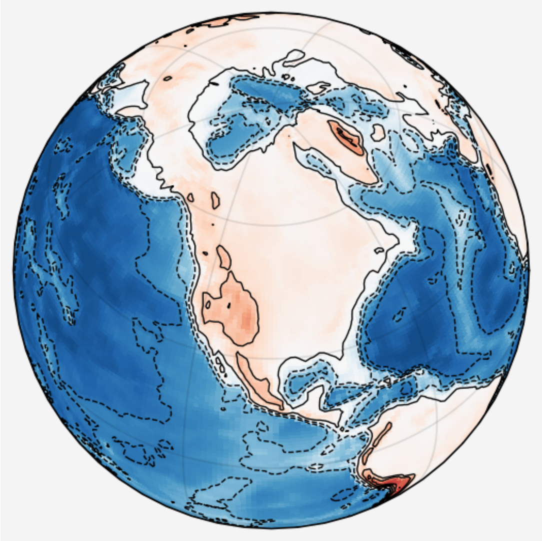
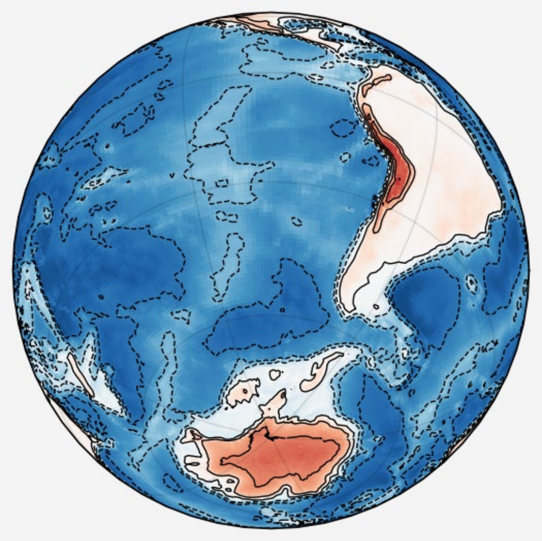
Mid-Pliocene climate forcing, sea-surface temperature pattern effects, and implications for modern-day climate sensitivity





PRISM4 proxy reconstruction of mid-Pliocene topography (Dowsett et al. 2012)

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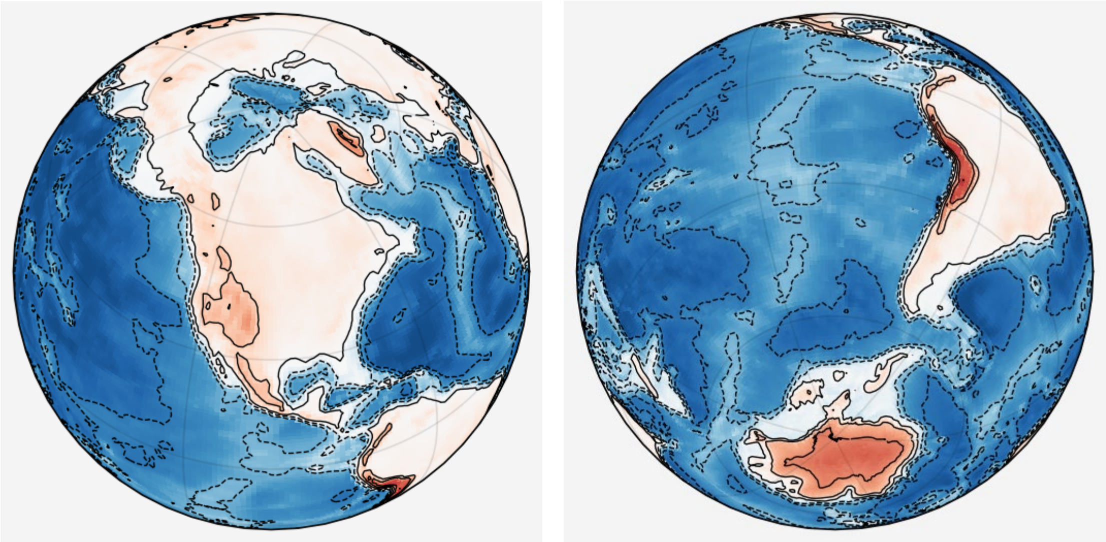
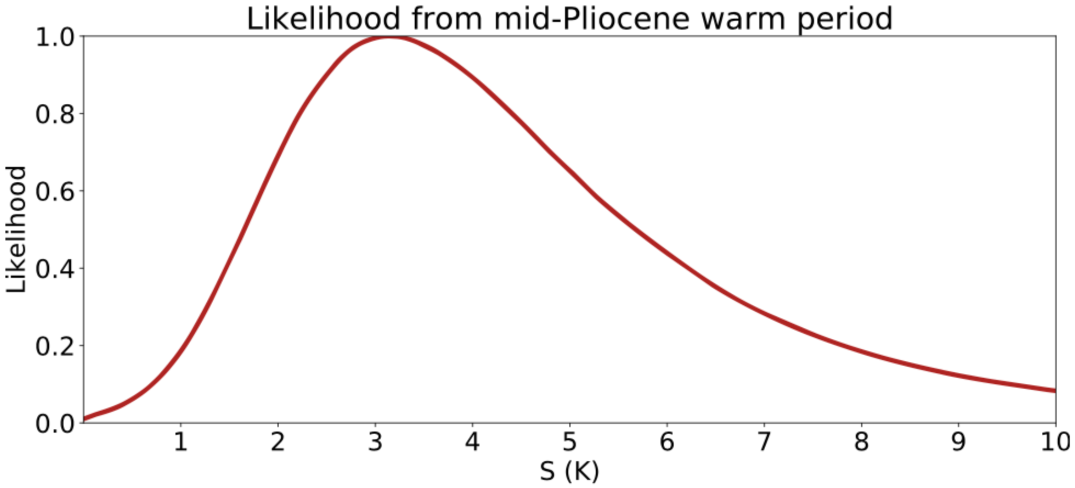
The mid-Pliocene (~3.3 Mya) has been widely used as an analog for future warming, and as a constraint on climate sensitivity



