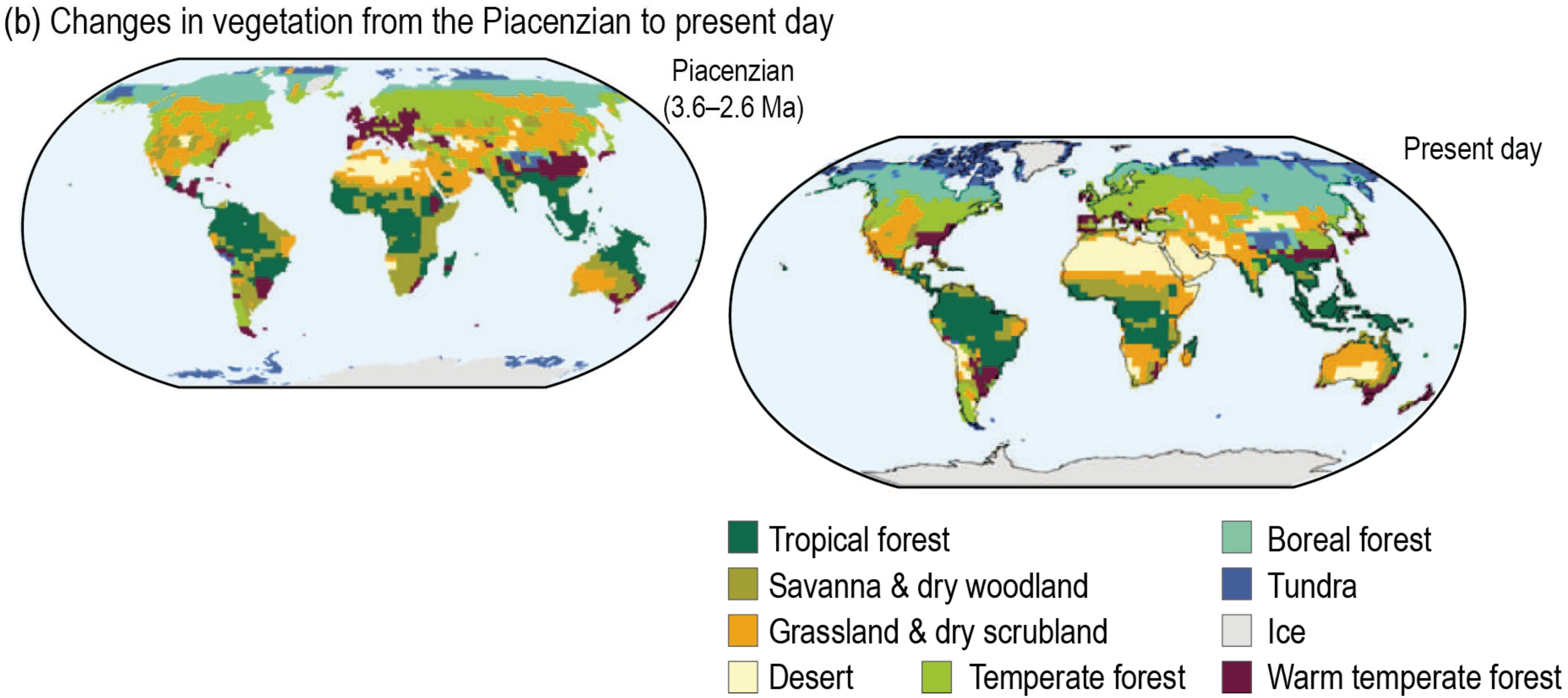
- **Paleo pattern effects *help* constrain** modern-day ECS

Combined lines of evidence	Median (5–95%) **Unif. λ prior**
Sherwood et al. (2020), updated paleo ΔT	3.3 K (2.4–**5.1 K**)
Including Pliocene $\Delta\lambda$	3.1 K (2.3–**4.7 K**)
Including Pliocene $\Delta\lambda$ & LGM $\Delta\lambda$	2.8 K (2.1–**4.0 K**)



Appendix

Pliocene vegetation (IPCC AR6)



Sherwood et al. (2020) equations for Pliocene

$$\Delta T = \frac{-\Delta F_{CO2}\,(1+f_{CH4})\,(1+f_{ESS})}{\dfrac{\lambda}{(1+\zeta)}}$$

Table 8
Parameters of the Distributions That Are Used to Estimate S From the mPWP, Equation 23

Term	Distribution
ΔT (K)	$N(3, 1)$
CO_2 (ppm)	$N(375, 25)$
ΔF_{2xCO2} (W m^{-2})	$N(4.0, 0.3)$
f_{CH4}	$N(0.4, 0.1)$
f_{ESS}	$N(0.5, 0.25)$
ζ	$N(0.06, 0.2)$

Note. Radiative forcing per CO_2 doubling from section 3.2.1.

Sherwood et al. (2020) equations for LGM

$$\Delta T = \frac{-(-0.57\,\Delta F_{2xCO2} + \Delta F')}{\frac{\lambda}{1+\zeta} + \frac{\alpha}{2}\Delta T},$$

Table 7
Parameters of the Distributions That Are Used to Estimate S From the Cold Climate States, Equation 22

Term	Distribution
ΔT (K)	$N(-5, 1)$
ΔF_{2xCO2} (W m^{-2})	$N(4.0, 0.3)$
$\Delta F'$ (W m^{-2})	$N(-6.15, 2)$
α	$N(0.1, 0.1)$
ζ	$N(0.06, 0.2)$

Note. Radiative forcing per CO_2 doubling from section 3.2.1.

What did Sherwood, Webb, et al. (2020) do for the LGM?

- Estimate ***observed** LGM feedback

$$\lambda^*_{\mathrm{LGM}} = -\frac{\Delta F_{\mathrm{ice}} + \Delta \mathrm{F}_{\mathrm{CO_2}} + \Delta \mathrm{F}_{\mathrm{CH_4,N_2O}} + \Delta \mathrm{F}_{\mathrm{dust}} + \Delta \mathrm{F}_{\mathrm{veg}}}{\Delta T}$$

$$\lambda^*_{\mathrm{LGM}} = -\frac{-3.2_{\mathrm{ice}} - 2.3_{\mathrm{CO_2}} - 0.8_{\mathrm{CH_4,N_2O}} - 1.0_{\mathrm{dust}} - 1.1_{\mathrm{veg}}\ \mathrm{Wm^{-2}}}{-5\ \mathrm{K}}$$

$$\lambda^*_{\mathrm{LGM}} = -\frac{-8.4\ \mathrm{Wm^{-2}}}{-5\ \mathrm{K}} = -1.7\ \mathrm{Wm^{-2}K^{-1}}$$

Accounting for pattern effect in estimates of ECS **for the LGM**

Historical Record

"Naive ECS" from ***Observations**

$$ECS = \frac{-\Delta F_{2xCO_2}}{\lambda^*_{Hist}}$$

Pattern Effect from **models**

$$\Delta\lambda_{pattern} = \lambda_{2xCO_2} - \lambda_{Hist}$$

"Revised ECS" **accounting for pattern effect**

$$ECS = \frac{-\Delta F_{2xCO_2}}{\lambda^*_{Hist} + \Delta\lambda_{pattern}}$$

Last Glacial Maximum (LGM)

$$ECS = \frac{-\Delta F_{2xCO_2}}{\lambda^*_{LGM} + \Delta\lambda_{Temperature}}$$

Research Question

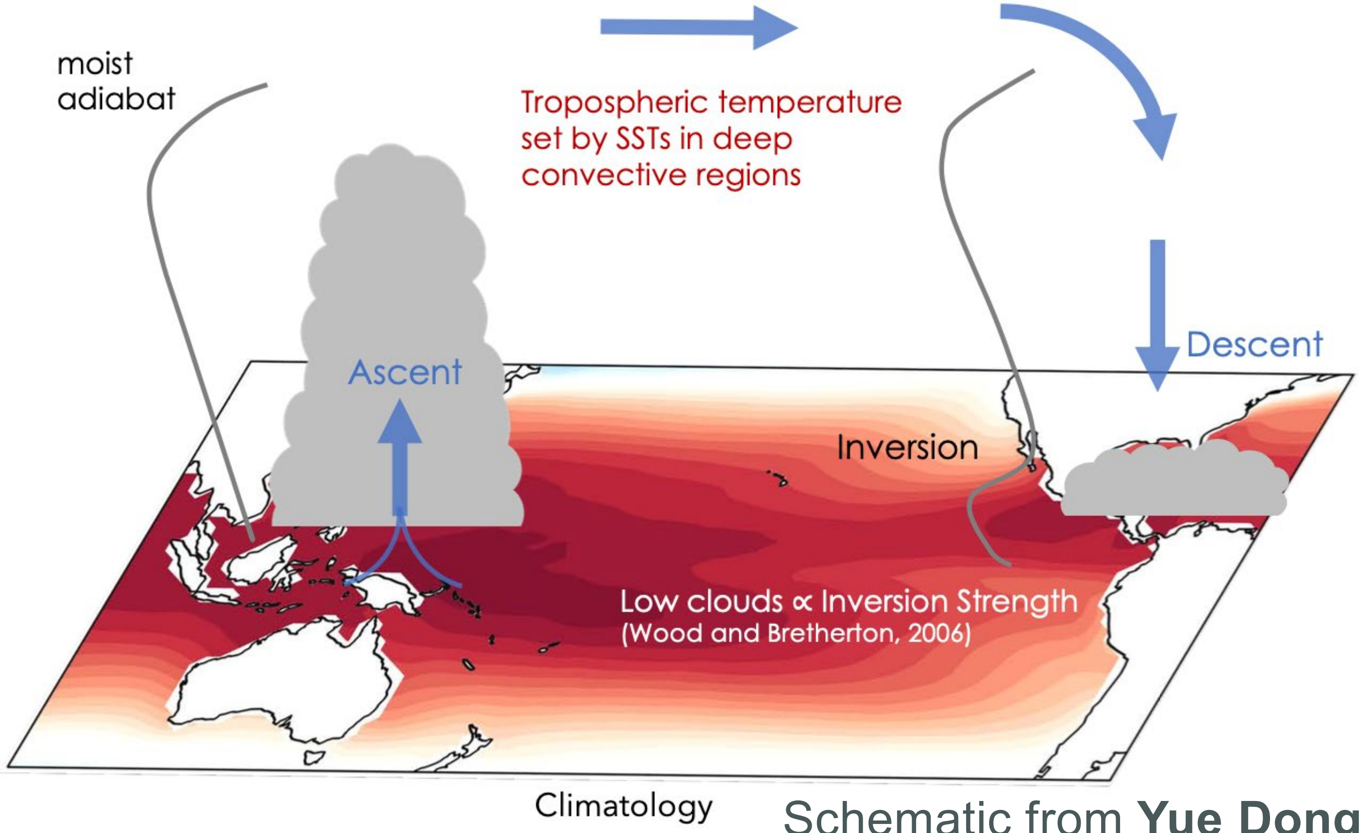
$$\Delta\lambda_{pattern} = \lambda_{2xCO_2} - \lambda_{LGM}$$

