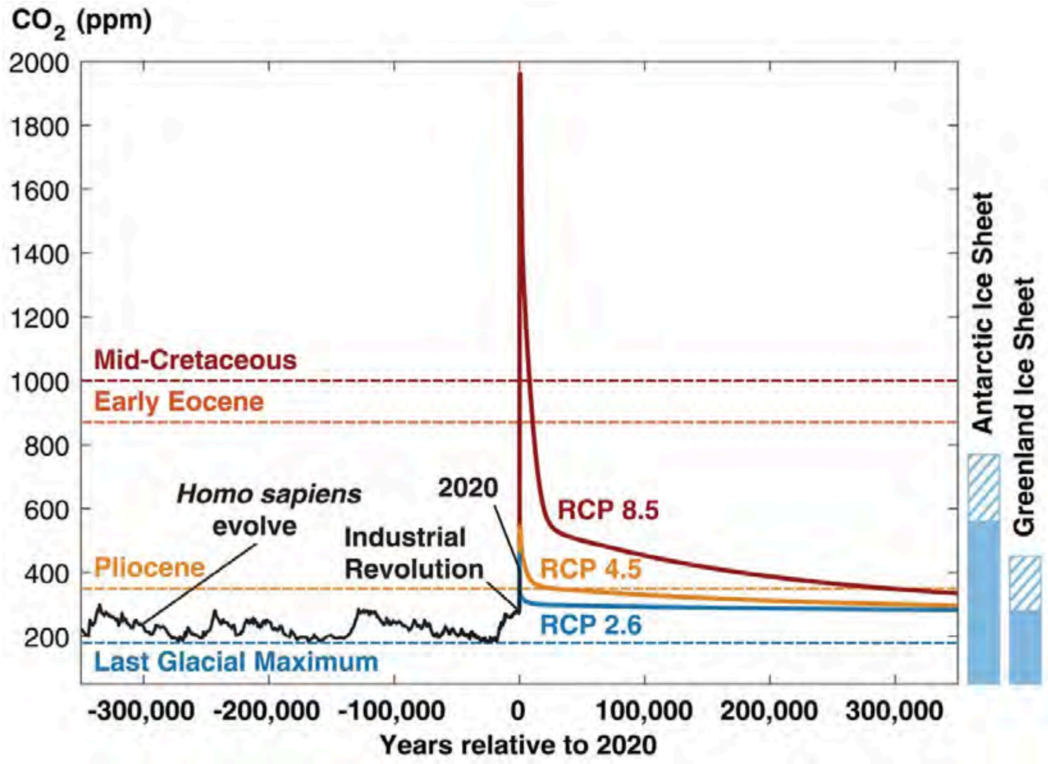
Paleo Perspectives on the Pattern Effect on deep-time scales

Natalie Burls

George Mason University

Using "deep-time" Paleoclimates to estimate Climate Sensitivity



Tierney et al. *Science* 2020

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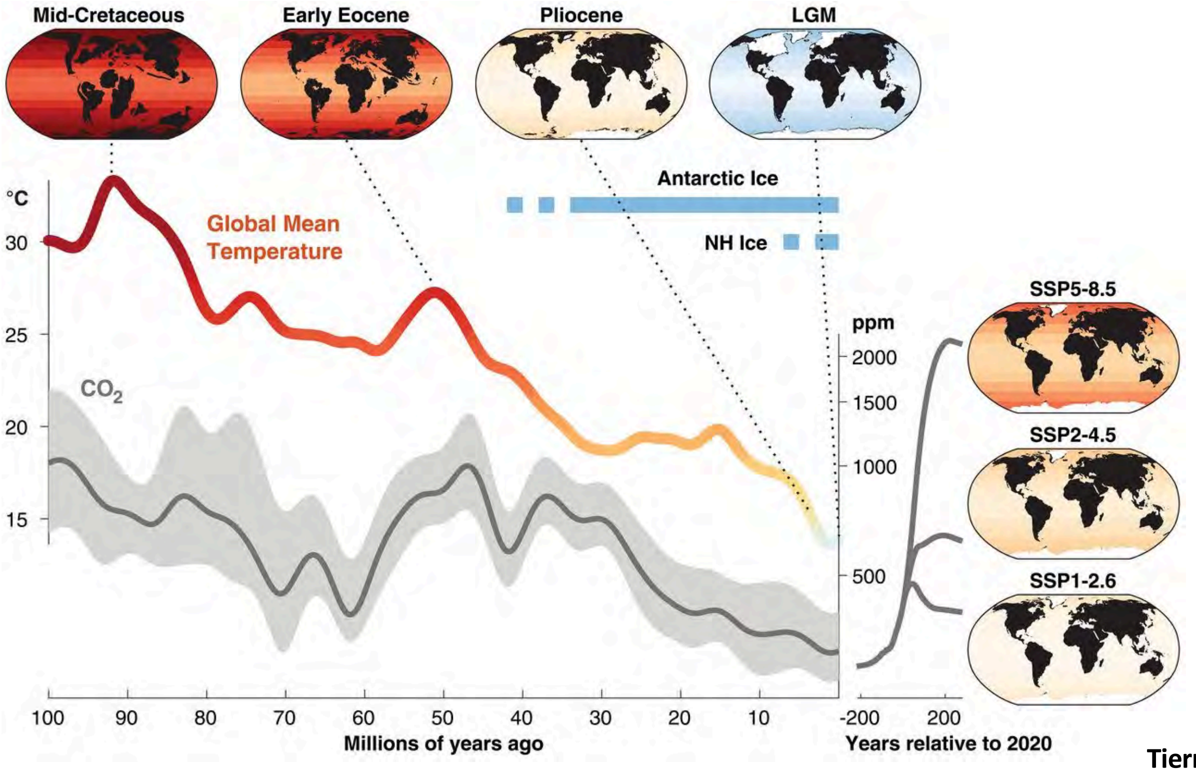

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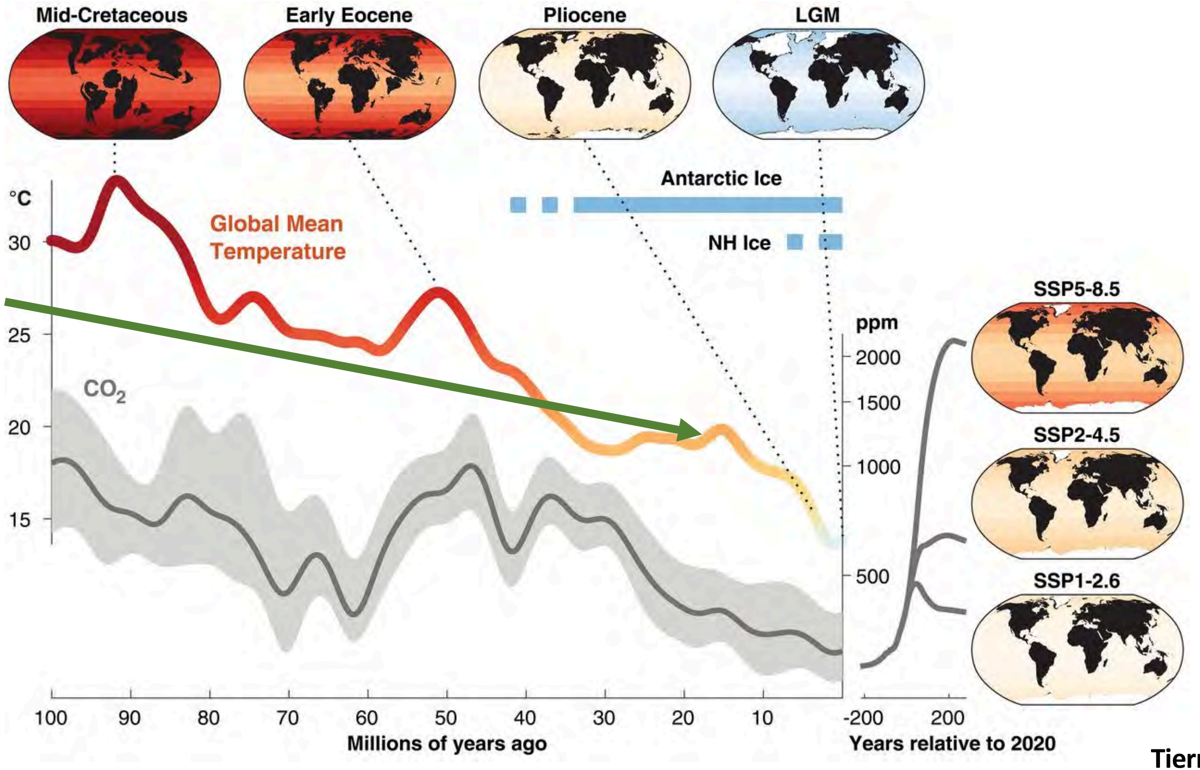


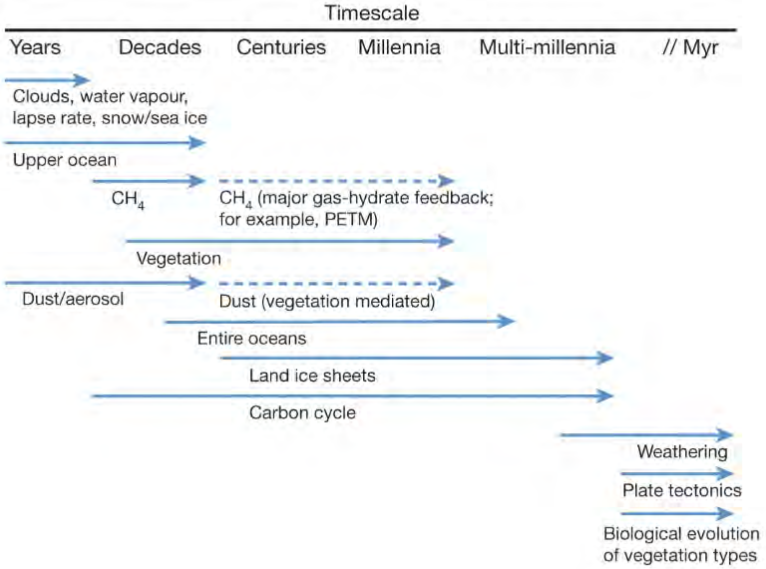
The Miocene (MioMIP)

Tierney et al. *Science* 2020

Using “deep-time” Paleoclimates to estimate Climate Sensitivity

It is important to distinguish between the role of:

- Fast feedbacks (Charney Sensitivity Feedbacks): water-vapor, clouds, lapse rate, snow and sea-ice feedbacks (~100 years in the modern context)
- Slow feedbacks: occur over much longer timescales e.g. land-ice and carbon cycle feedbacks (>1000 years)



Rohling et al. 2012

Using "deep-time" Paleoclimates to estimate Climate Sensitivity

- It is important to distinguish between the role of:
  - Fast feedbacks (Charney Sensitivity Feedbacks): water-vapor, clouds, lapse rate, snow and sea-ice feedbacks (~100 years in the modern context)
  - Slow feedbacks: occur over much longer timescales e.g. land-ice and carbon cycle feedbacks (>1000 years)
- This leads to the distinction being made between ECS and "Earth System Sensitivity" that includes some or all of the slow feedbacks (e.g. land ice and vegetation) in addition to the fast feedbacks

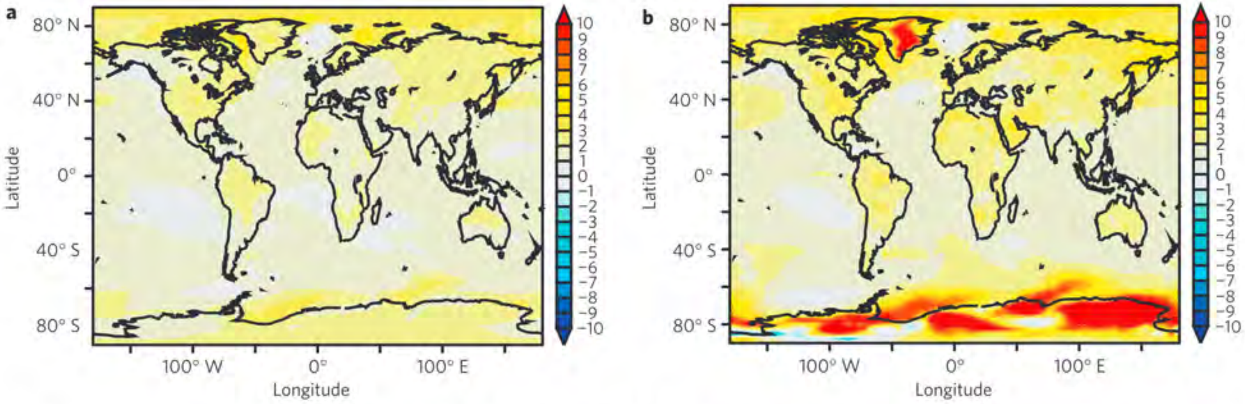


Figure 1 | Charney sensitivity and Earth system sensitivity. a, CS = ΔT_c (°C). **b**, ESS (°C) calculated from Supplementary Equations S16 and S17.

Lunt et al. 2010

Using “deep-time” Paleoclimates to estimate Climate Sensitivity

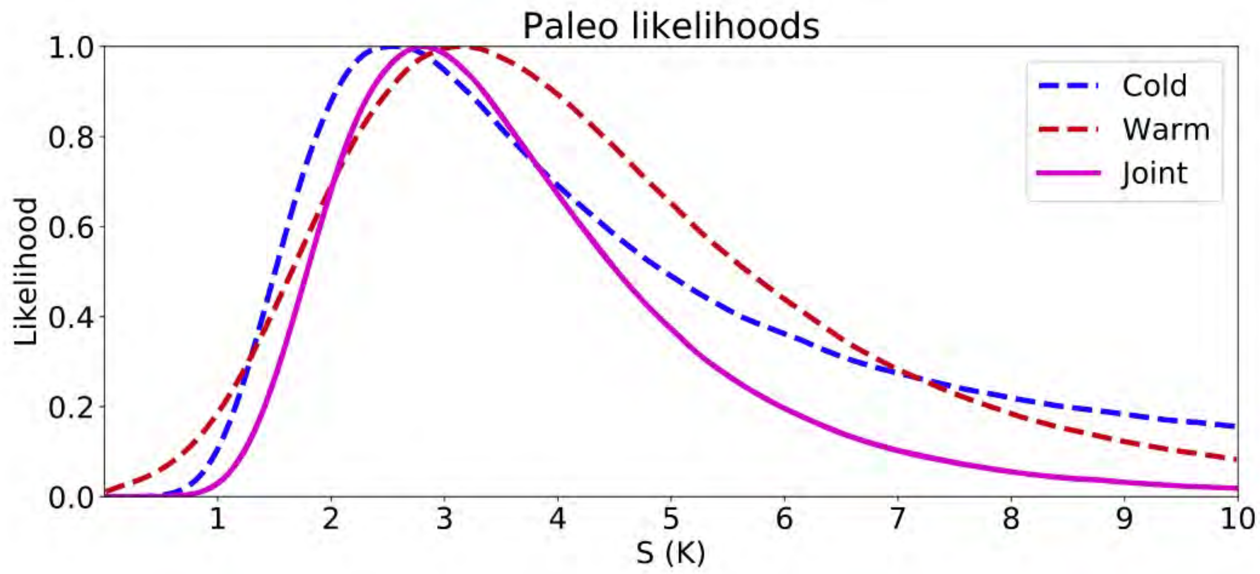
- PALAEOSENS (Rohling et al. 2012) framework = constrain the fast feedbacks by treating the radiation changes due to the slow feedbacks as a forcing
- In practice however, paleoclimate modeling is needed to quantify the radiative influence of the slow feedbacks that need to be treated as forcing e.g. the radiative impacts of a very different paleogeography or atmospheric aerosol concentrations (Royer 2016)

$$S_{[\mathrm{CO_2}, P_1^s, \cdots, P_m^s]} = \frac{\Delta T}{\Delta R_{[\mathrm{CO_2}]} + \sum_{j=1}^{m} \Delta R_{[P_j^s]}},$$

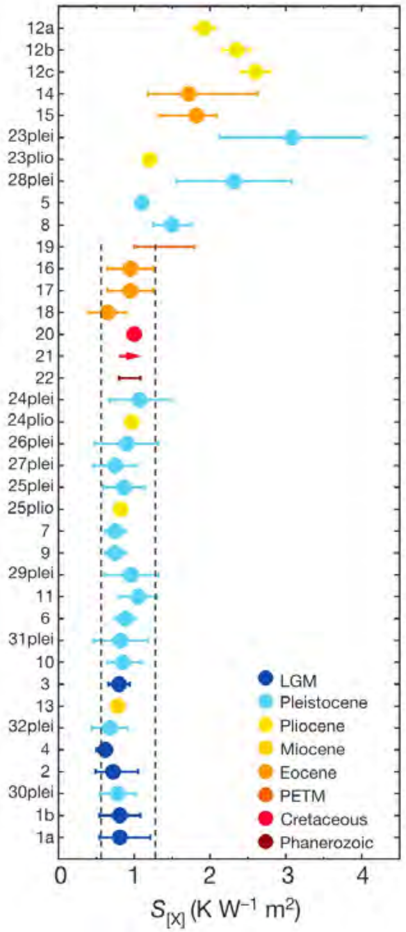
P^s = slow feedback processes like land ice and vegetation changes

Rohling et al. 2012

Using Paleoclimates to estimate Climate Sensitivity

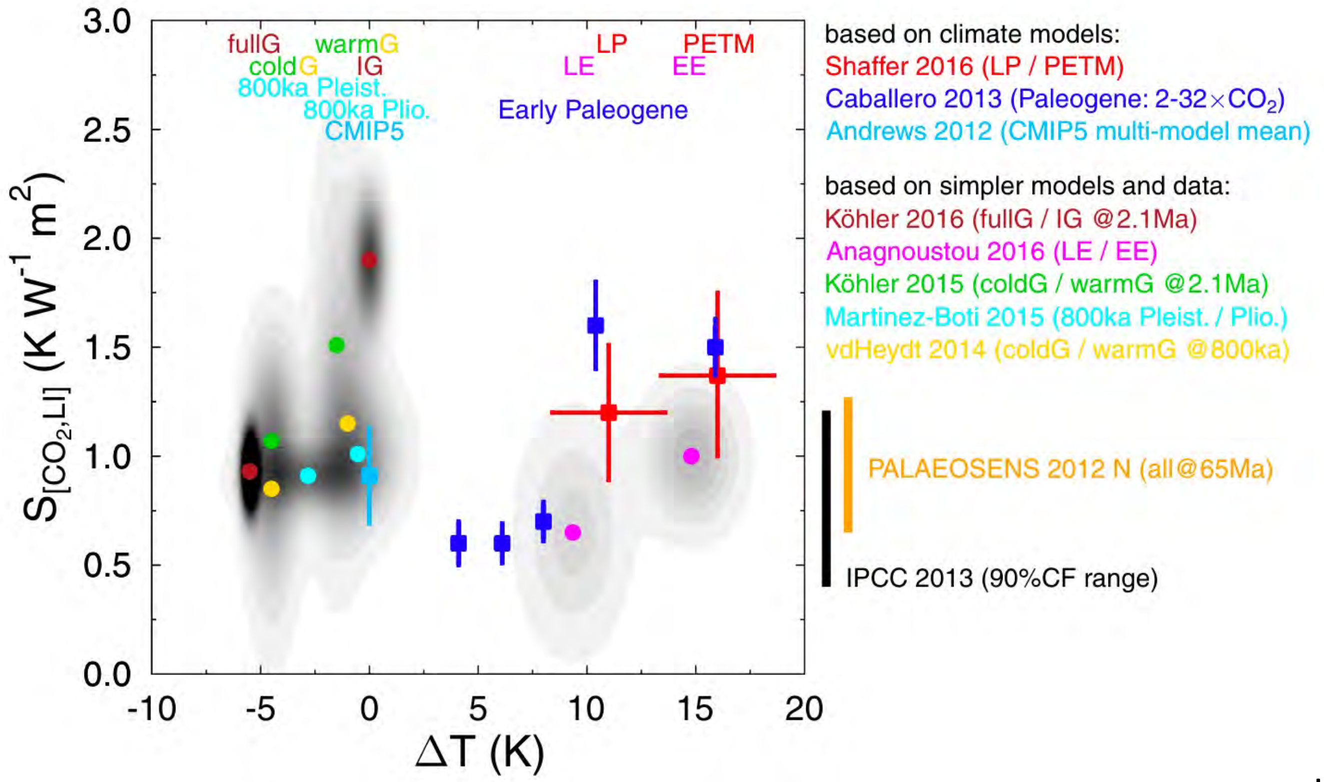


Sherwood et al. 2020



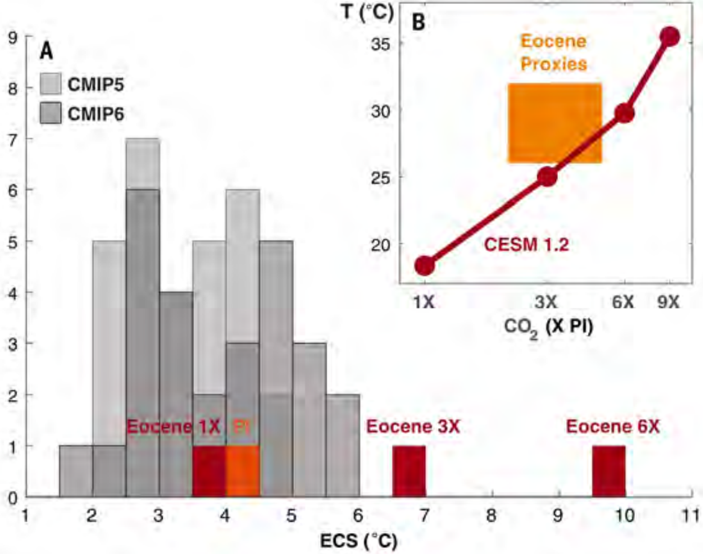
PALAEOSENS (Rohling et al. 2012)