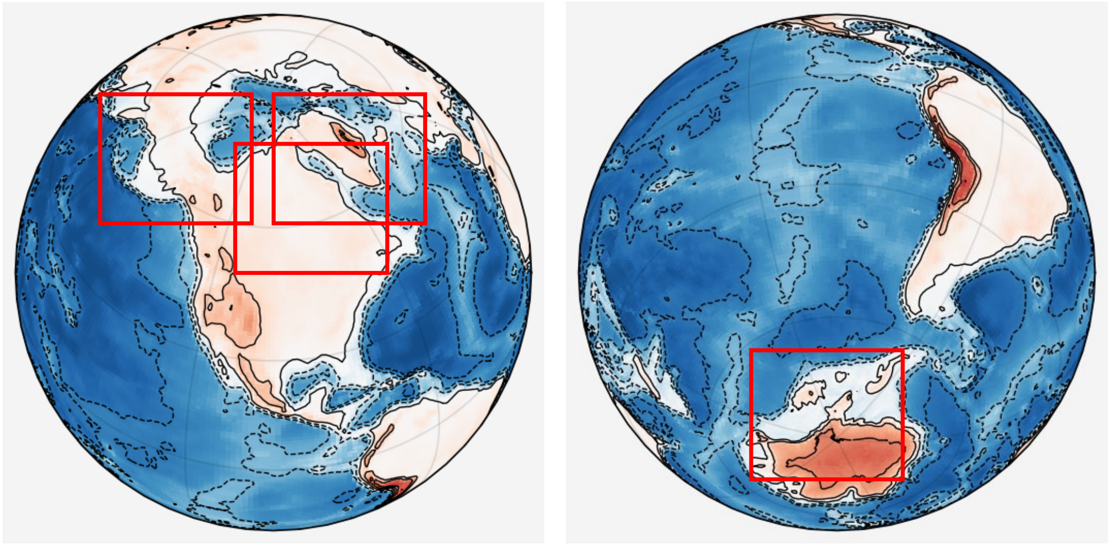
PRISM4 proxy reconstruction of mid-Pliocene topography (Dowsett et al. 2012)

The midPliocene was approximately 3°C warmer than the pre-industrial, at CO_2 concentrations ~400ppm

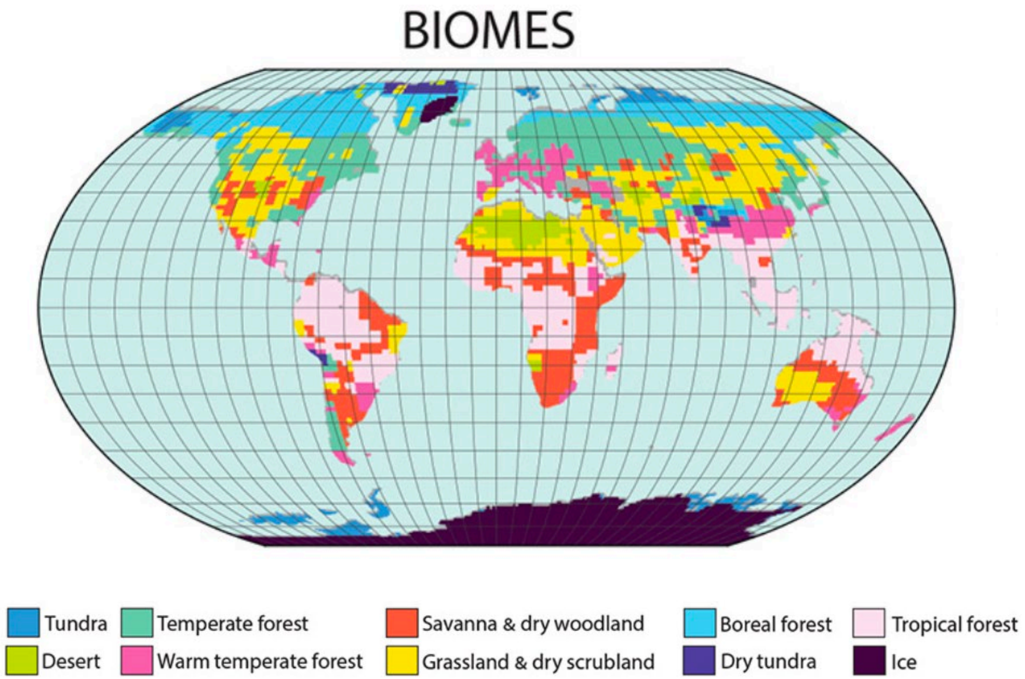


Climate sensitivity inferred from mid-Pliocene simulations and proxy reconstructions (Sherwood et al. 2020)

The mid-Pliocene (~3.3 Mya) has been widely used as an analog for future warming, and as a constraint on climate sensitivity

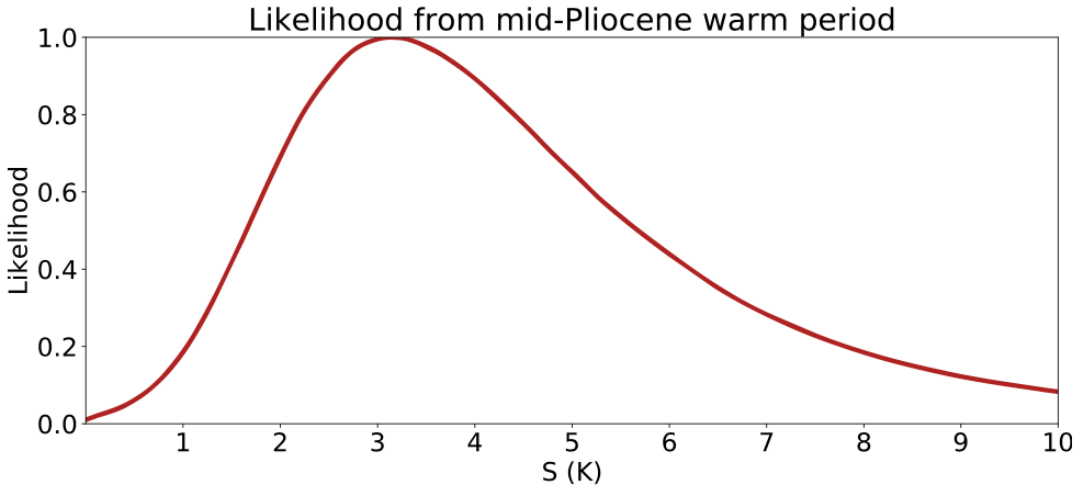


PRISM4 proxy reconstruction of mid-Pliocene topography (Dowsett et al. 2012)



PRISM4 proxy reconstruction of mid-Pliocene biomes (Dowsett et al. 2012)

The mid-Pliocene (~3.3 Mya) has been widely used as an analog for future warming, and as a constraint on climate sensitivity