Research Question

$$ECS = \frac{-\Delta F_{2xCO_2}}{\lambda^*_{LGM} + \Delta\lambda_{Temp.} + \Delta\lambda_{pattern}}$$

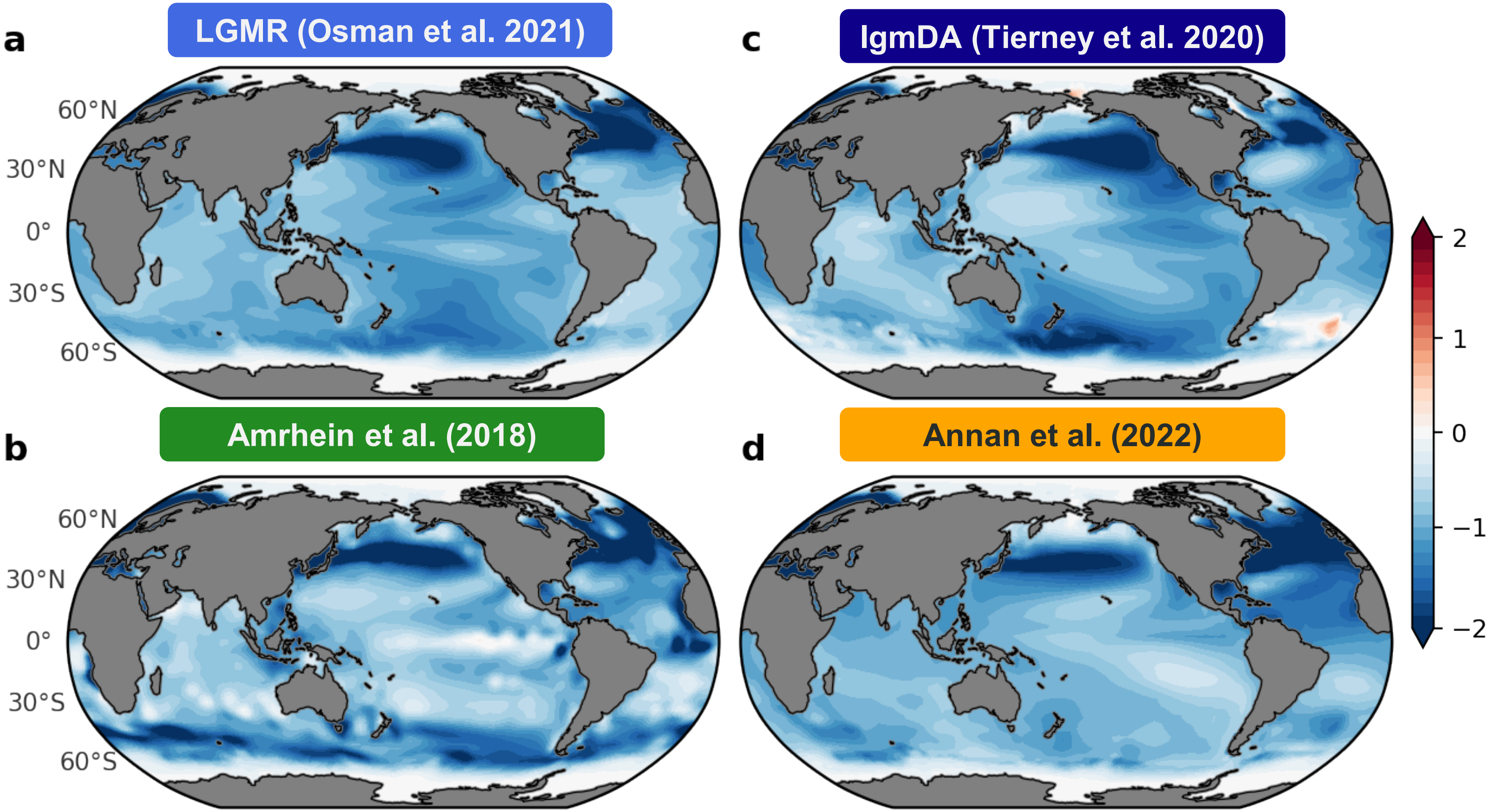
Pattern effect:
Net feedback (λ) depends on **pattern of SST anomalies**