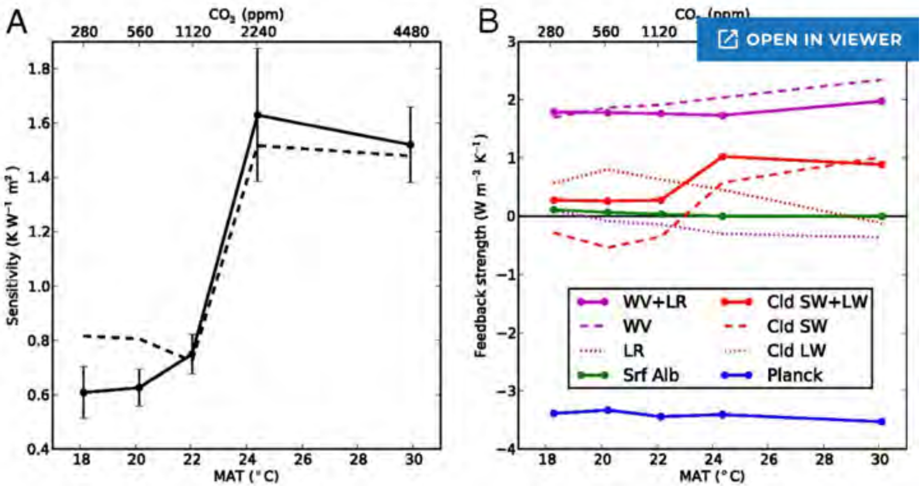
State Dependance



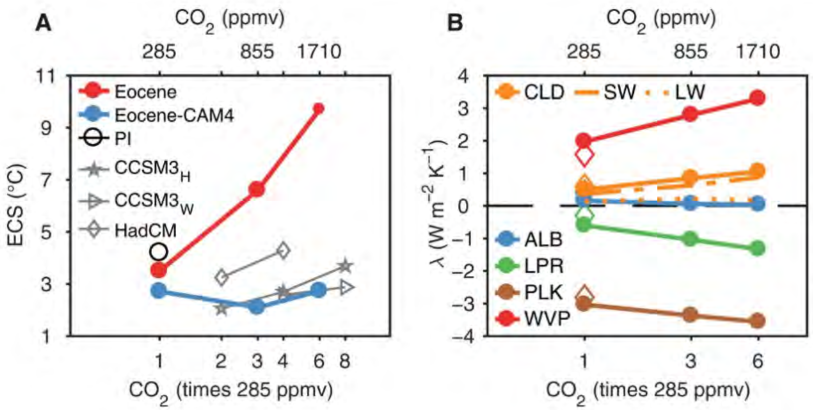
von der Heydt et al., 2016

State Dependance





Caballero & Huber, 2013

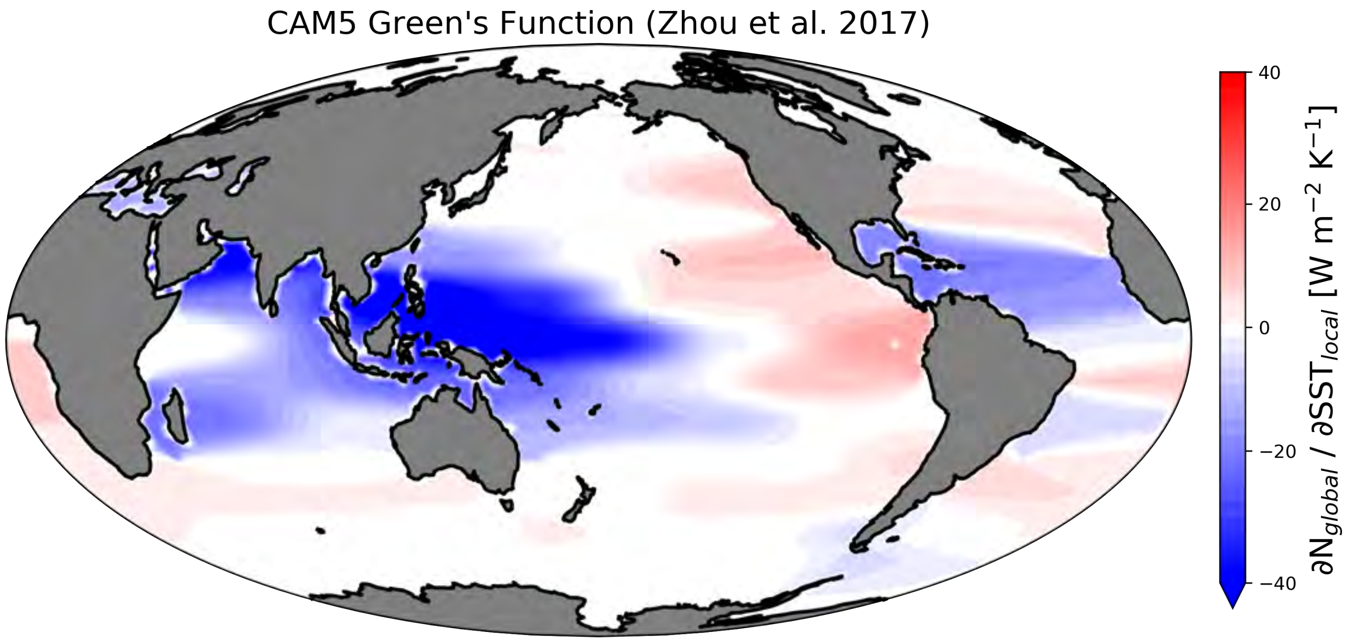


Zhu et al., 2019; Tierney et al. *Science* 2020

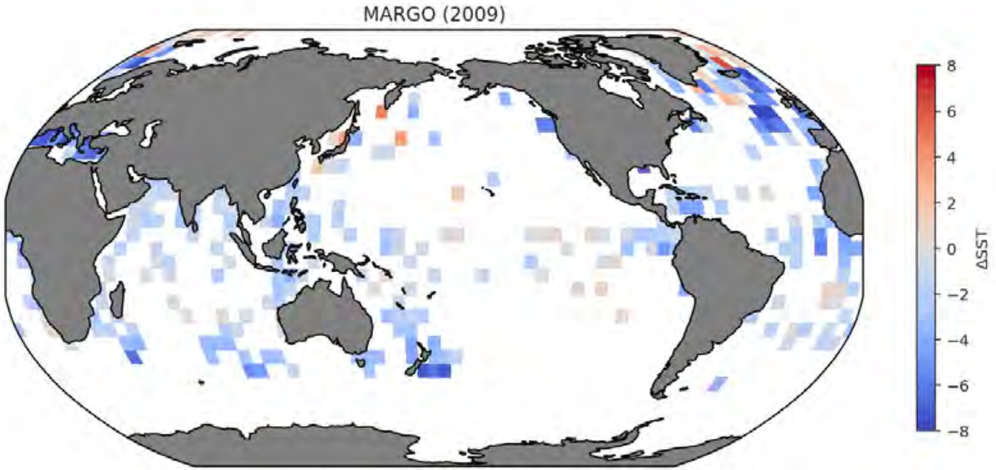
But what about the Pattern Effect?

- We know that the global top-of-atmosphere radiative response depends not only on *global* surface warming but also on the *spatial pattern* of surface warming – the so-called “pattern effect”
- Can we account for the pattern effect associated with a given deep-time paleoclimate state?

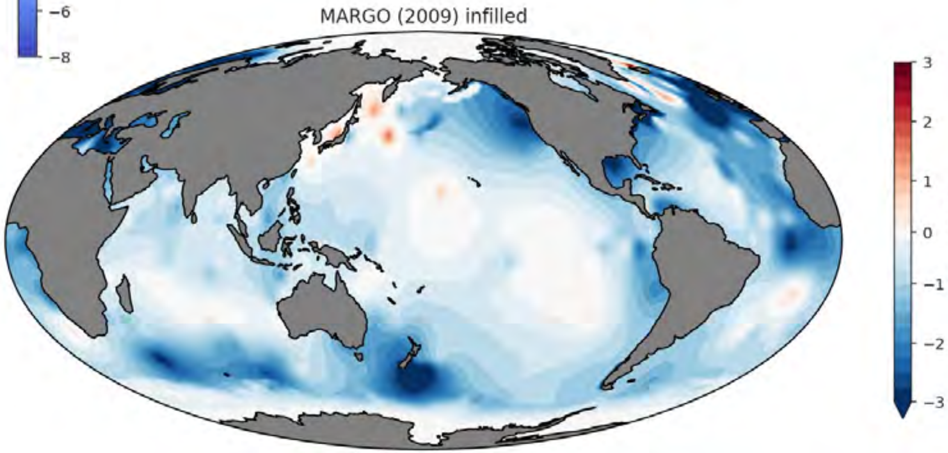
Global Radiative feedback response to local warming



Pattern Effect for the LGM



MARGO Project Members, 2009



From Vince Cooper (UW)