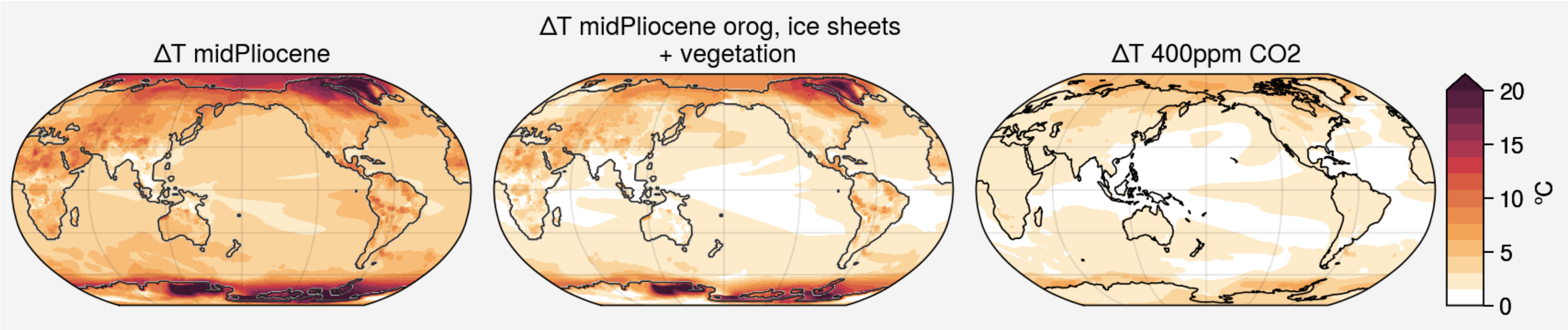


$$\Delta T = \frac{-\Delta F_{\mathrm{CO2}} \left(1 + f_{\mathrm{CH4}}\right) \left(1 + f_{ESS}\right)}{\lambda}$$

Earth System Sensitivity inflation factor - a representation of the forcing from large-scale ice sheet and vegetation changes, which occur on long timescales

(Sherwood et al. 2020)

These boundary conditions have been shown to have a large effect on global temperature in simulations



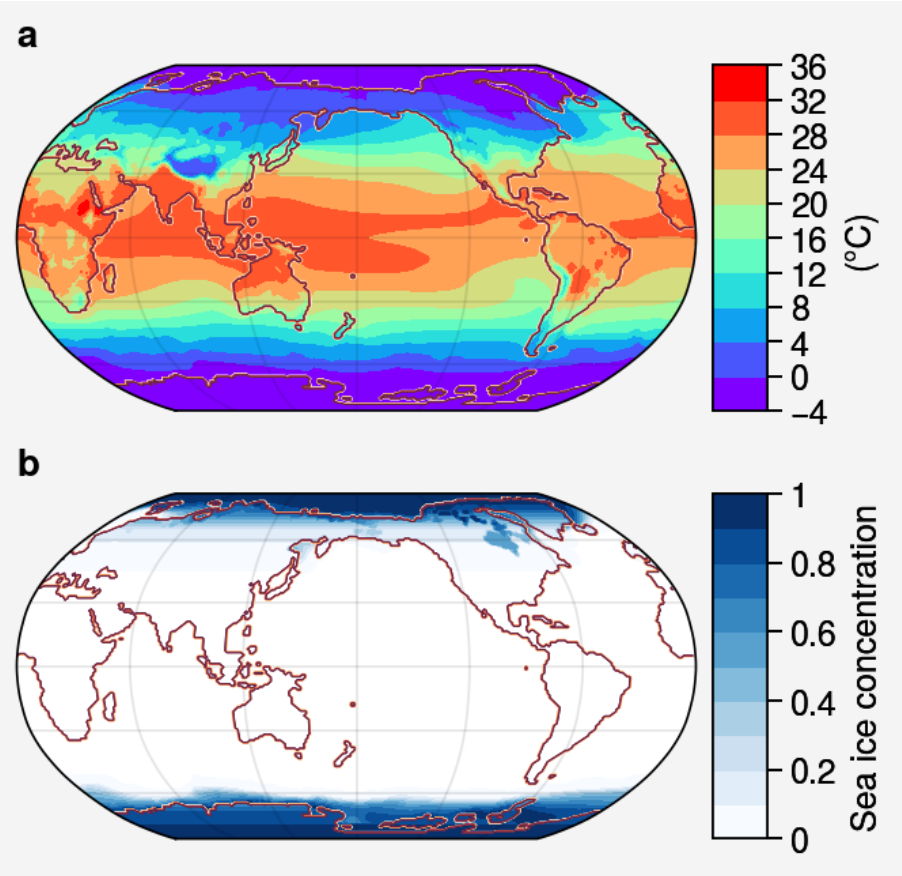
$\overline{\Delta T} = 5.1°C$ $\overline{\Delta T} = 2.9°C$ $\overline{\Delta T} = 2.0°C$

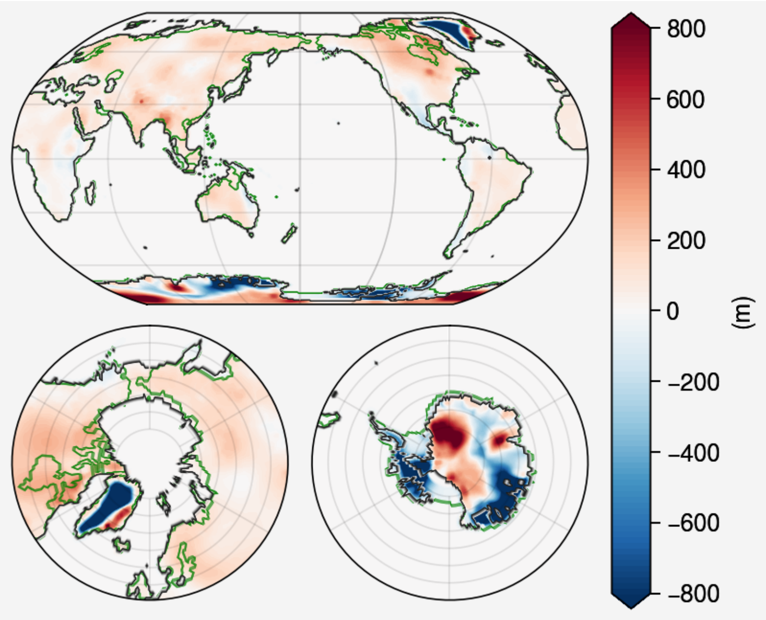
In CESM2, the boundary conditions alone contribute >1/2 of total global temperature change

→Is this warming a response to large forcings? or
→Are feedbacks enhancing the response to boundary condition forcing?