Ascent vs. descent regions explain pattern effect

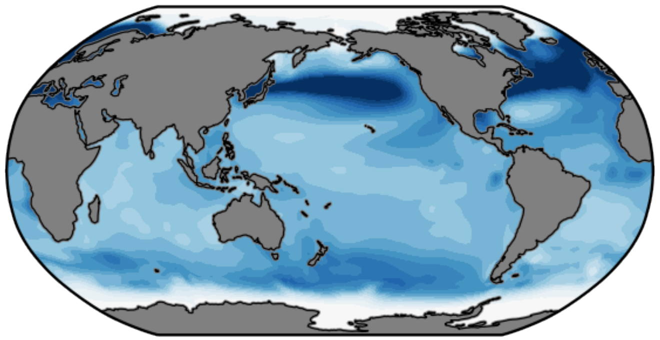


Schematic from **Yue Dong**

…But DA results have substantial disagreements in LGM patterns



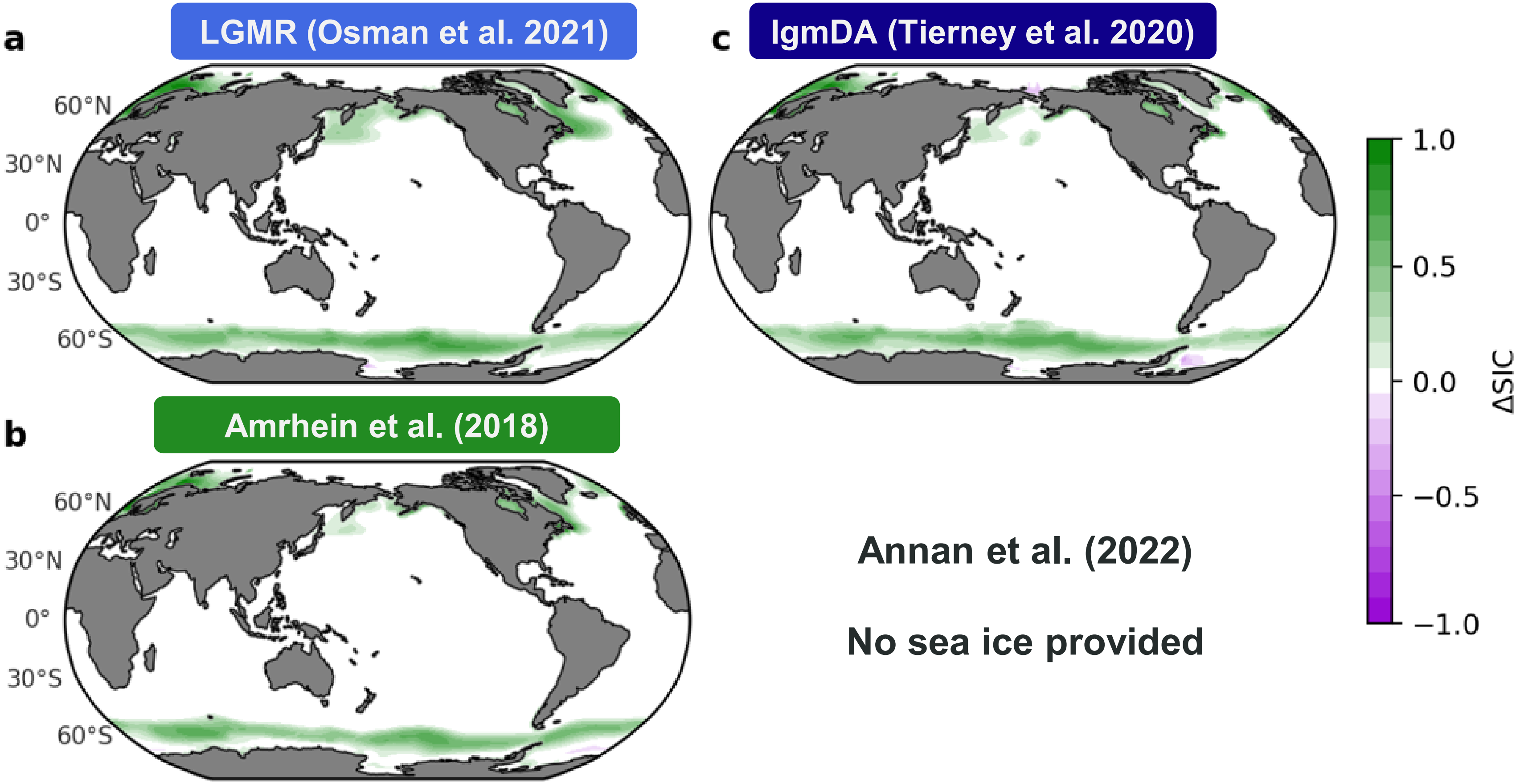
Mean of all four patterns



Patterns of SST anomalies relative to preindustrial/late Holocene

…But DA results have substantial disagreements in LGM patterns

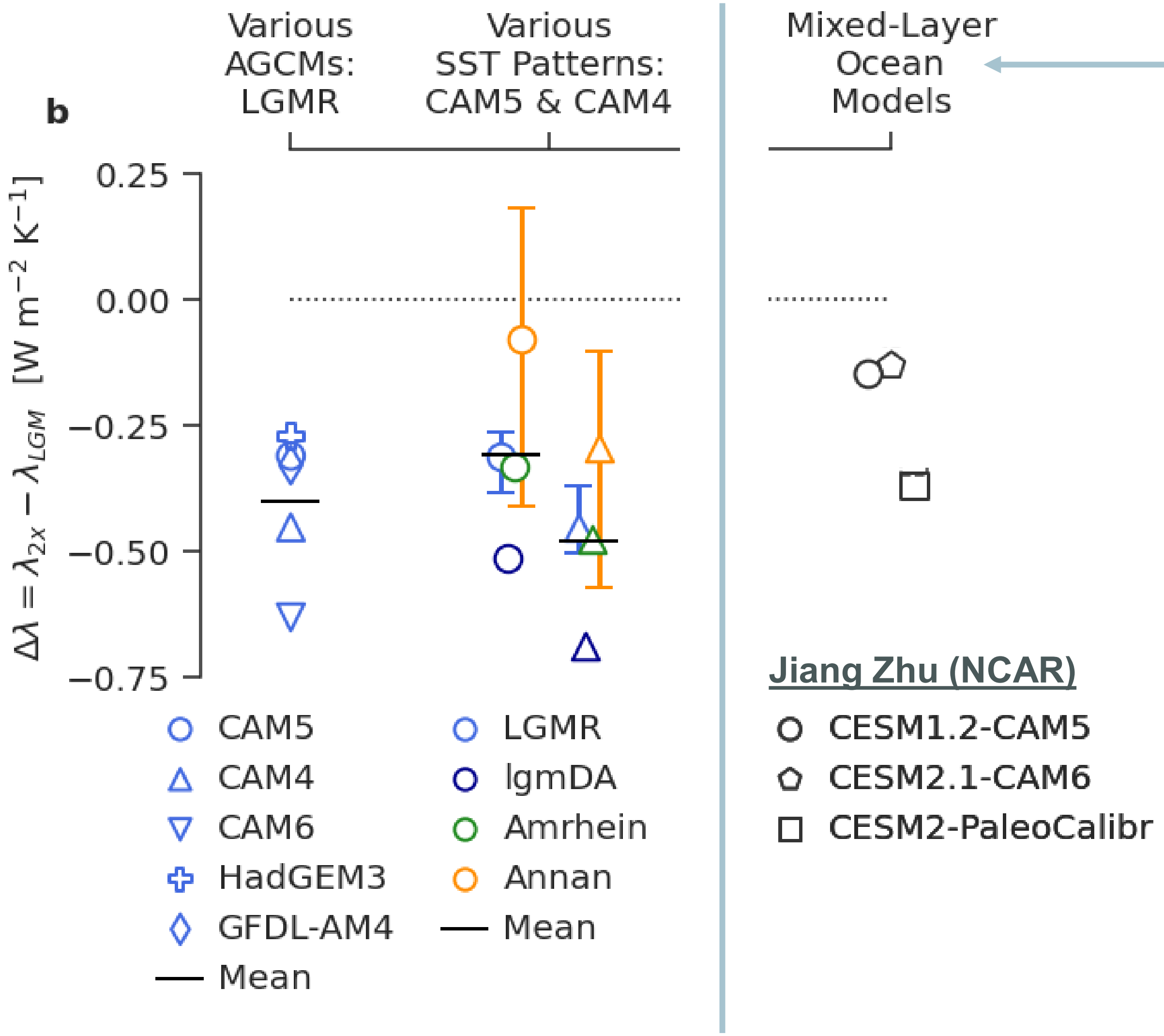
- Sea ice concentrations add to uncertainty



Sea ice concentration (SIC) anomalies relative to late Holocene

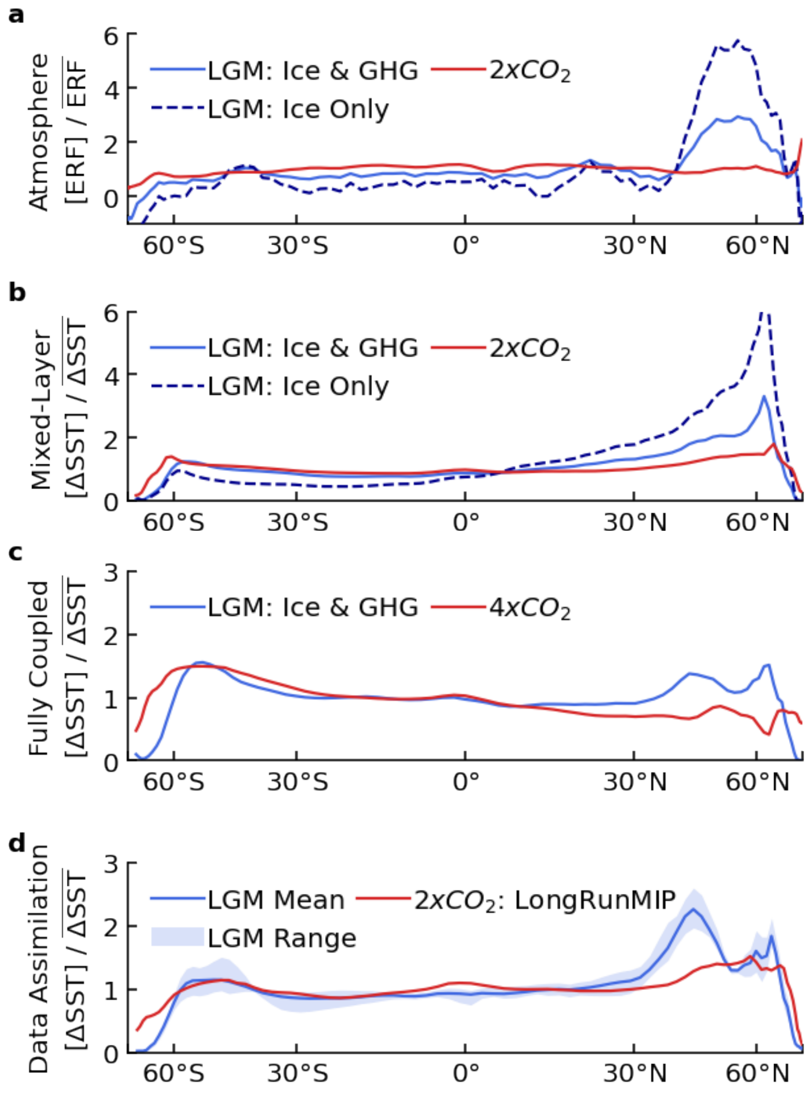
Results: Pattern effect from DA in atmosphere models (AGCMs)

LGM Pattern Effect: $\Delta\lambda = \lambda_{2x} - \lambda_{LGM}$



Do **coupled (slab ocean) models** without data assimilation show similar $\Delta\lambda$?

SST response to LGM ice sheets: amplified in NH extratropics



Mechanism: Feedback decomposition of our AGCM experiments

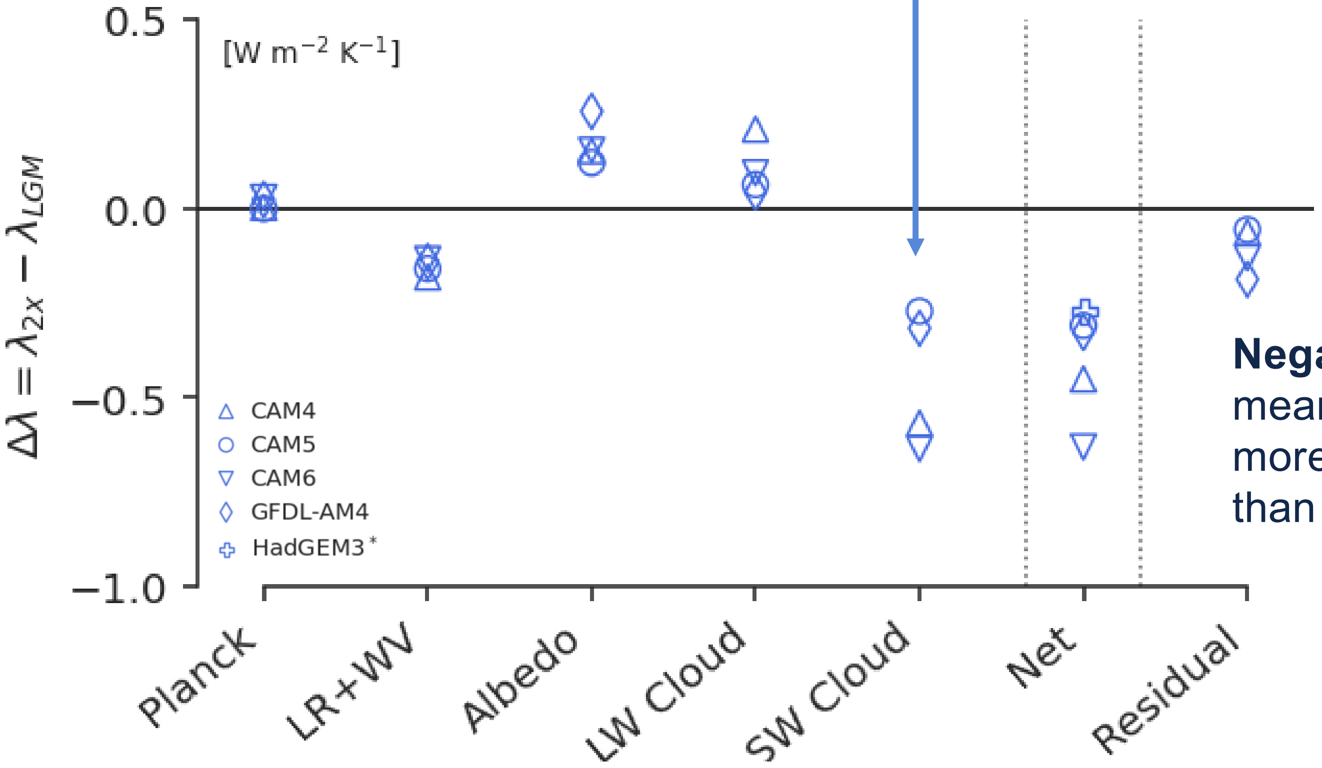
1) SST response to LGM ice sheets is amplified in NH extratropics

2) Big difference in SW cloud feedbacks

Decomposition using radiative kernels

$$\Delta\lambda = \lambda_{2x} - \lambda_{LGM}$$

***Attributing** the pattern effect*
to specific feedbacks



Negative Δλ means LGM more sensitive than $2xCO_2$

Mechanism: SST "patterns" vs. global-mean temperature impact on $\Delta\lambda$

LGM Pattern Effect:

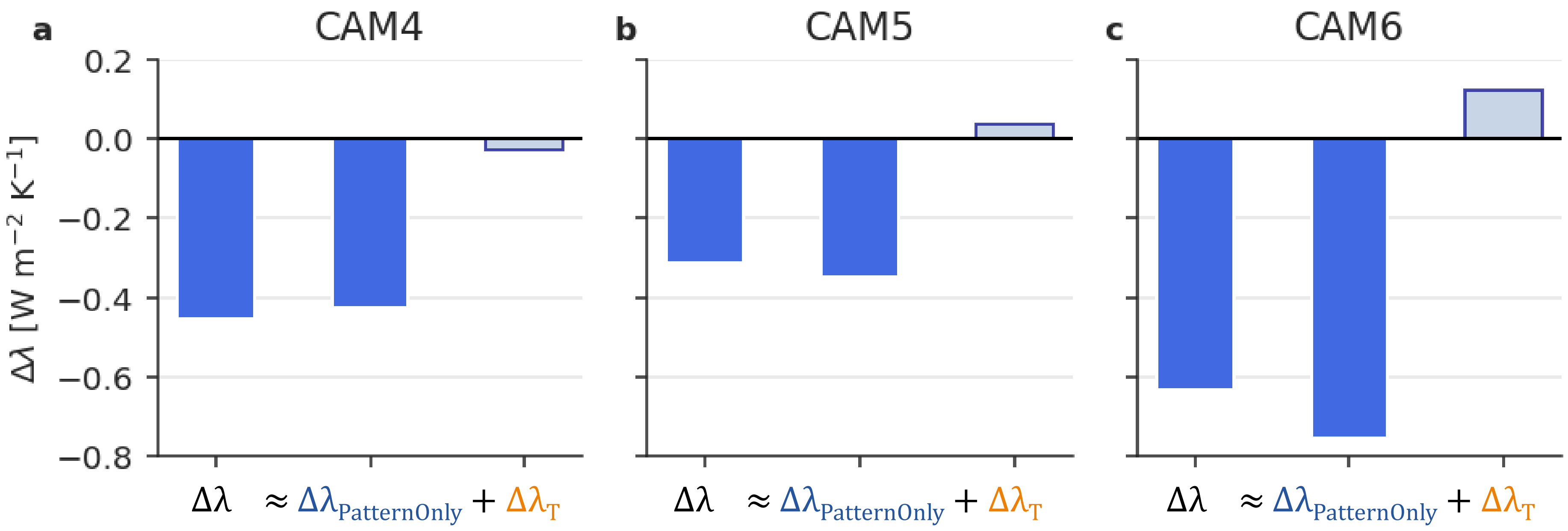
$$\Delta\lambda = \lambda_{2x} - \lambda_{LGM}$$

New Experiments: $\Delta SST = -0.5\ K$
$\Delta SIC = 0$ (constant)

$$\Delta\lambda_{\mathrm{PatternOnly}} = \lambda_{2x}^{-0.5K} - \lambda_{LGM}^{-0.5K}$$

$$\Delta\lambda \approx \Delta\lambda_{\mathrm{PatternOnly}} + \Delta\lambda_{\mathrm{Temperature}}$$

$$\Delta\lambda_{\mathrm{Temperature}} \approx \Delta\lambda - \Delta\lambda_{\mathrm{PatternOnly}}$$



Mechanism: Stationary Wave Response

Amaya et al. 2021

- Winter: topography slows down the poleward flank of westerlies, and the equatorward flank accelerates (equatorward shift + stronger jet, and deeper Aleutian low)
- Summer: albedo essential for surface cyclonic circulation, and ocean provides persistence
- Winter topography and summer albedo have same directional contribution to stationary wave response

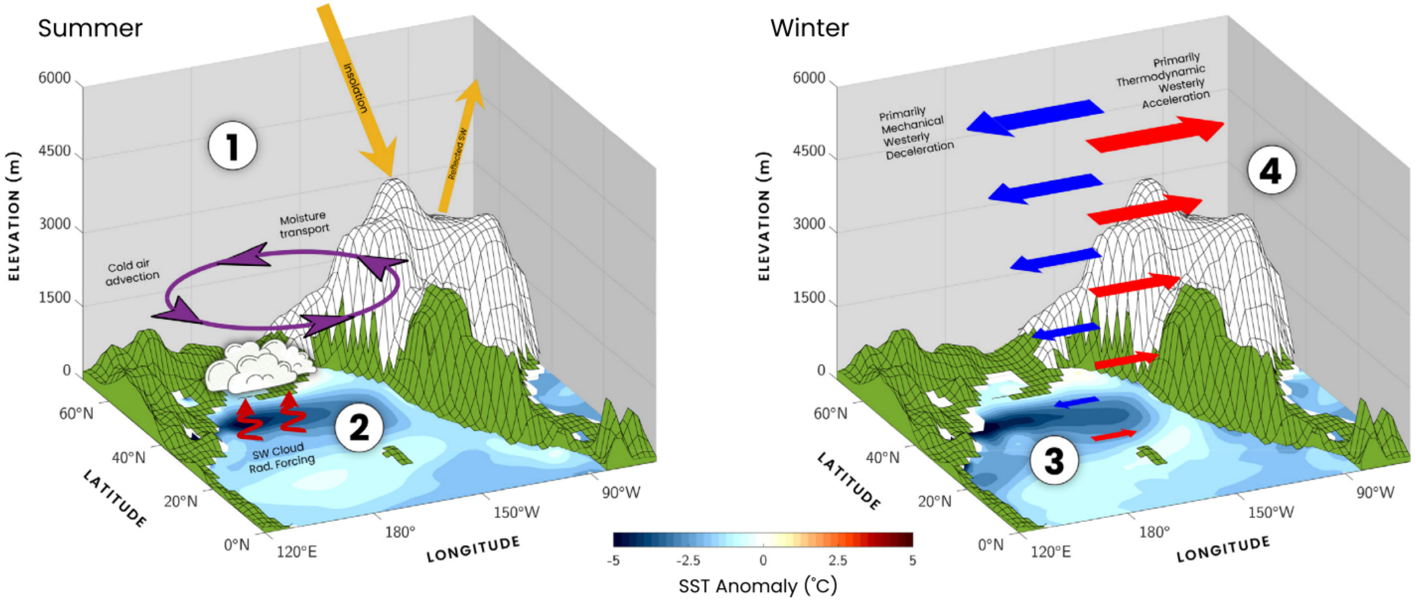
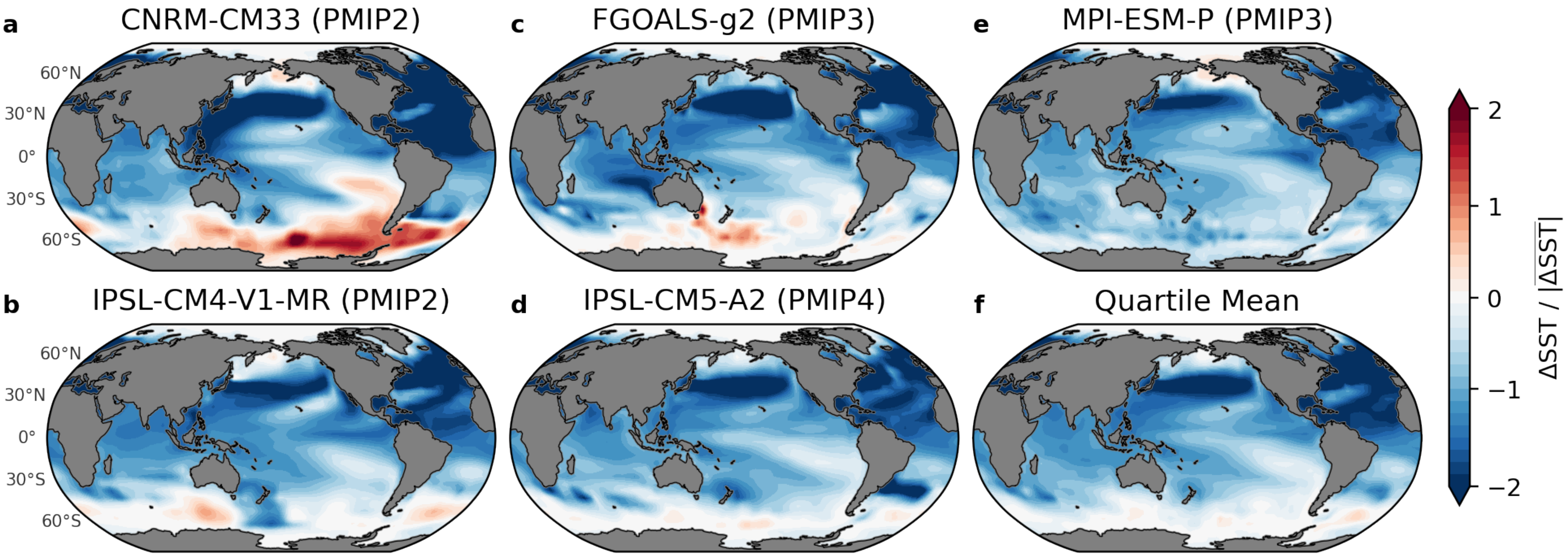
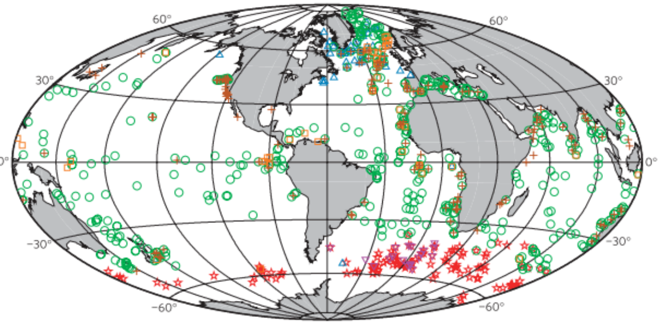


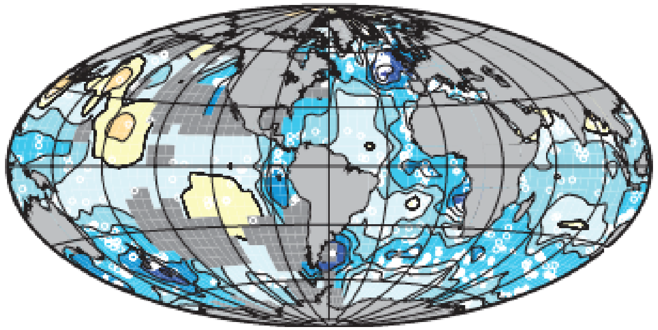
Fig. 9. Schematic summary of the North Pacific coupled climate response to tall/bright North American ice sheets during the LGM. (1) A direct stationary wave response to the tall/bright ice sheets during boreal summer produces a low-level cyclonic circulation over the North Pacific. These circulation anomalies drive cold air advection in the western North Pacific and increased water vapor transport in the eastern North Pacific. (2) Enhanced stability coupled with increased atmospheric moisture leads to more marine stratocumulus clouds, which reflect sunlight and cool the North Pacific Ocean near ~40°N. (3) Low cloud-SST feedback and ocean dynamical adjustments amplify the SST and cloud changes, persisting them into boreal winter. (4) The enhanced North Pacific meridional temperature gradient accelerates the westerlies on the equatorward flank of the jet stream, while mechanical interactions with ice sheet topography decelerate the flow on the poleward flank. Overall, this leads to a southward shift of the North Pacific jet stream and a redistribution of North American west coast hydroclimate during the LGM.