Pattern Effect for the LGM

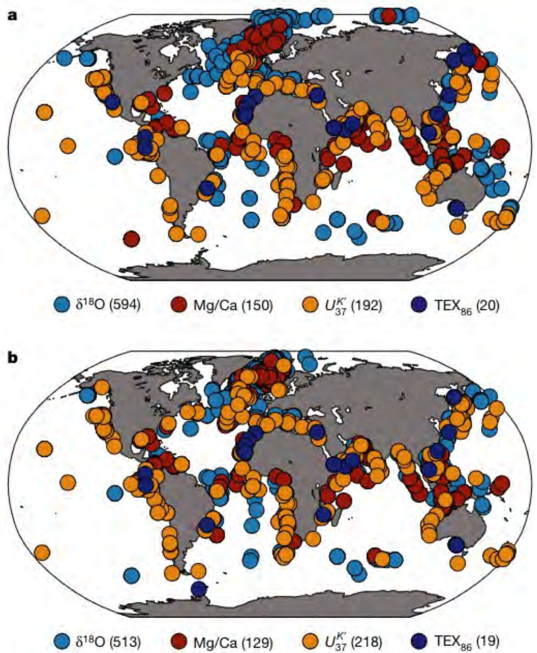
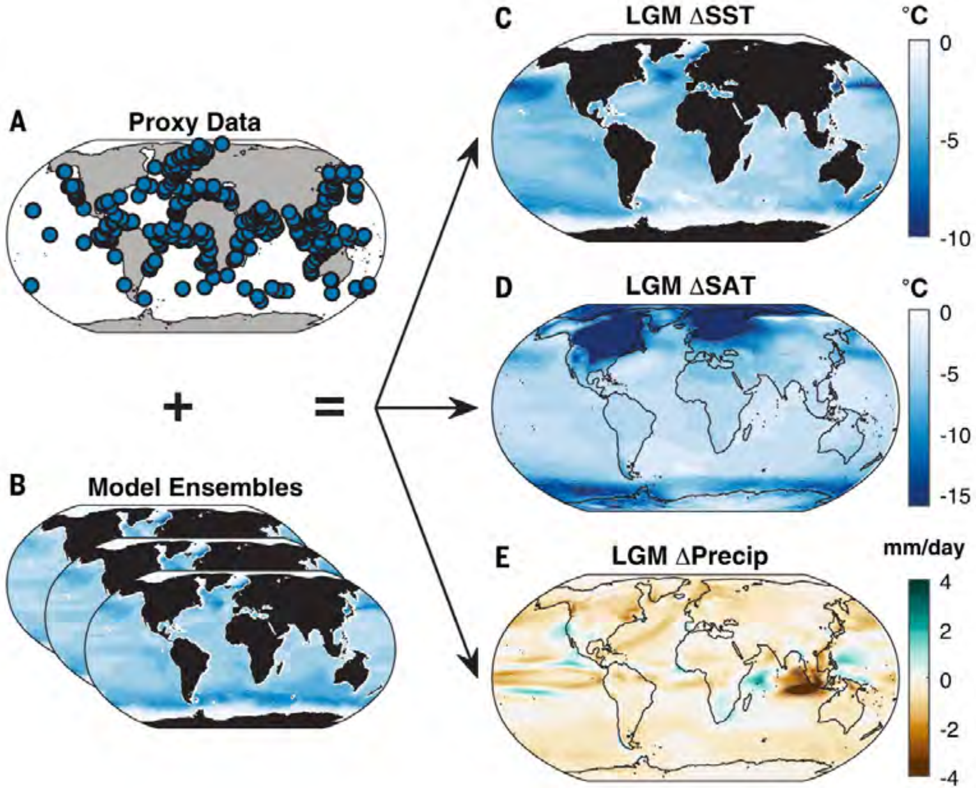


Fig. 1 | Locations of geochemical SST proxies used for the LGM climate reconstruction. a, Proxy sites for the LGM (956). **b**, Proxy sites for the late Holocene (LH; 879). Proxies are colour-coded by type and the number of each is shown in parentheses.

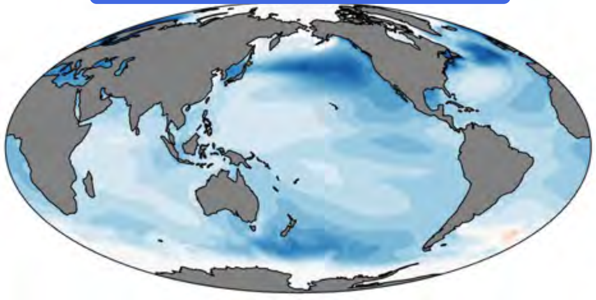
Tierney et al. 2021



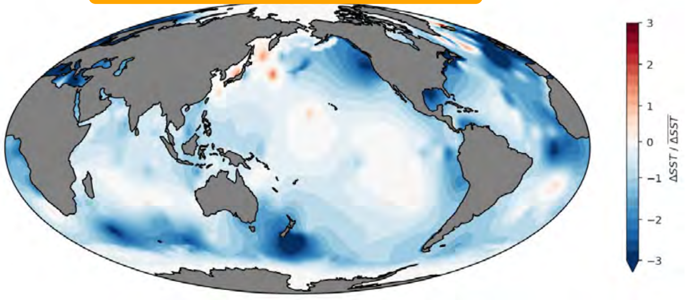
Tierney et al. 2020

LGM vs. 4xCO_2 SST Anomaly Patterns

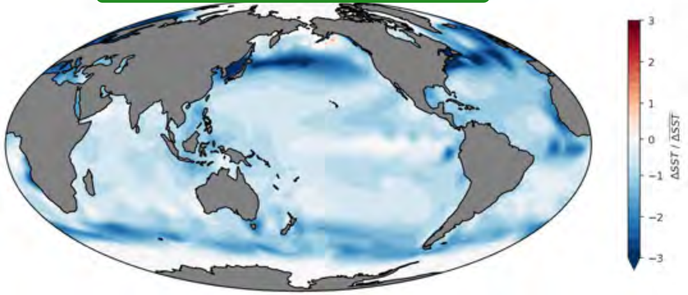
lgmDA (Tierney et al. 2020)



MARGO (2009) infilled



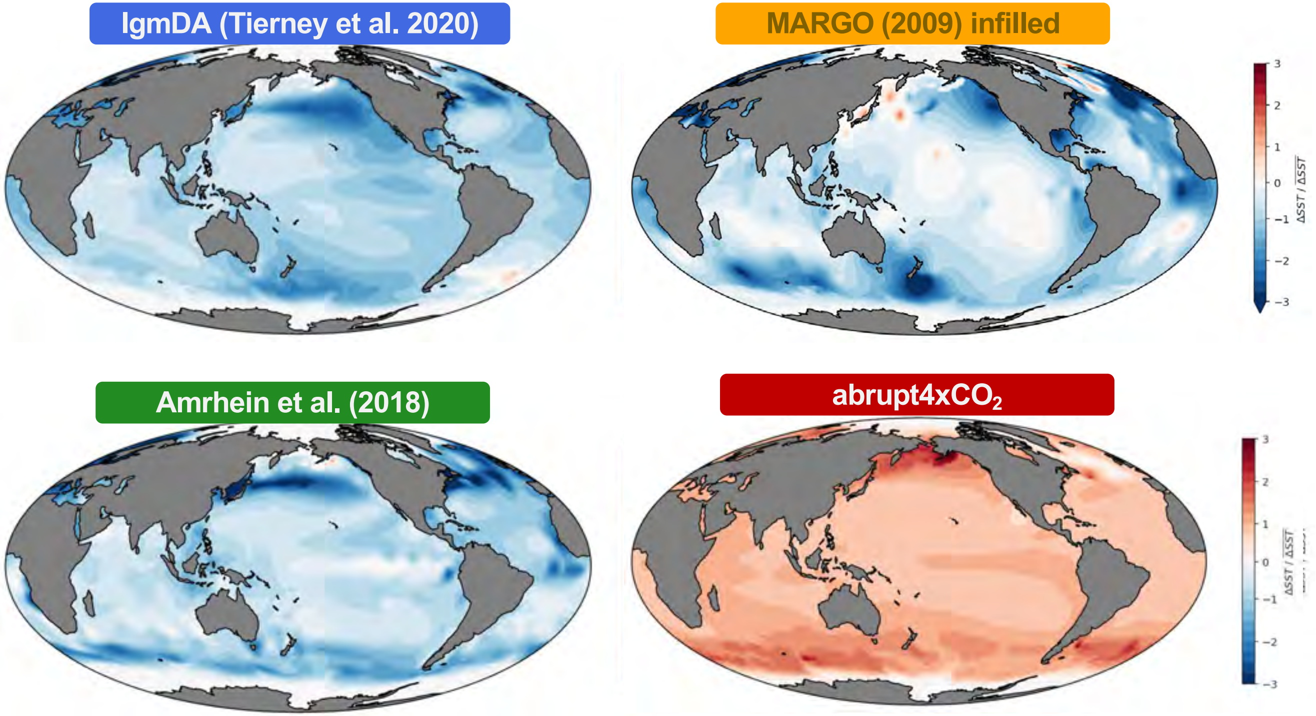
Amrhein et al. (2018)



Patterns are infilled to modern land mask and normalized by global mean SST anomaly

Slide from Vince Cooper (UW)