1. Atmosphere-only fixed SST simulations allow quantification of midPliocene ERF

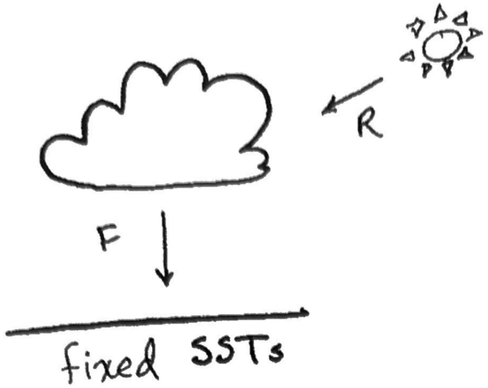
- 1° x 1° CAM6 simulations were run with midPliocene boundary conditions and CO_2 concentrations (400 ppm), boundary conditions only, and 400ppm CO_2 only
- Simulations were run for ~35 years
- SST/sea ice field is diagnosed from fully-coupled preindustrial control CESM2 simulations (a, b)
- In the region of the oceanized West Antarctic, sea ice concentrations are prescribed to 100% (b), and SSTs are set to -1.8°C

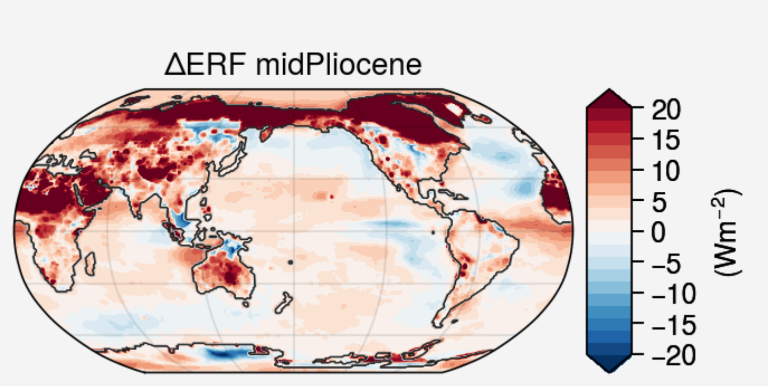




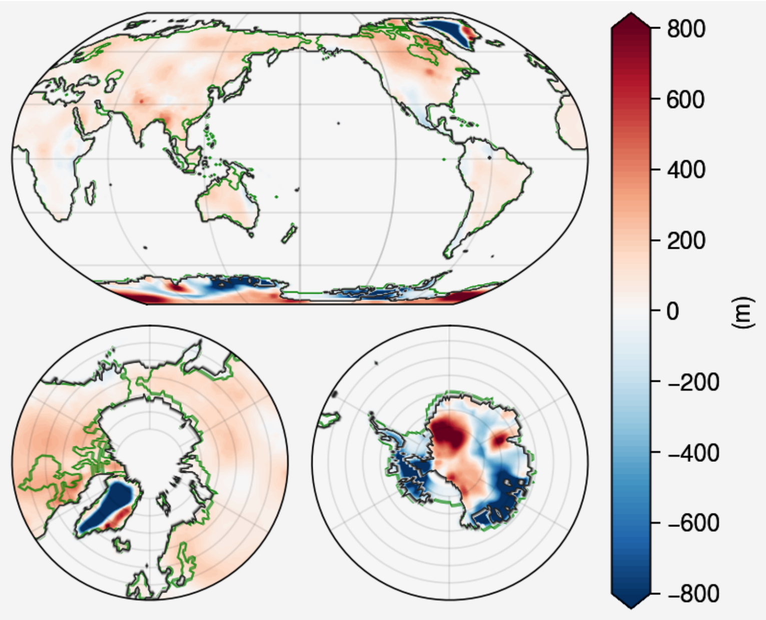
Fixed-SST simulations reveal only small forcing from boundary conditions

Topographic mask in CESM2 mid-Pliocene simulations (surface height anomaly from preindustrial)