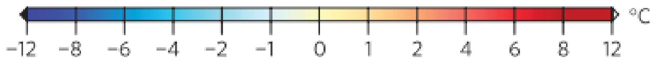
Annan Posterior Ensemble Members with Strong Negative LGM Feedback



MARGO (2009) proxy data including seasonal proxies

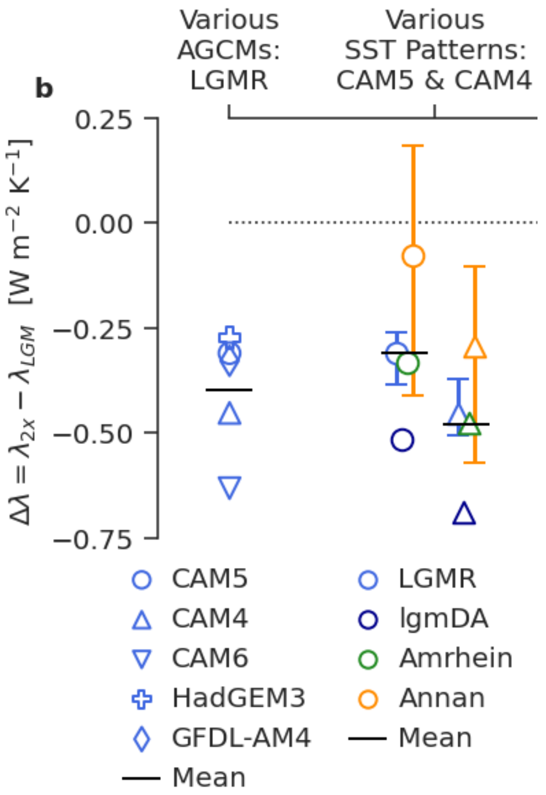


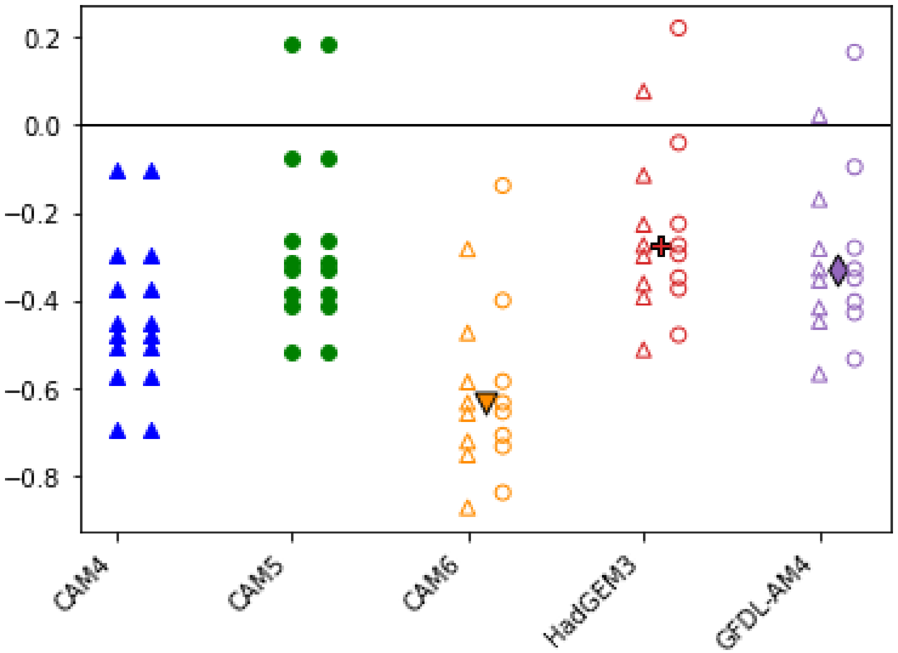


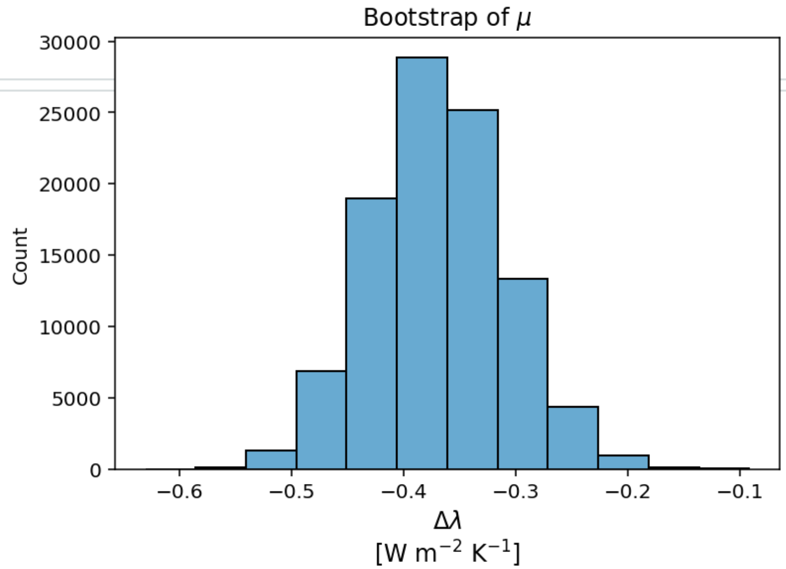


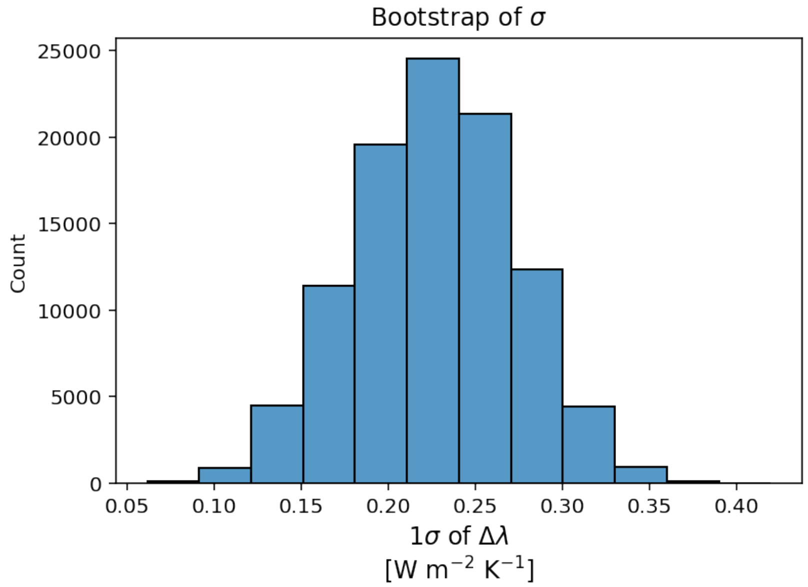
MARGO (2009) Southern Hemisphere summer

Bootstrapping (n=19)









Bootstrap of mean pattern effect
Mean: -0.37
Std. Dev.: 0.06
95% CI: [-0.48 -0.25]

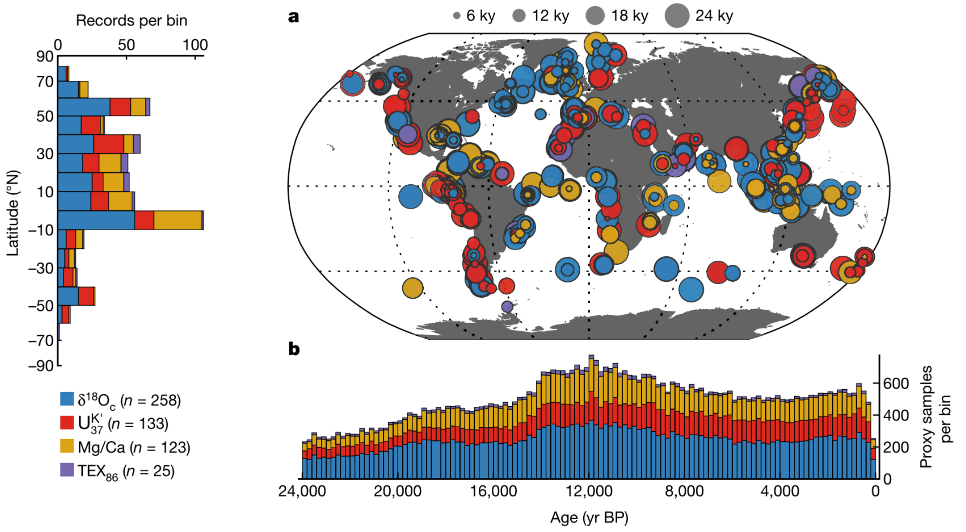
Bootstrap of pattern effect standard deviation
Mean: 0.227
Std. Dev.: 0.046
95% CI: [0.137 0.315]

LongRunMIP Models

- CESM1.0.4
- CNRM CM6.1
- HadCM3L
- MPI ESM 1.2
- MIROC 3.2
- GFDL ESM2M

LGMR

- LGMR
  - We focus on geochemical proxies for SST including alkenone U37 K' (146 records), the TetraEther indeX of 86 carbons (TEX86; 28 records), the elemental ratio of Mg to Ca in planktic foraminifera (Mg/Ca; 129 records), and the oxygen isotopic composition of planktic foraminifera (δ18 Oc; 270 records)
  - No terrestrial data were included in the data set compiled, and few data are available for the central Pacific, Indian and Southern oceans, leaving some questions as to how accurate the reconstruction is across these large expanses of water and continents.
  - Reduced proxies relative to lgmDA, because they only use timeseries
- Prior spread comes from…