LGM vs. 4xCO_2 SST Anomaly Patterns

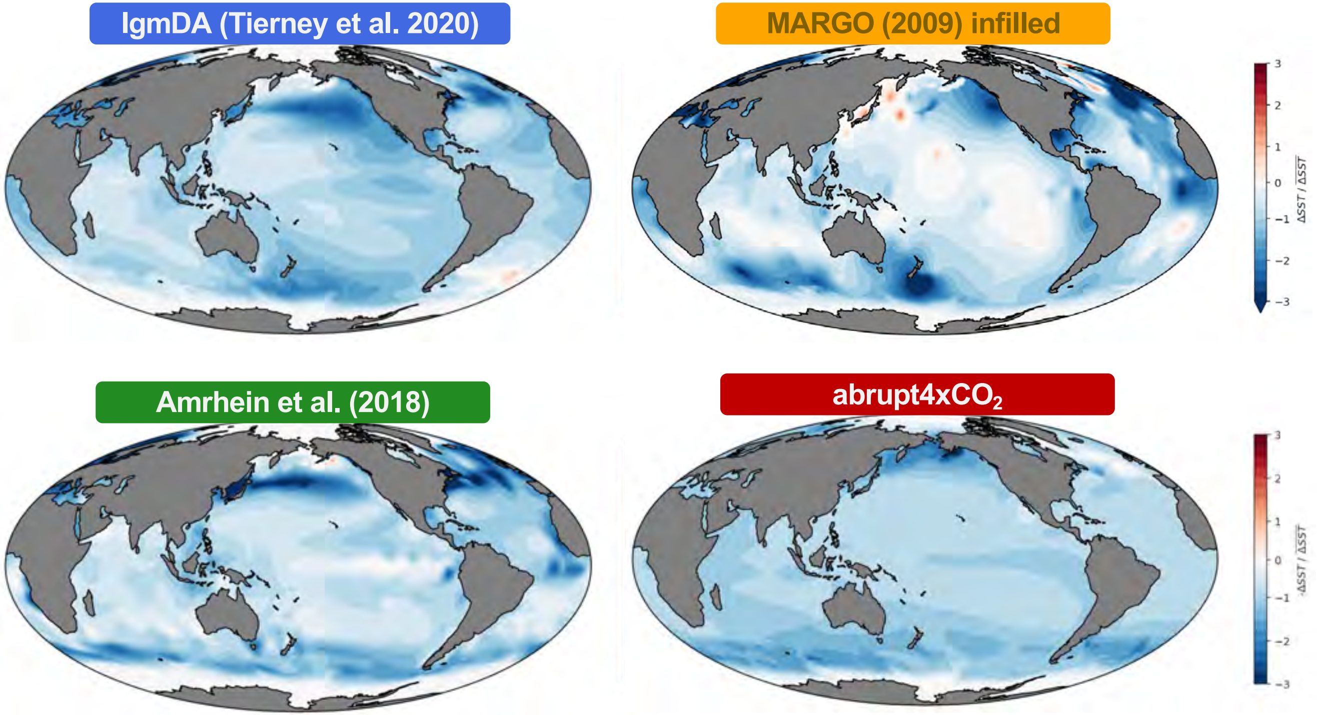


CCSM4-CAM4, mean of years 130-150)

Patterns are infilled to modern land mask and normalized by global mean SST anomaly

Slide from Vince Cooper (UW)

LGM vs. 4xCO_2 SST Anomaly Patterns

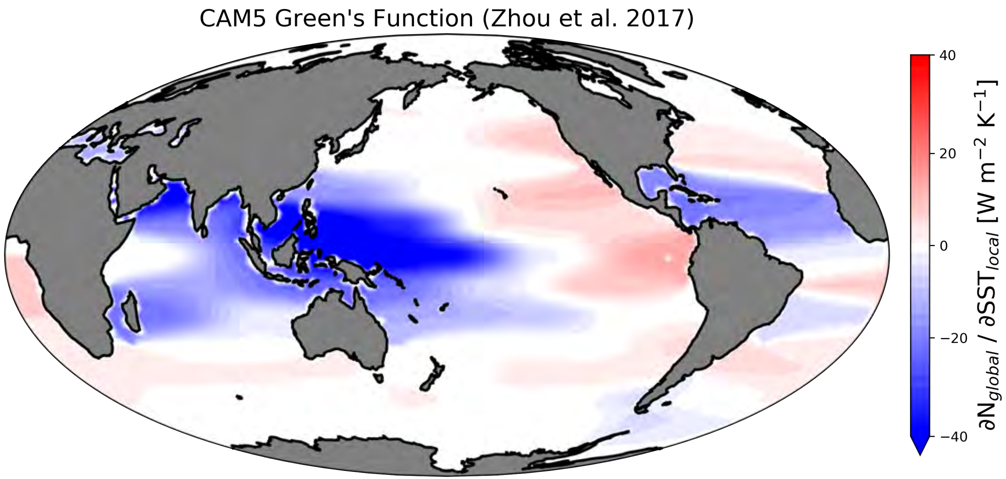


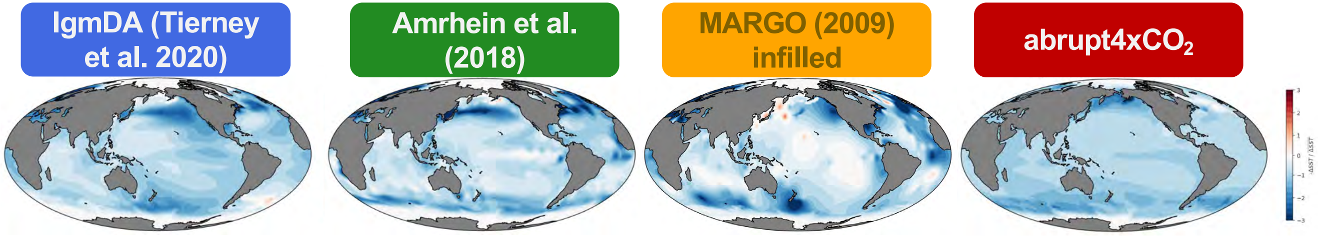
CCSM4-CAM4, mean of years 130-150
(opposite sign of anomaly)

Patterns are infilled to modern land mask and normalized by global mean SST anomaly

Slide from Vince Cooper (UW)

Green's Function for TOA response



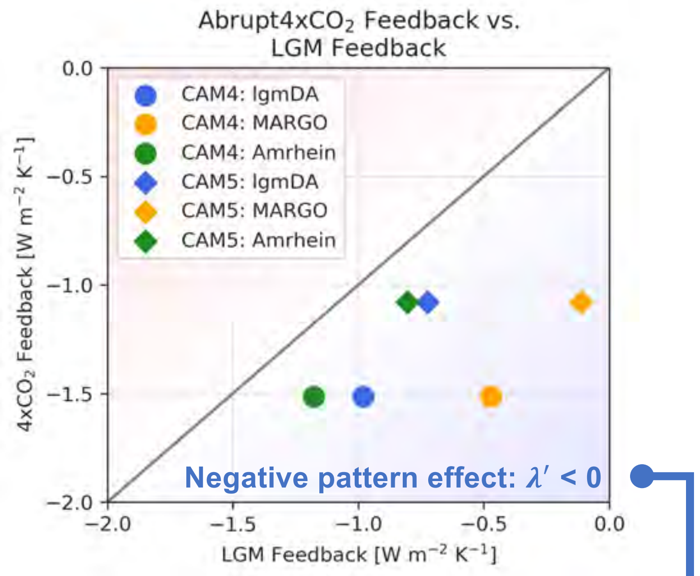


Note: Green's function plot values are scaled up by number of SST grid cells

Slide from Vince Cooper (UW)

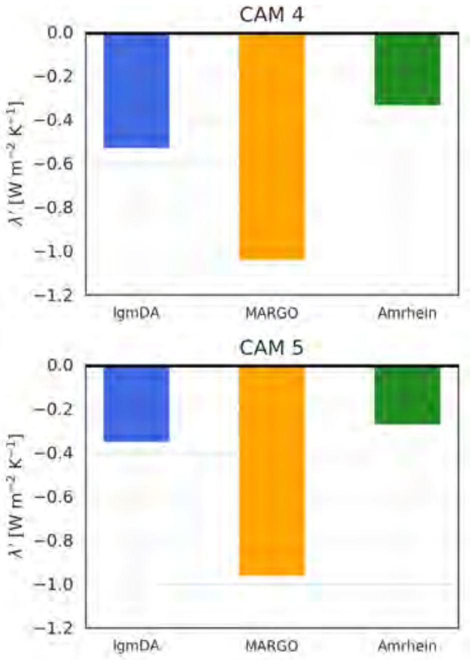
LGM Pattern Effect

Preliminary results from AGCMs with prescribed SST/SIC



LGM feedback is weaker (less negative) than $4xCO_2$ feedback

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



Slide from Vince Cooper (UW)

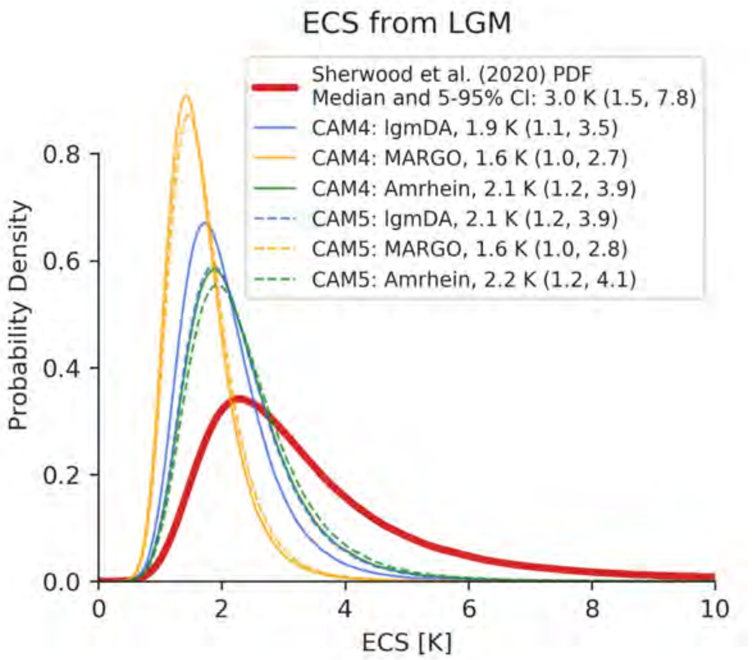
LGM Pattern Effect: Impact on Modern-day ECS

Preliminary results

- Adjust λ_{LGM} for pattern effect $\boldsymbol{\lambda'}$ when using LGM to estimate modern-day ECS:

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

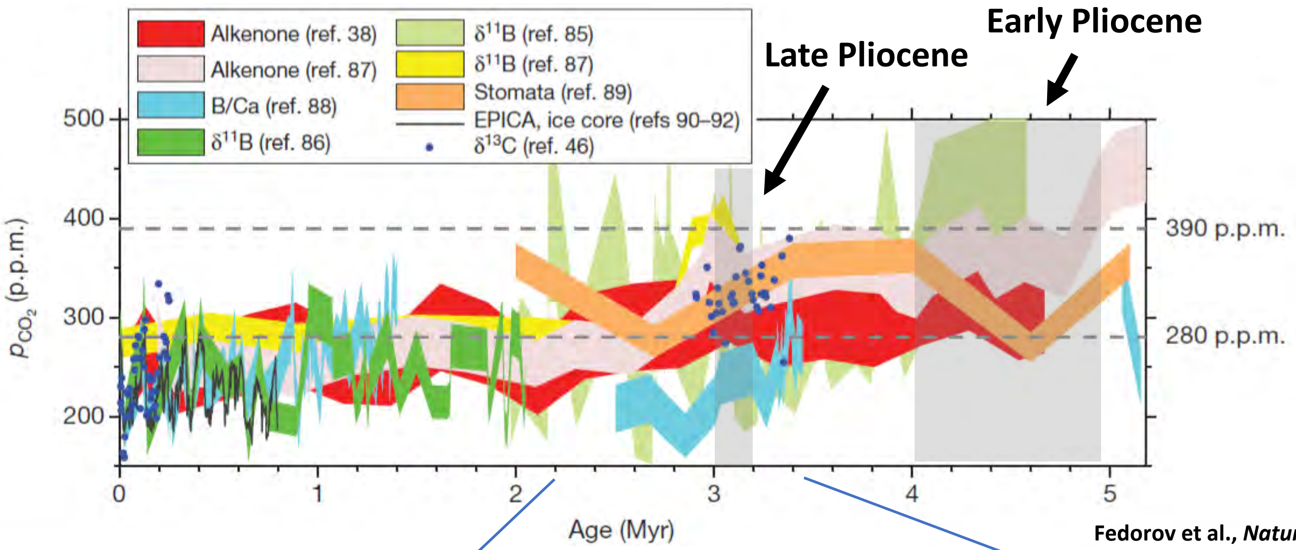
- $\boldsymbol{\lambda'} < \mathbf{0}$ in all datasets and AGCM experiments
  - Accounting for pattern effect **reduces modern-day ECS**



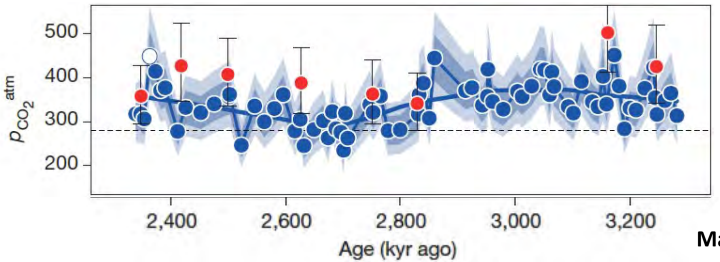
Poster session (Vince Cooper):
"The Last Glacial Maximum Pattern Effect"
Co-authors: Kyle Armour, Cristian Proistosescu, Philip Chmielowiec, Jessica Tierney, Matthew Osman, Yue Dong, Gregory Hakim, Daniel Amrhein, Natalie Burls, and Scott Knapp

Slide from Vince Cooper (UW)

What does the warm Pliocene tell us about how the tropical Pacific will respond to global warming?

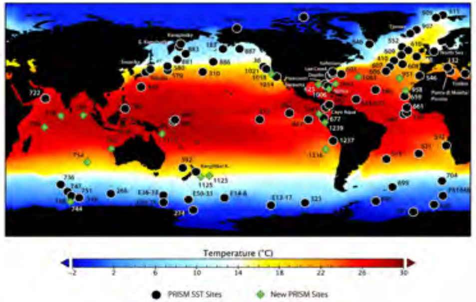


Fedorov et al., *Nature*, 2013

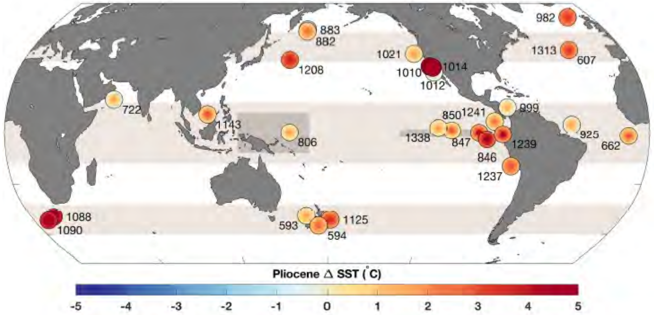


Martínez-Botí et al., *Nature*, 2015

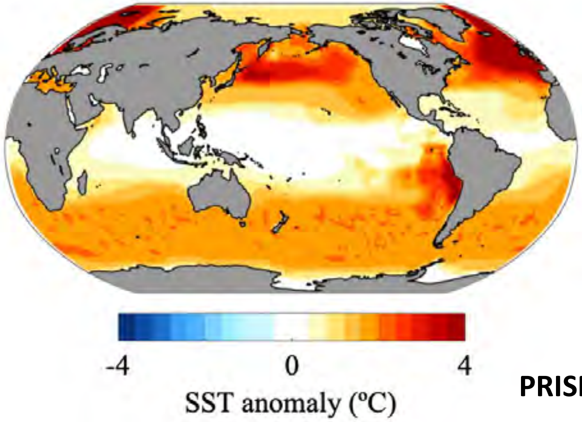
Pattern Effect for the Late Pliocene?



3.264 - 3.025 Ma

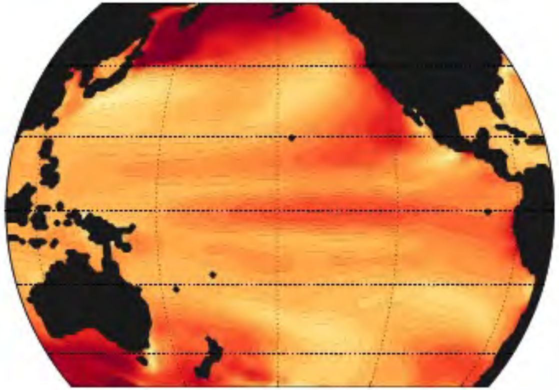


Pliocene sea-surface temperature anomaly (PRISM)



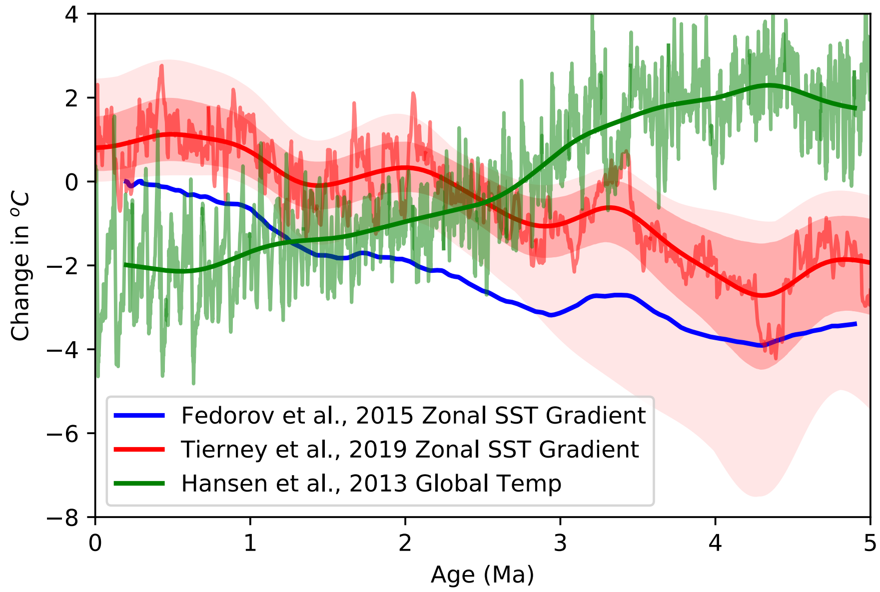
PRISM; Dowsett et al. 2010

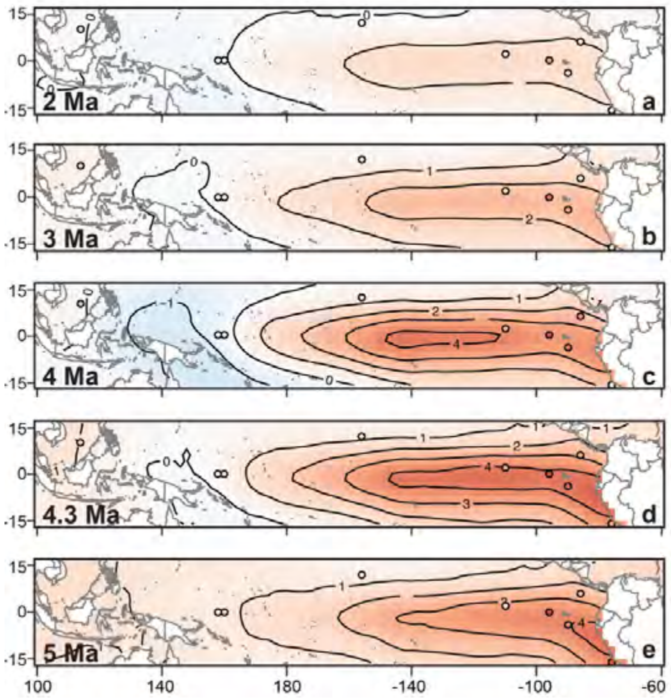
b. CESM Pliocene



Tierney et al. (2019)

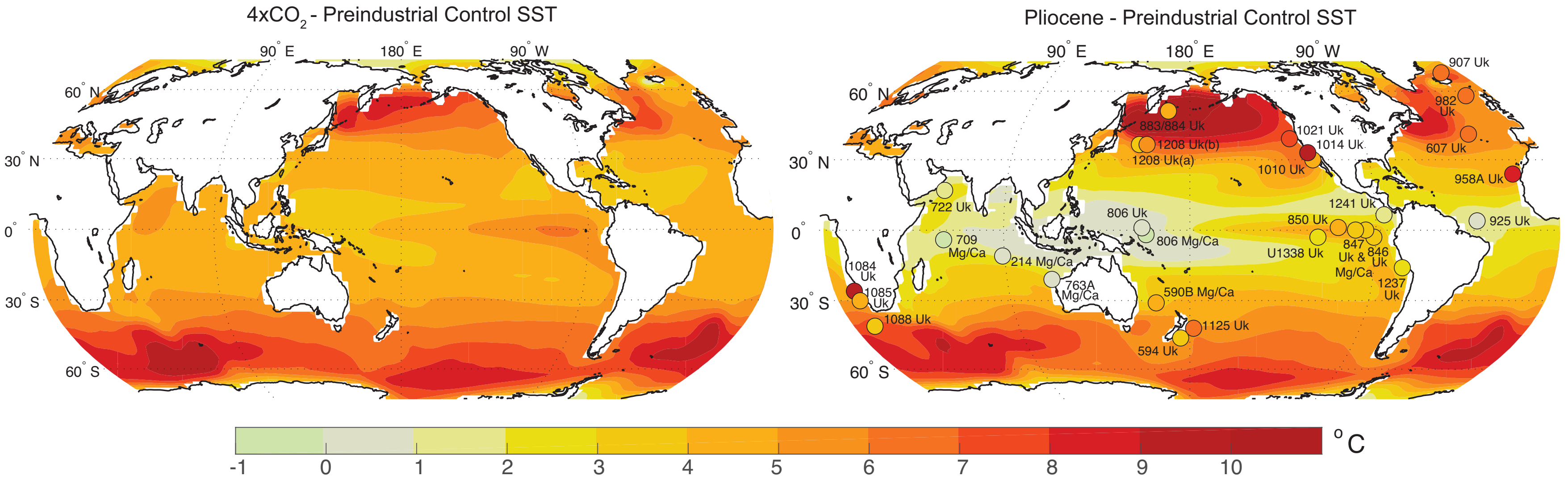
Pattern Effect for the Early Pliocene?