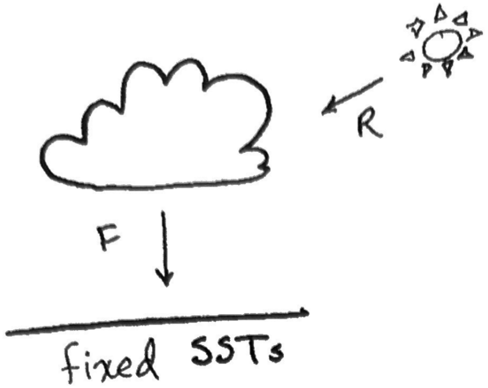


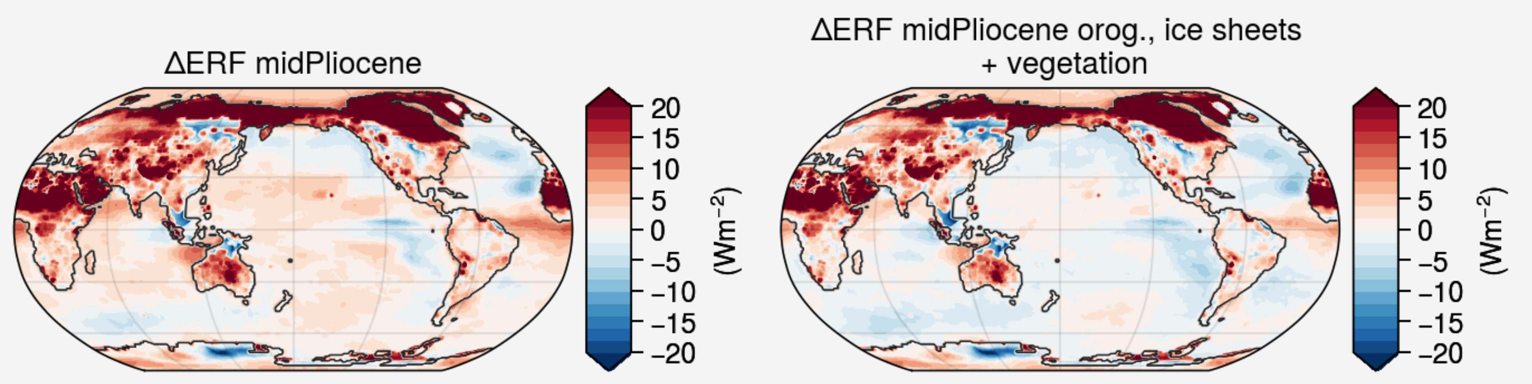


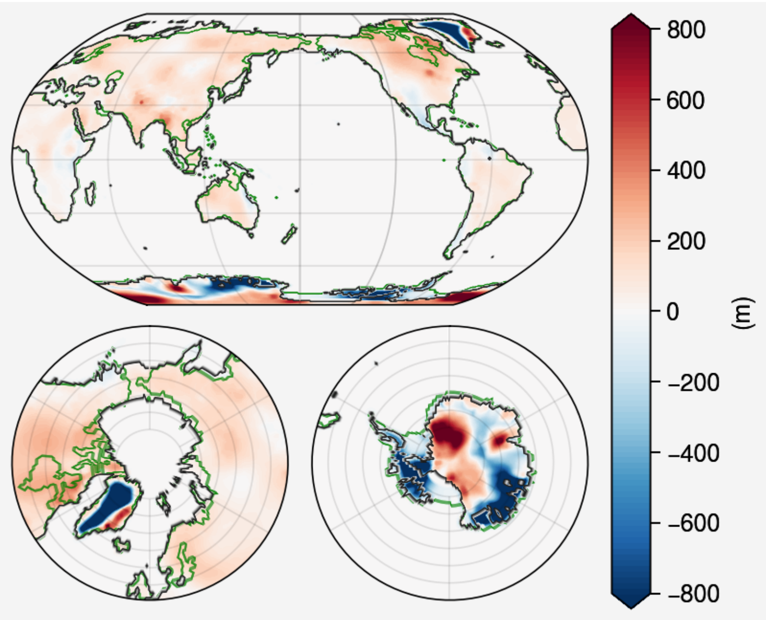
Fixed-SST simulations reveal only small forcing from boundary conditions



Topographic mask in CESM2 mid-Pliocene simulations as topographic height anomaly from preindustrial

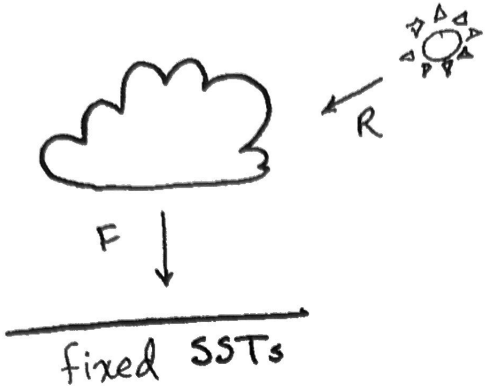


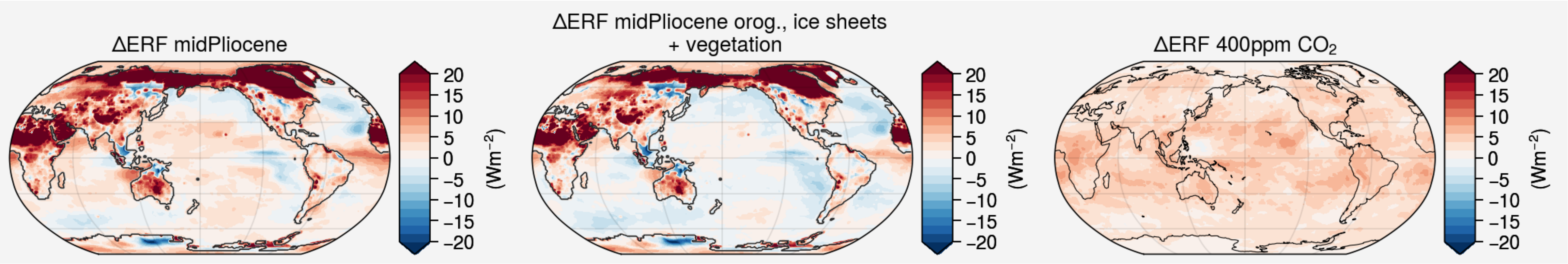




Fixed-SST simulations reveal only small forcing from boundary conditions

Topographic mask in CESM2 mid-Pliocene simulations as topographic height anomaly from preindustrial