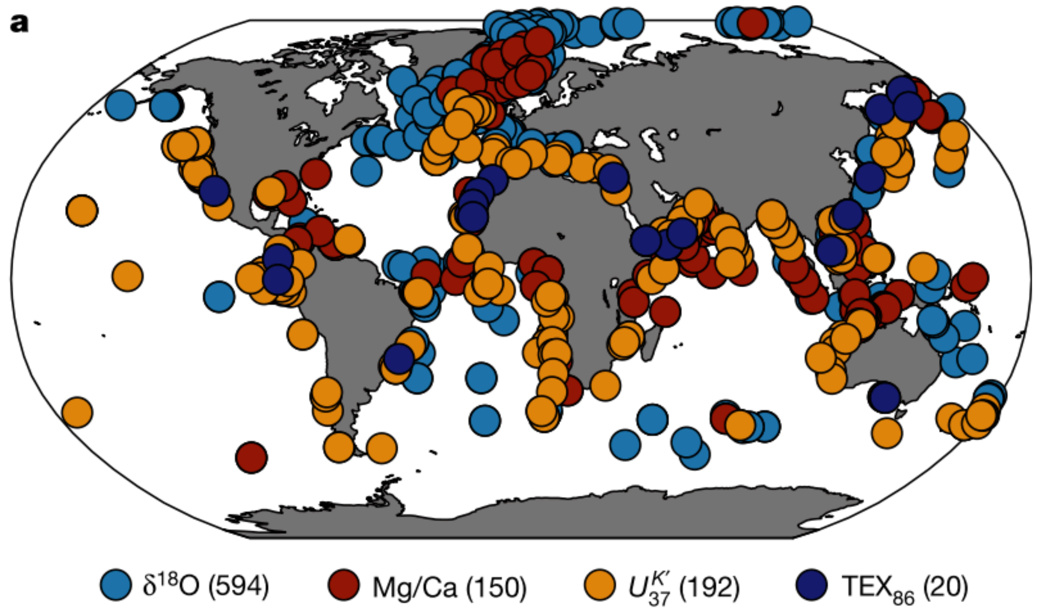
Extended Data Table 1 | Information on the iCESM simulations used for generating model priors

Age (ka)	Model description	Number of priors	Greenhouse gas ($CO_2/CH_4/N_2O$)	Global $\delta^{18}O_{sw}$	GMST range (°C)	Citation
0	iCESM1.2: PI	16	285 / 792 / 276	0.05	14.03–14.25	10
0	iCESM1.2: PI	10	285 / 792 / 276	0.05	13.22–13.33	61
0	iCESM1.3: PI	10	285 / 792 / 276	0.05	13.68–13.84	61
0	iCESM1.2 Last Millennium Member #2: 850-1850 CE	20	Transient	0.05	12.96–13.26	62
0	iCESM1.2 Last Millennium Member #3: 850-1850 CE	20	Transient	0.05	12.98–13.27	62
3	iCESM1.2: 3 ka	16	275 / 580 / 270	0.05	13.99–14.14	10
6	iCESM1.2: 6 ka w/ Sahara & 50–90°N greened	16	264 / 597 / 262	0.05	14.14–14.62	This study
6	iCESM1.2: 6 ka	8	264 / 597 / 262	0.05	14.03–14.19	This study
9	iCESM1.2: 9 ka w/ Sahara greened	16	260 / 659 / 255	0.34	13.87–14.09	This study
12	iCESM1.2: 12 ka	16	253 / 478 / 236	0.59	12.61–12.76	This study
12	iCESM1.2: 12 ka w/ freshwater over N. Atl.	4	253 / 478 / 236	0.59	10.79–11.77	This study
14	iCESM1.2: 14 ka	16	238 / 637 / 255	0.73	10.05–10.32	This study
16	iCESM1.2: 16 ka	16	224 / 452 / 199	0.90	9.27–9.45	This study
16	iCESM1.2: 16 ka w/ freshwater over N. Atl.	4	224 / 452 / 199	0.90	7.63–8.45	This study
18	iCESM1.2: 18 ka	16	190 / 370 / 245	1.02	8.00–8.13	10
21	iCESM1.2: 21 ka	16	190 / 375 / 200	1.05	7.41–7.87	10
21	iCESM1.3: 21 ka	18	190 / 375 / 200	1.05	6.40–7.37	61

Greenhouse gas concentrations are in ppm for CO_2 and ppb for CH_4 and N_2O. Global mean seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) is in ‰ relative to the Vienna Standard Mean Ocean Water (VSMOW). See Methods for details of the implementation of vegetation and freshwater forcing in related simulations.

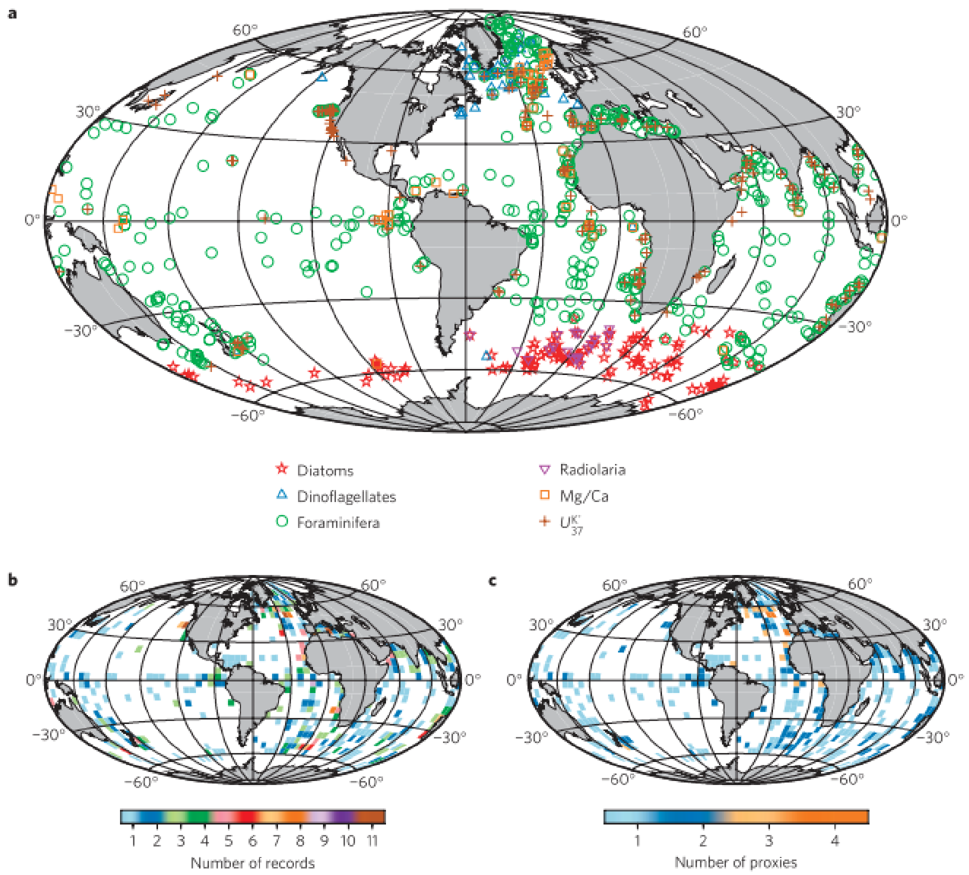
lgmDA

- lgmDA v2.1
    - Our data collection consists of 956 LGM (23–19 kyr ago, ka) and 879 late Holocene (4–0 ka) SST proxies
        - 636 and 664 unique locations
    - Lots of proxies which can go into iCESM, building on MARGO but not actually using all of MARGO data
- Prior is "50 yr average states from simulations of glacial state"



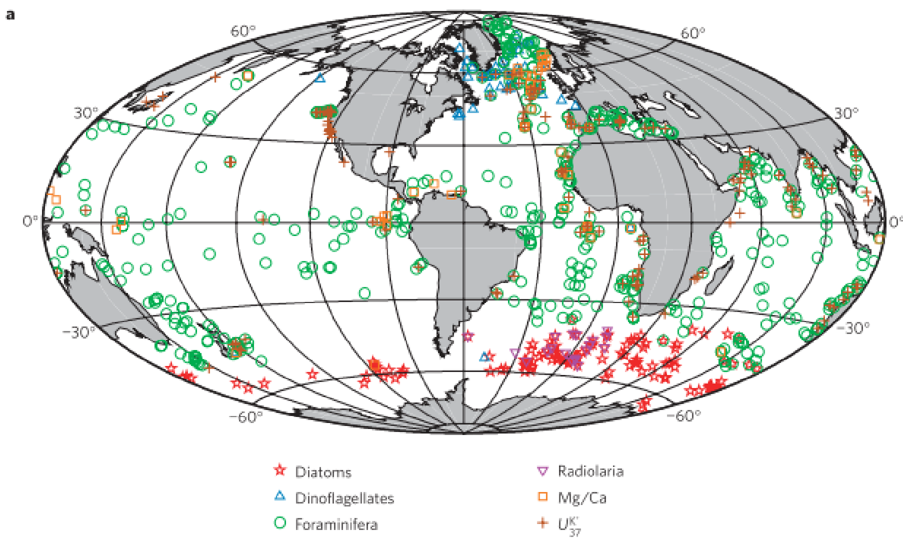
Amrhein

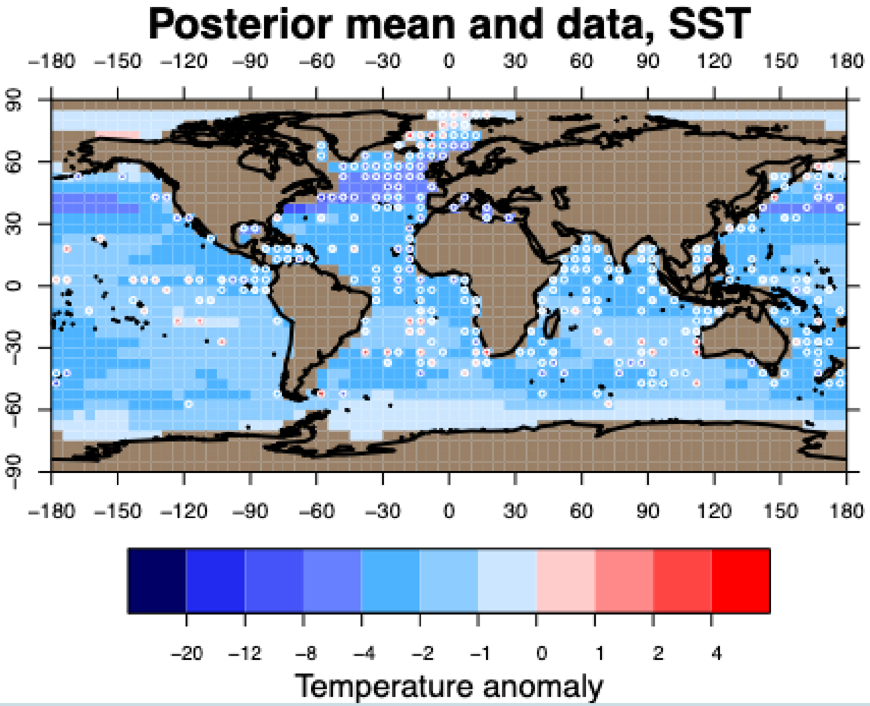
- Amrhein
  - Fit MITgcm ocean model to MARGO (2009) SST data within uncertainties using least-squares with Lagrange multipliers