Wycech et al., 2020

Pattern Effect for the Early Pliocene?



Burls and Fedorov, 2017

Modified Cloud Albedo and Abrupt CO_2 Sensitivity Experiments

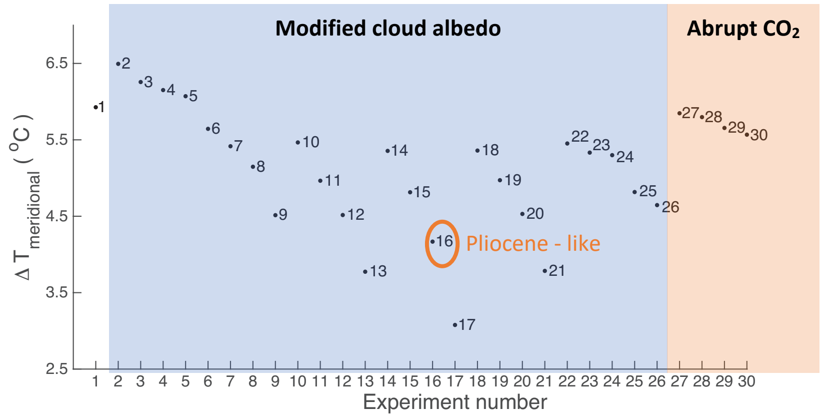
Experimental Setup

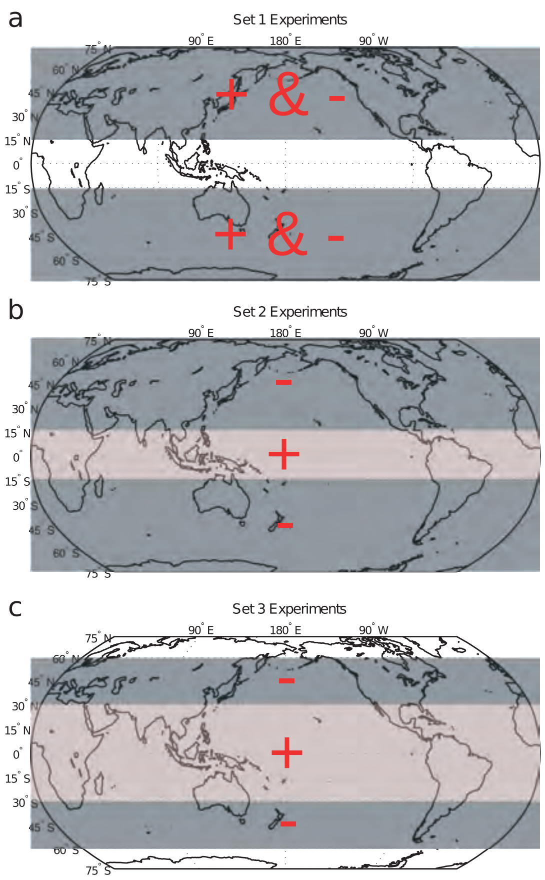
- The Community Earth System Model (CESM)
- Modified Cloud albedo experiments

  Reflectivity of clouds changed by modifying the atmospheric liquid and ice water path, but only in the shortwave radiation scheme. The changes imposed are hypothetical.

- Abrupt 2x, 4x, 8x and 16x CO_2 experiments

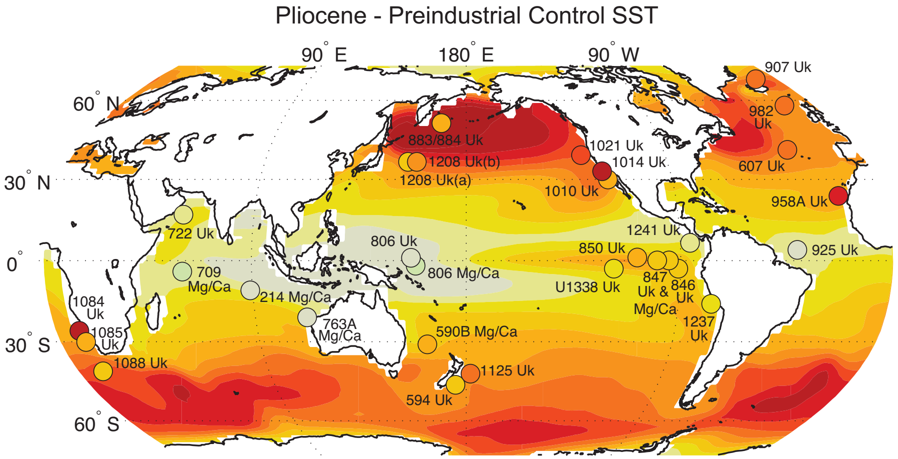
Simulating a broad range of meridional SST gradients

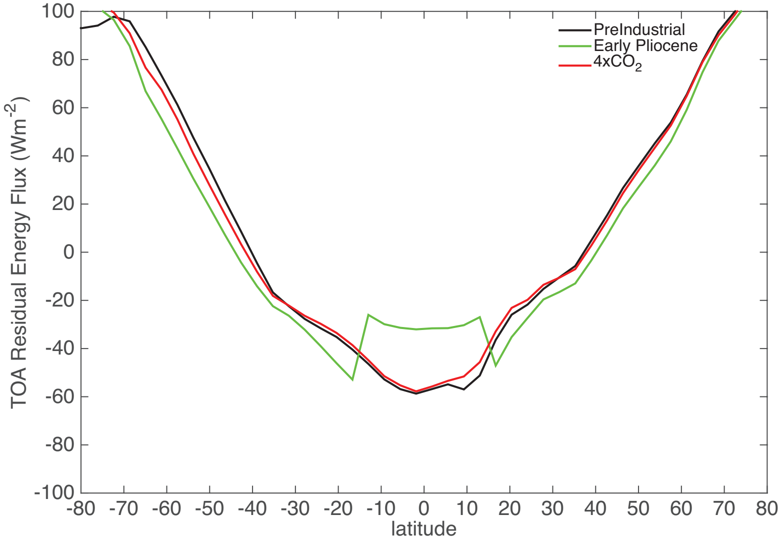




Burls & Fedorov, Journal of Climate, 2014

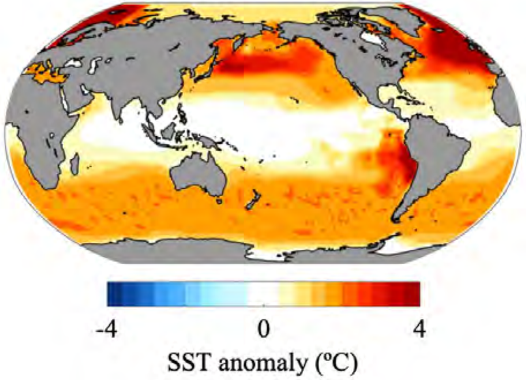
Pattern Effect for the Early Pliocene?



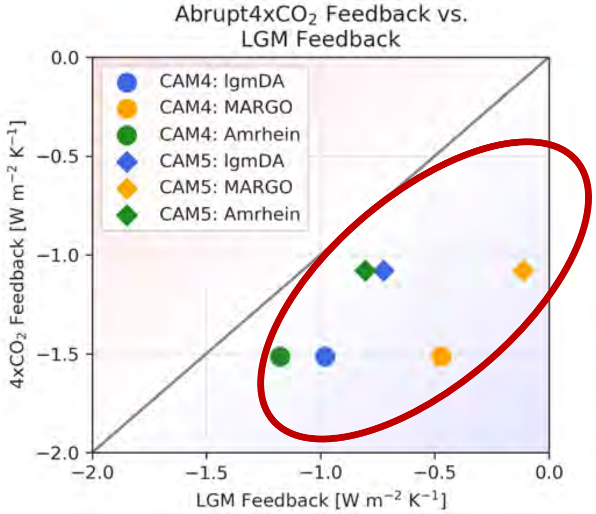


Pattern Effect for the Pliocene?

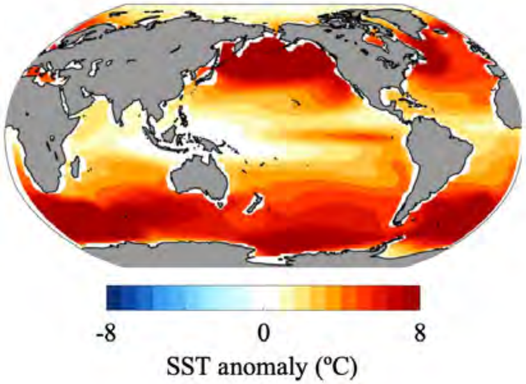
Pliocene sea-surface temperature anomaly
(PRISM)

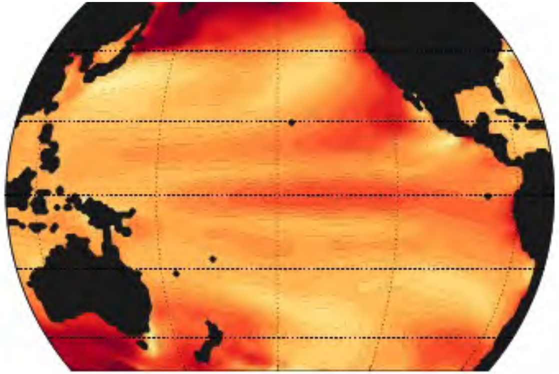


PRISM; Dowsett et al. 2010



Pliocene sea-surface temperature anomaly
(Burls and Fedorov 2017)





Tierney et al. (2019)

What is needed?