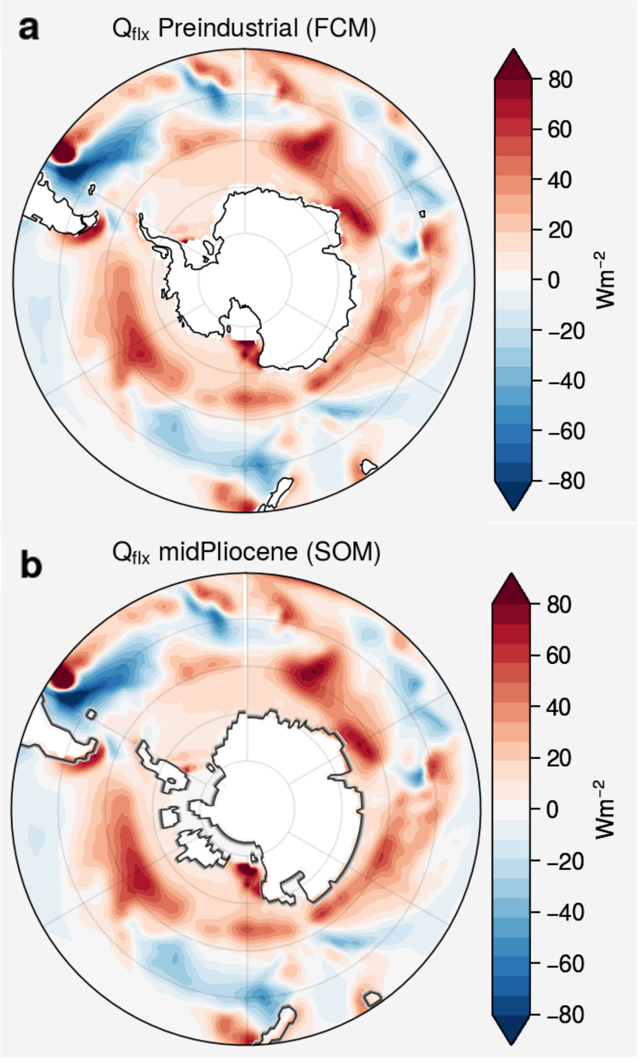
$\overline{\Delta ERF} = 3.8\ Wm^{-2}$

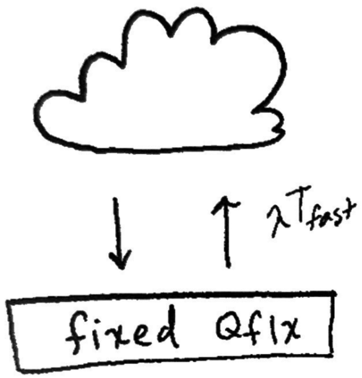
$\overline{\Delta ERF} = 1.7\ Wm^{-2}$

$\overline{\Delta ERF} = 2.2\ Wm^{-2}$

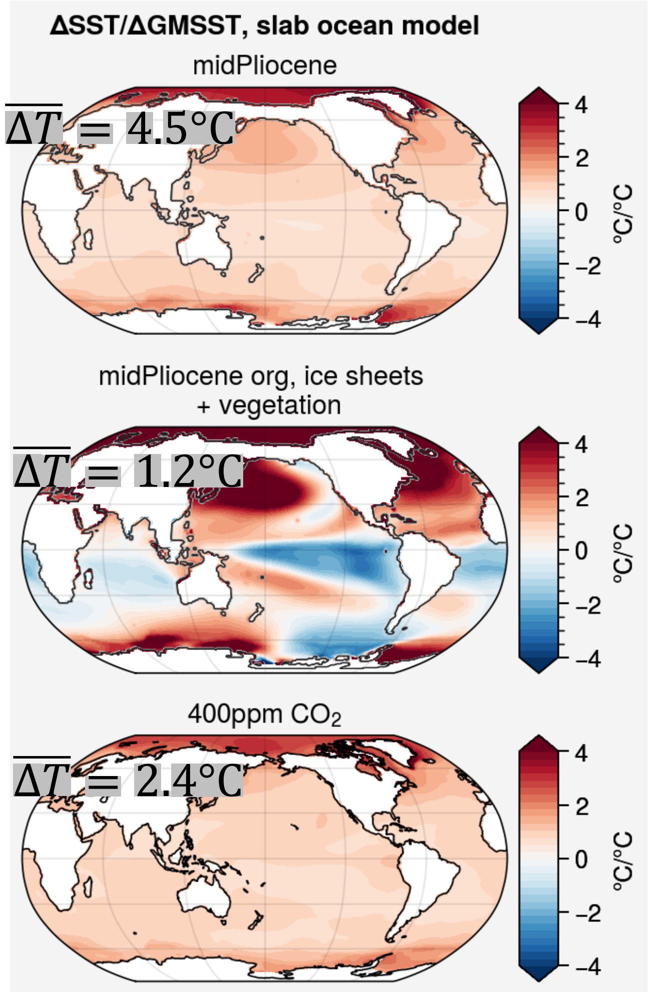
2. Slab ocean simulations enable examination of midPliocene SST patterns and fast feedbacks

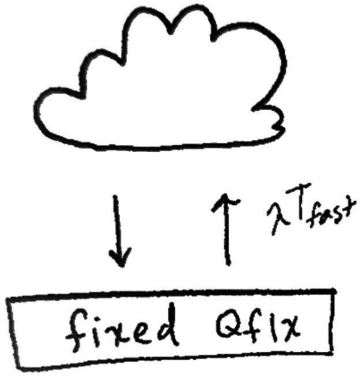
- 1° x 1° CESM2 simulations were run in slab ocean mode with fixed mixed layer depth and ocean heat flux convergence (Q_{flx})
- Simulations were run until equilibrium (75-125 years)
- Qflx field is diagnosed from fully-coupled preindustrial control CESM2 simulations (a)
- In the region of the oceanized West Antarctic, Q_{flx} is set to 0 (b)





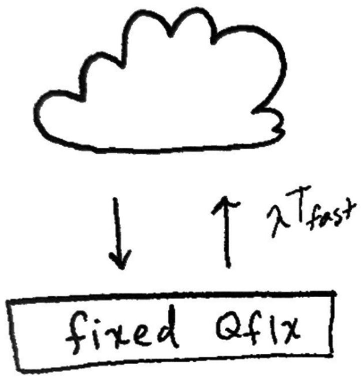
Slab ocean simulations show distinct SST response to boundary conditions