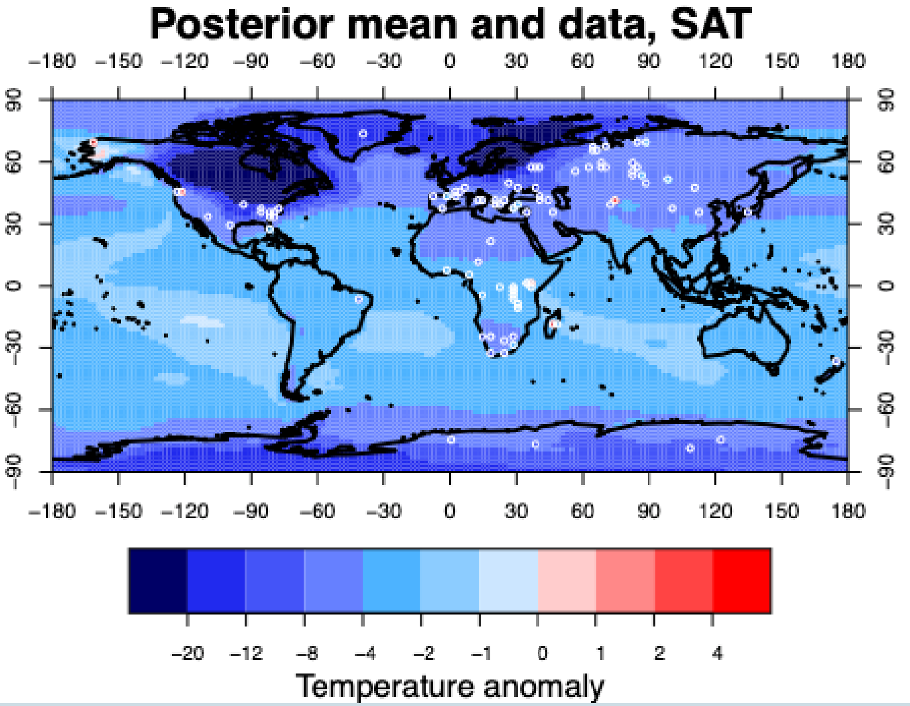


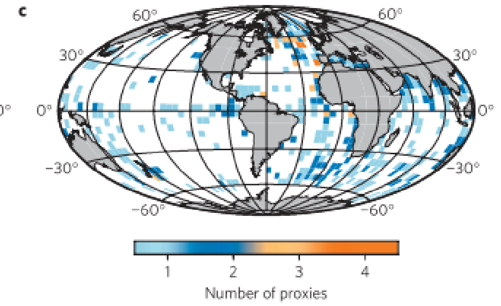
Annan

- Annan
    - PMIP2 (launched in 2002)
    - PMIP4 (launched in 2017)
- SST from MARGO (2009) and Tierney (2020)
- Pollen from Bartlein 2011 and ice core from Schmittner 2011
- Translate prior to be pre-centered around proxy data
- Annual rather than seasonal proxy data