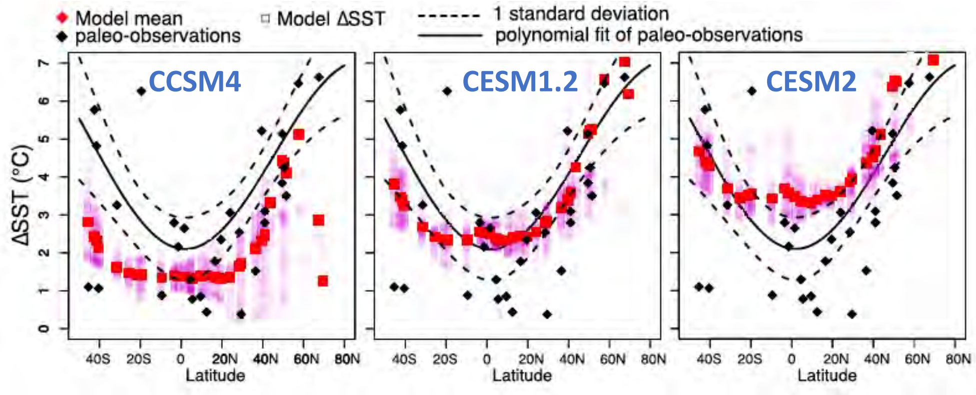
- As seen for historical versus equilibrium warming, the pattern effects matter for paleoclimate estimates of ECS - a global-mean temperature reconstruction is not enough
- There is a need to differentiate between state dependance and the pattern effect

Challenges

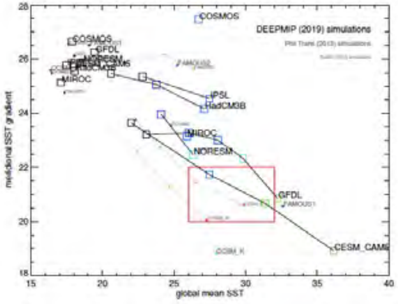
- Accurate reconstructions of SST and sea ice patterns with uncertainty quantification, particularly in the tropical Pacific where the radiative response is very sensitive to the details of SST changes
- We have to deal with significant uncertainty in the forcing and its pattern in the deep-time paleoclimate context
- What is the pattern effect for the future? The pattern effect in climate model projections versus in paleoclimates

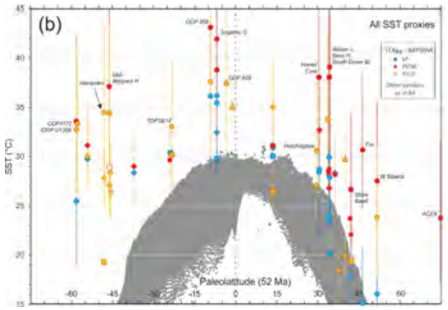
Insights from deep-time Paleoclimate

Paleoclimate warming is polar amplified and our models generally struggle to capturing the full extent of polar and subtropical warmth without warming the deep tropics too much.



Feng et al., 2020

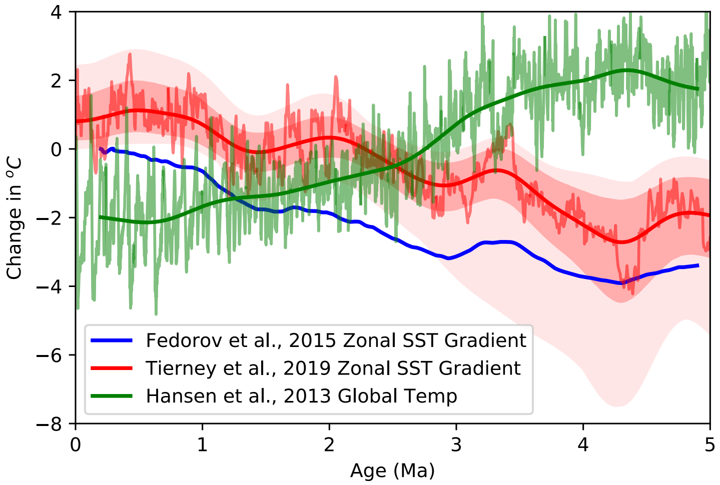


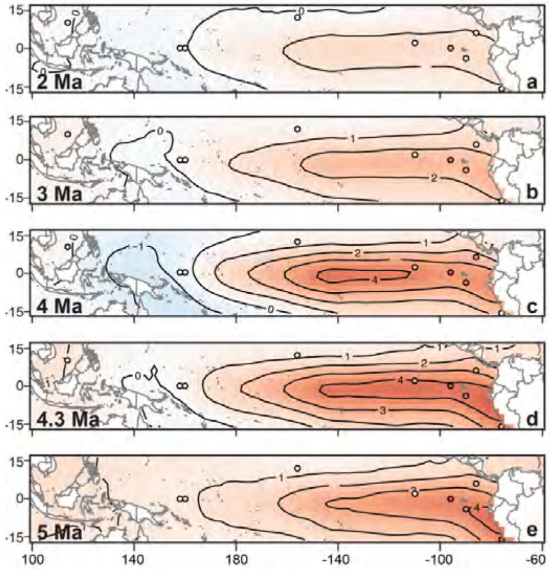


Hollis et al., 2019, Lunt et al., 2020

Insights from deep-time Paleoclimate

The zonal SST gradient in the equatorial Pacific likely reduces in response to warming as equilibrium is approached (with modernish paleogeography)





Wycech et al., 2020

Paleoclimates provide out-of-sample tests for Climate Models

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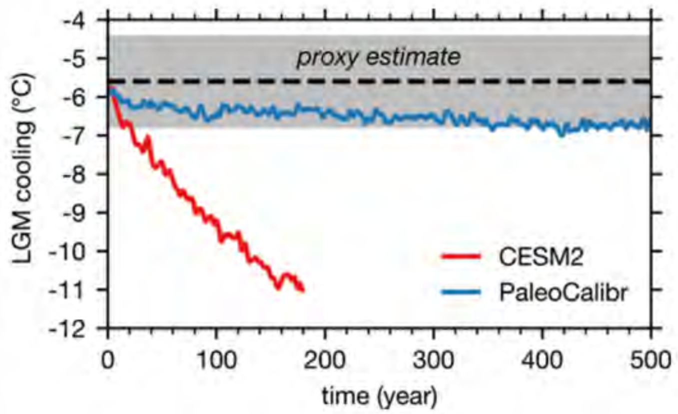
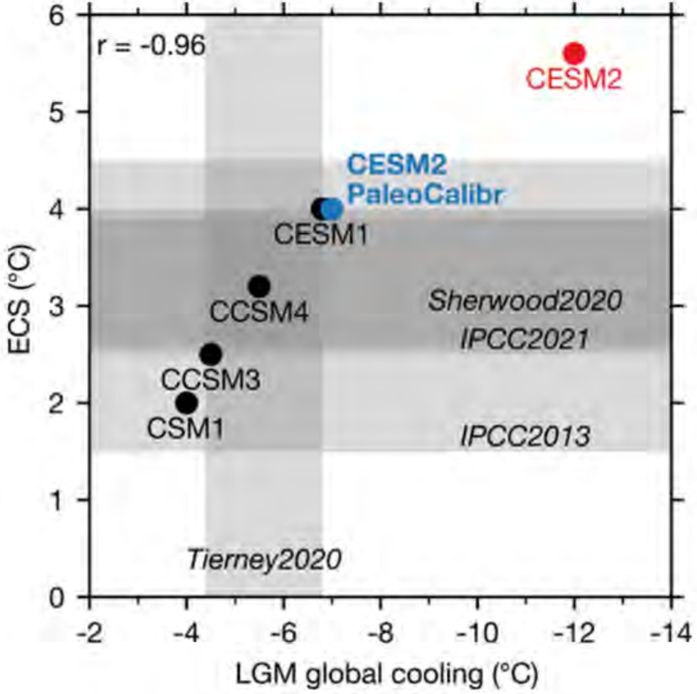
First published: 25 February 2022 | https://doi.org/10.1029/2021MS002776





Zhu et al., 2021; Zhu et al., 2022

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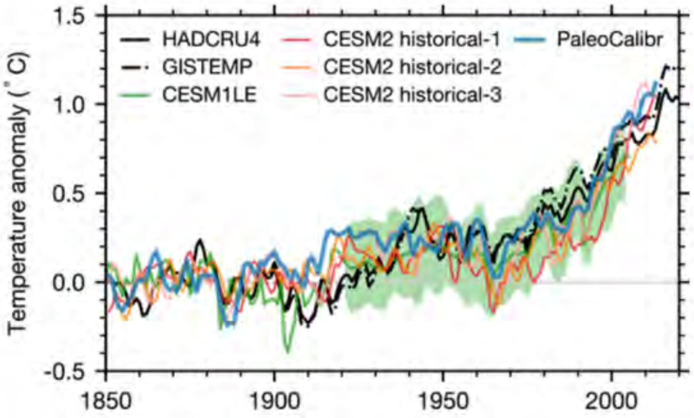

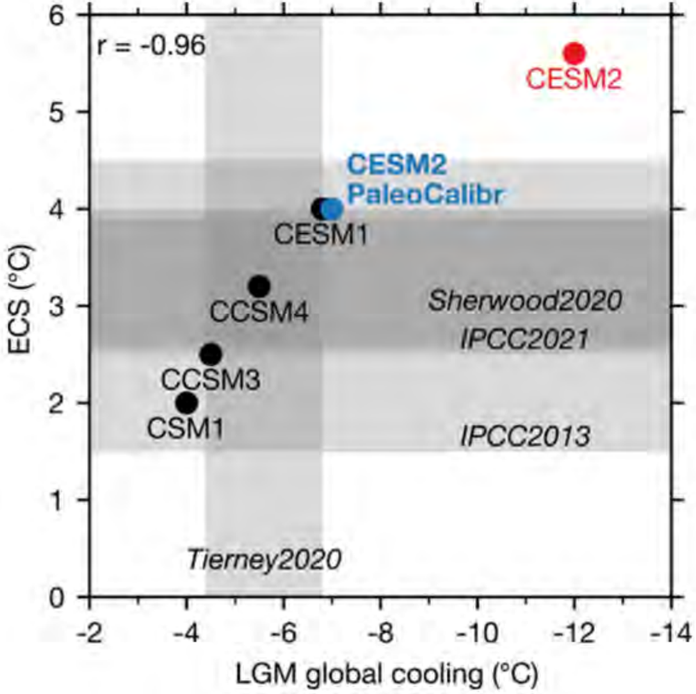

Zhu et al., 2021; Zhu et al., 2022