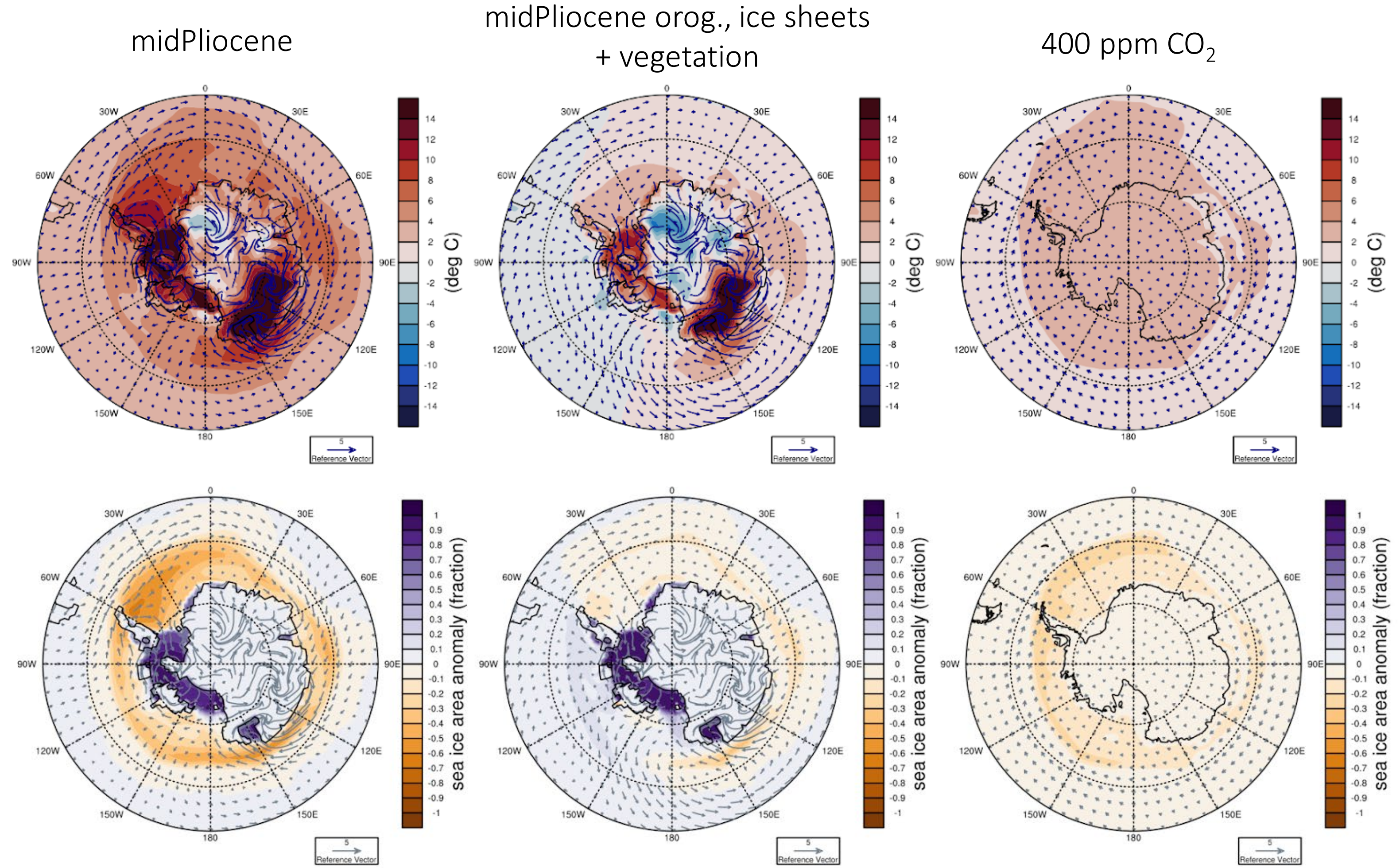




- Fully midPliocene and CO_2-forcing experiments show similar patterns of warming
- Boundary conditions alone induce a la-Nina like SST pattern, with significantly lower global temperature

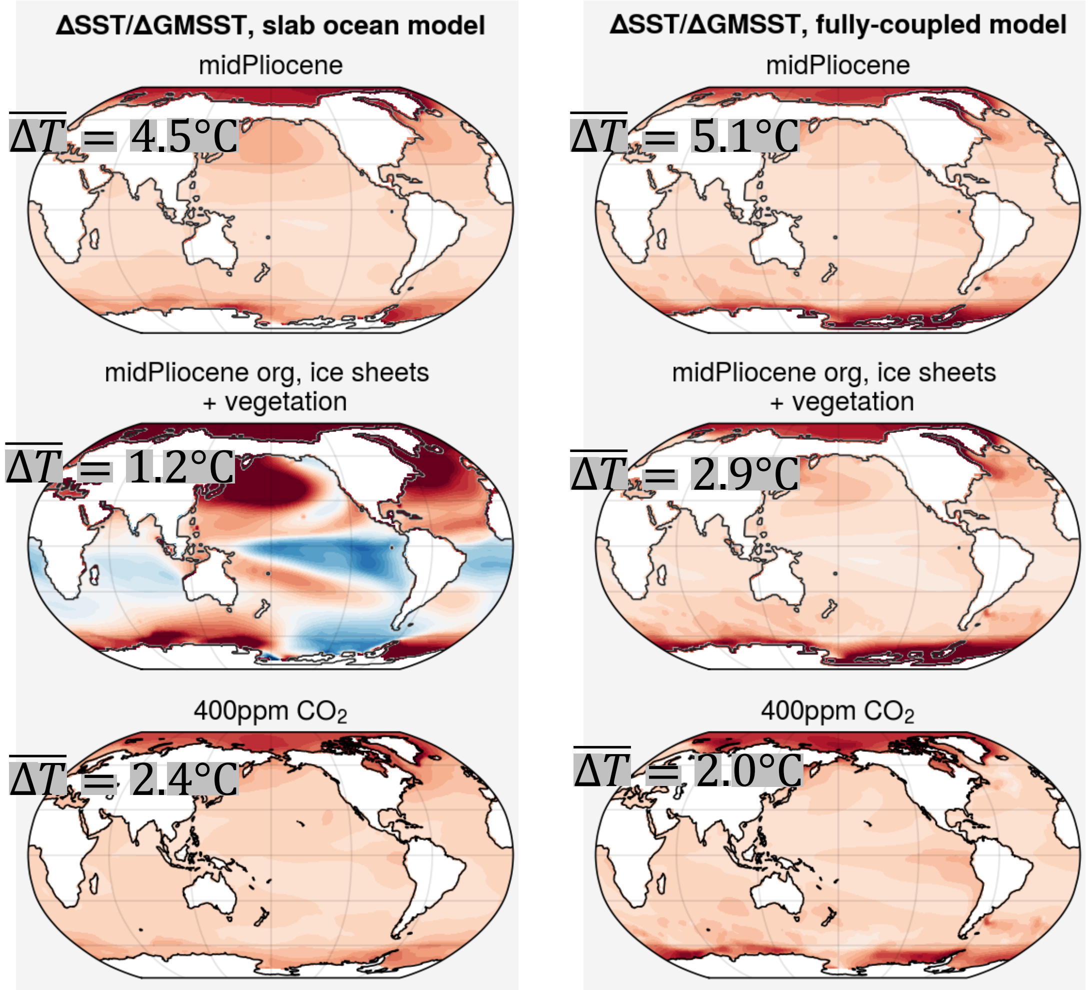
Slab ocean simulations show distinct SST response to boundary conditions