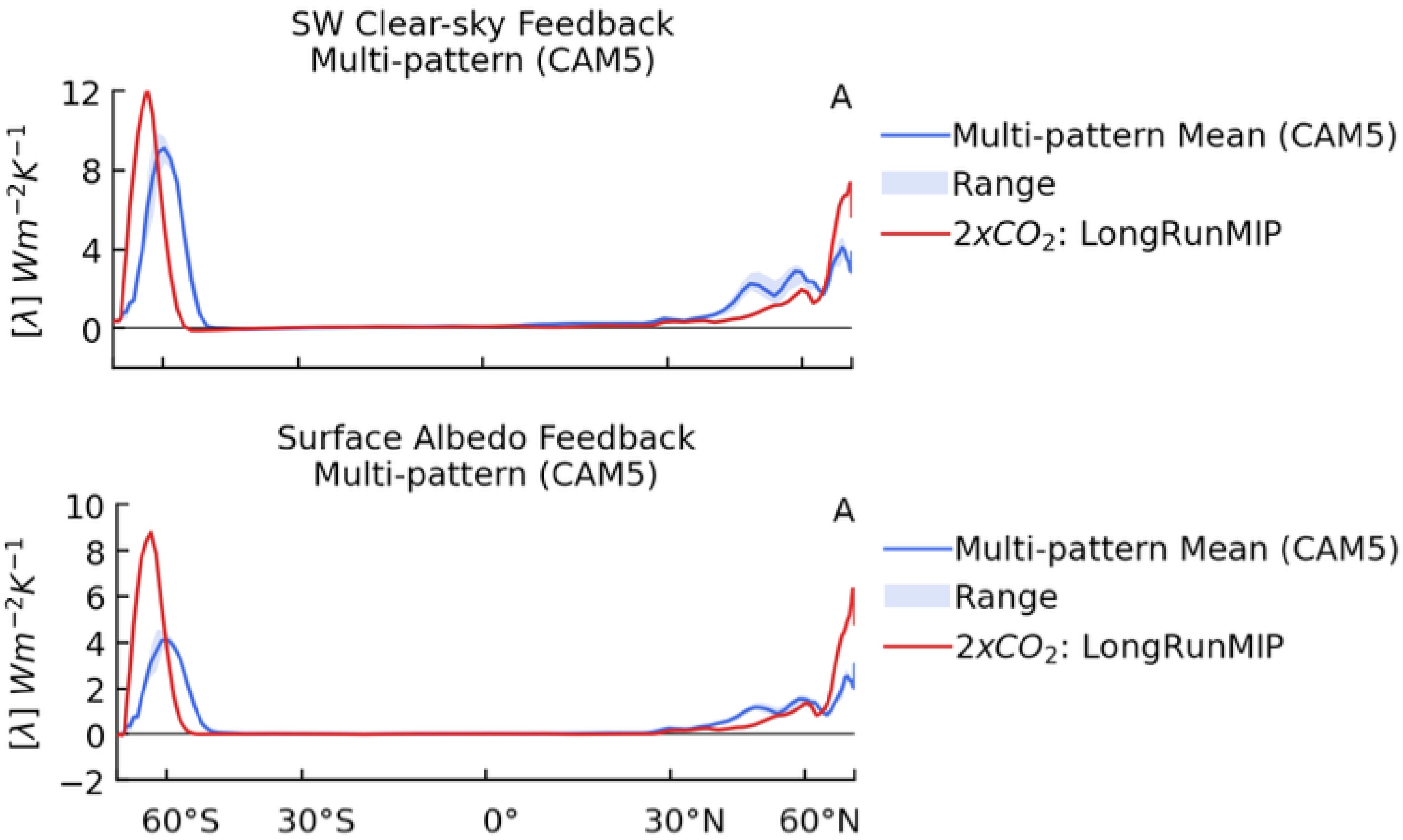




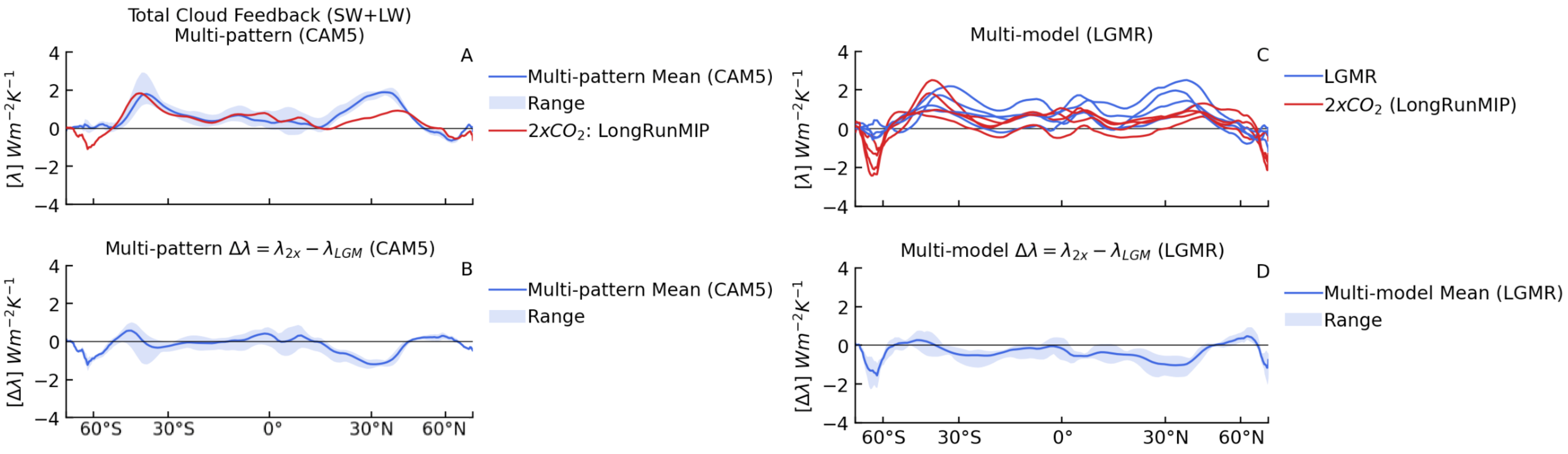




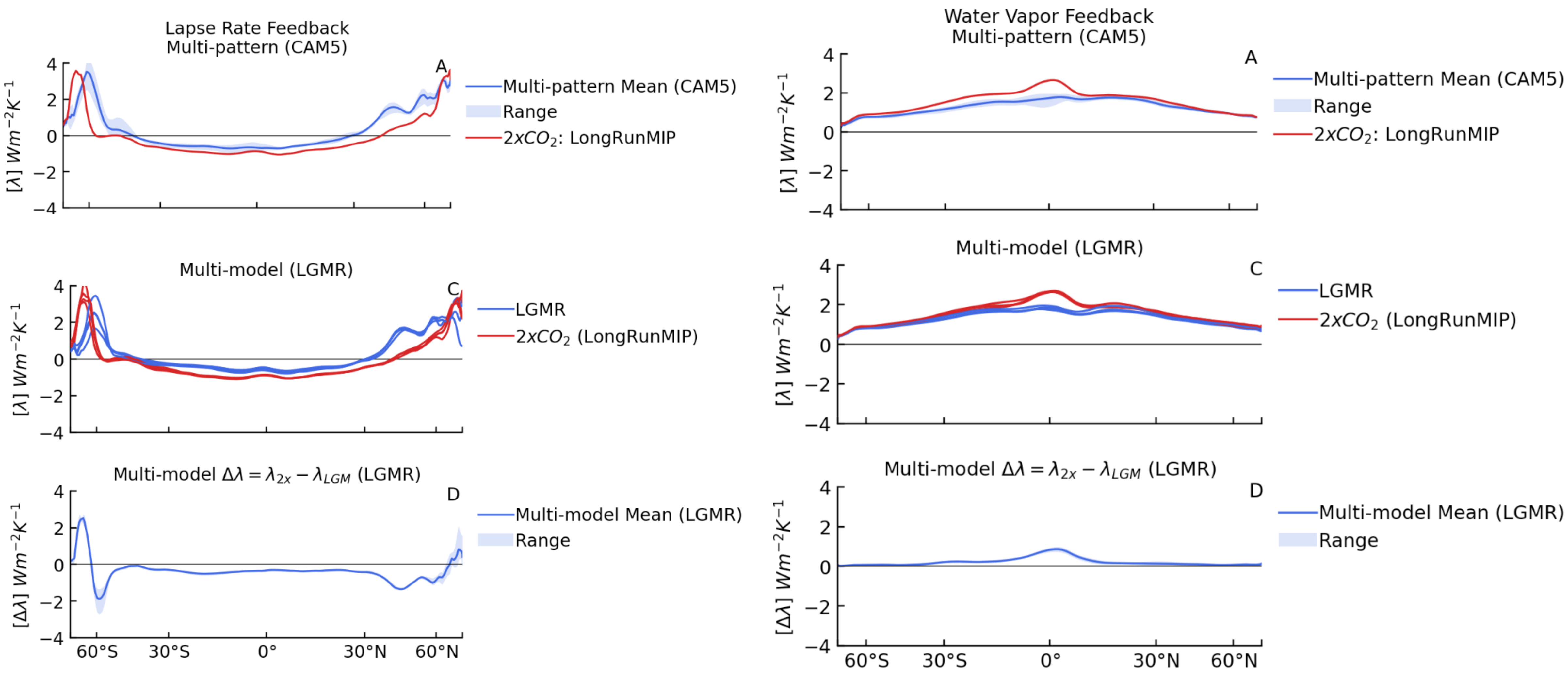
Why doesn't the surface albedo feedback make cold climate more sensitive?



Cloud feedback spread across patterns and models



LR+WV Feedbacks



LGM Supplement

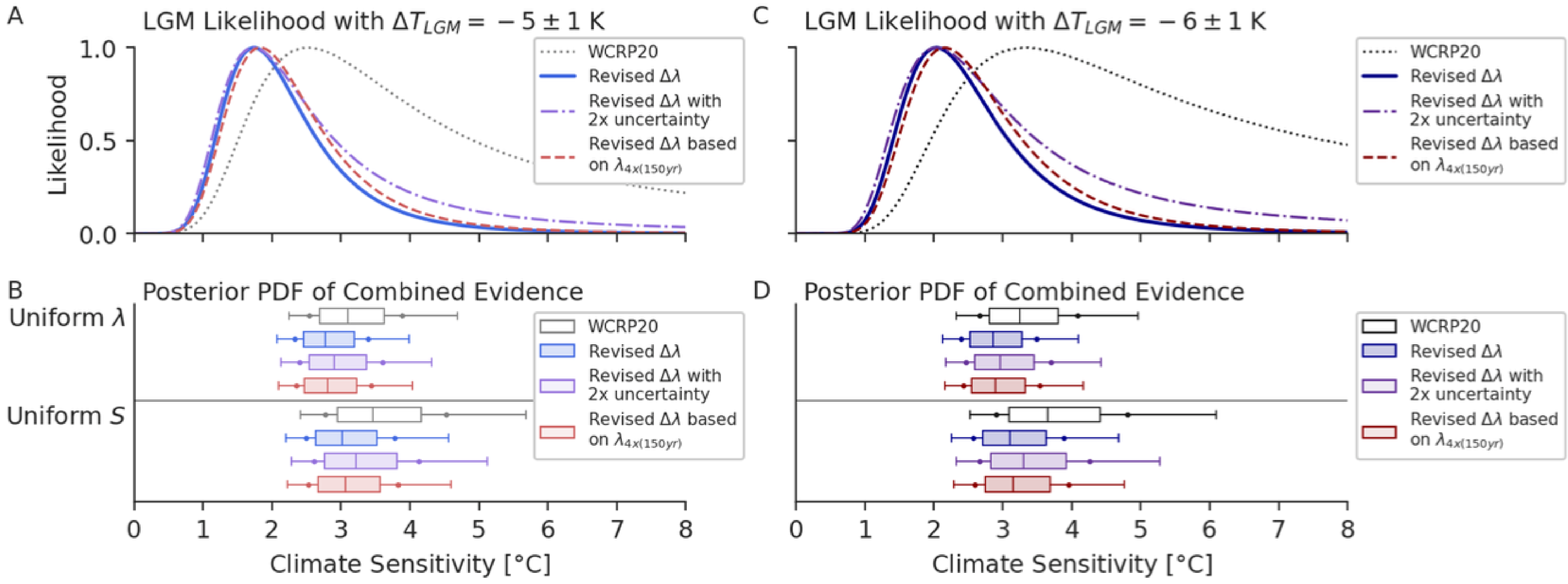


Fig. S4. Uncertainty tests for modern-day climate sensitivity including LGM pattern effects.

LGM Supplement

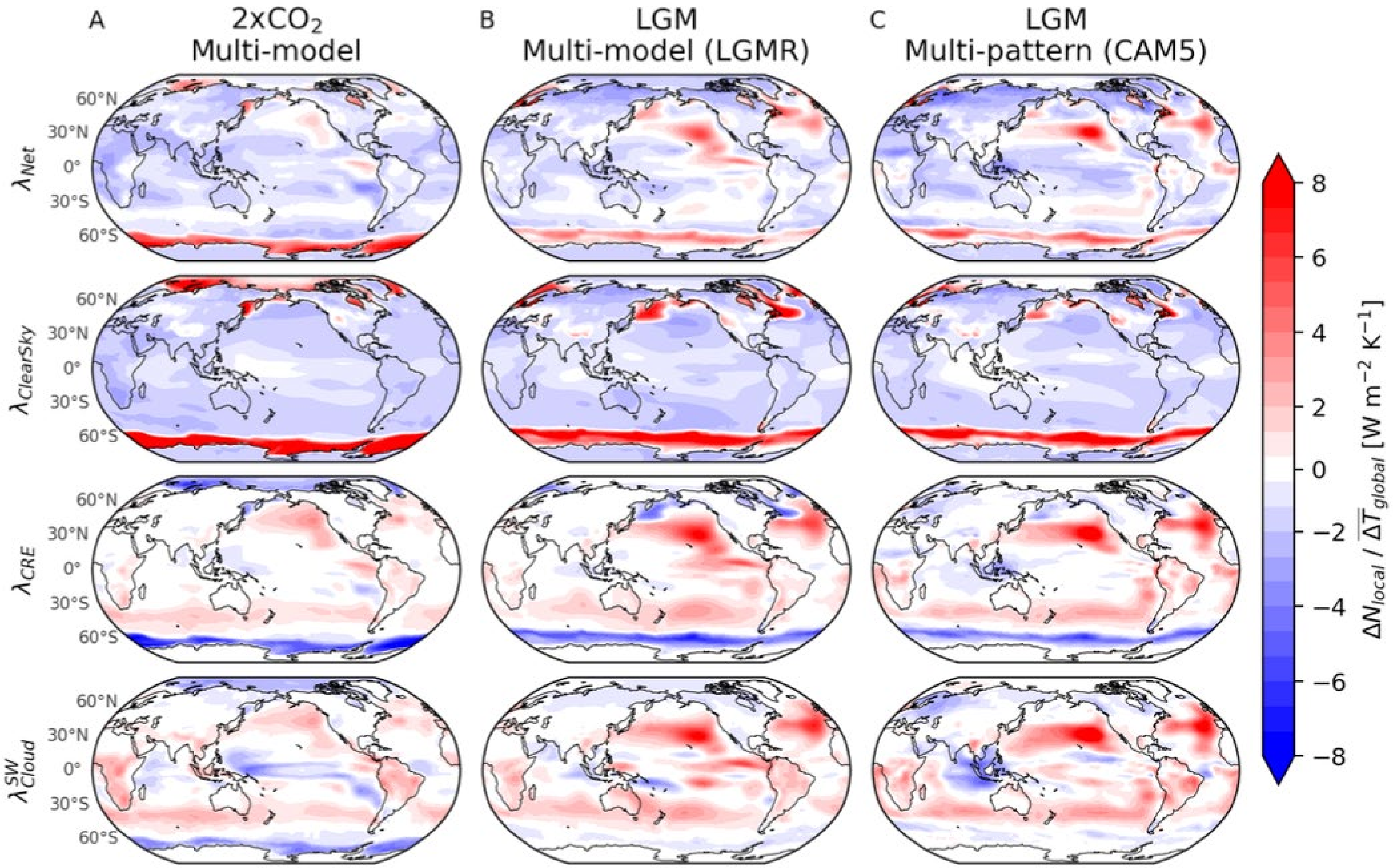


Fig. S7. Spatial decomposition of Last Glacial Maximum (LGM) and $2xCO_2$ local climate feedbacks in atmospheric general circulation models (AGCMs).