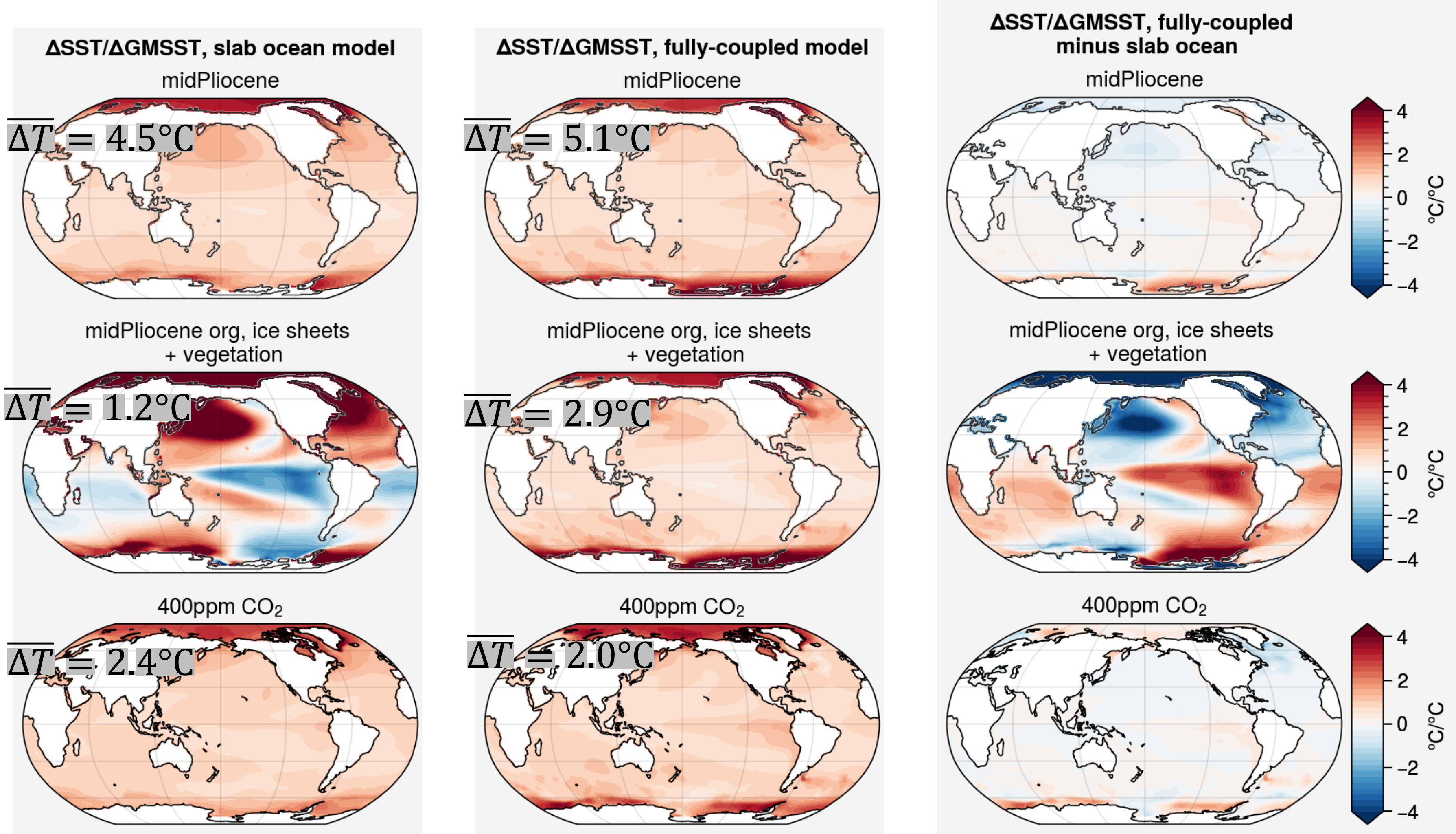


- Absence of West Antarctic ice sheet induces cyclonic wind anomaly
- Cold air advection from the pole results in broad cooling and sea ice growth at PI CO_2
- Other idealized, slab ocean simulations (Steig et al. 2012) also show cooling in response to flattening of West Antarctic topography

Slab ocean simulations show distinct SST response to boundary conditions



Slab ocean simulations show distinct SST response to boundary conditions

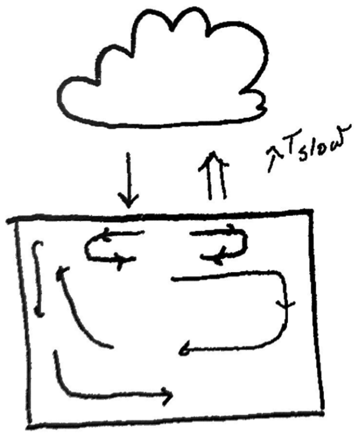


$\overline{\Delta T_{FCM}} - \overline{\Delta T_{SOM}} = 0.6°C$

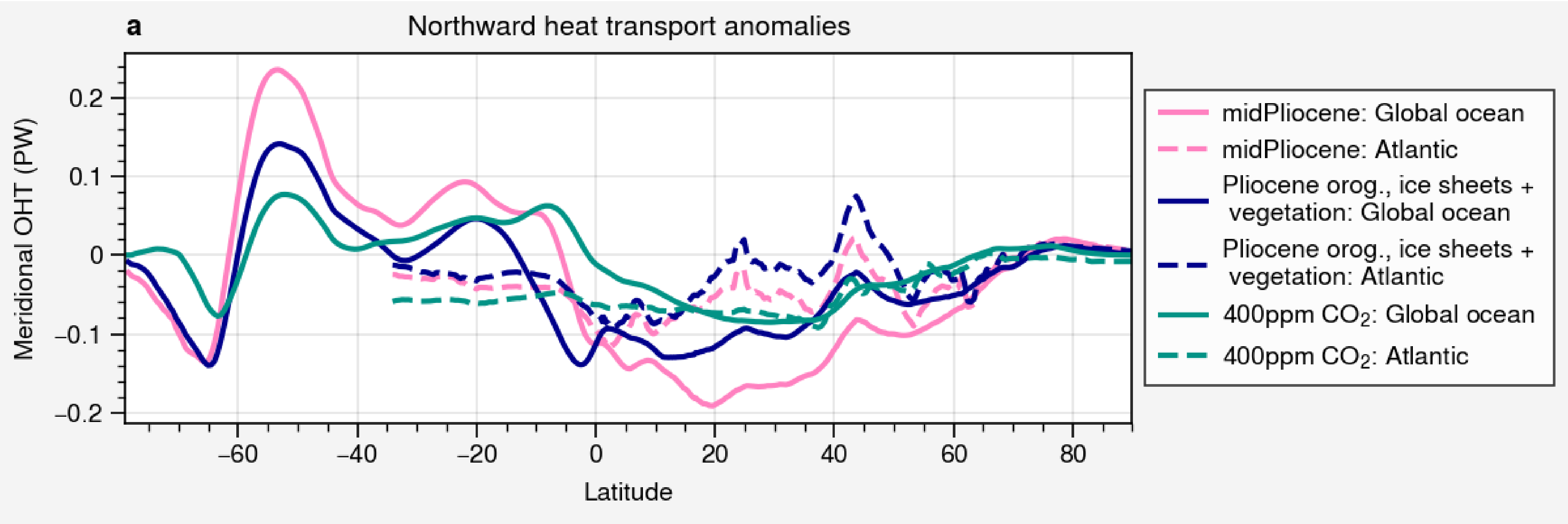
$\overline{\Delta T_{FCM}} - \overline{\Delta T_{SOM}} = 1.7°C$

$\overline{\Delta T_{FCM}} - \overline{\Delta T_{SOM}} = -0.4°C$

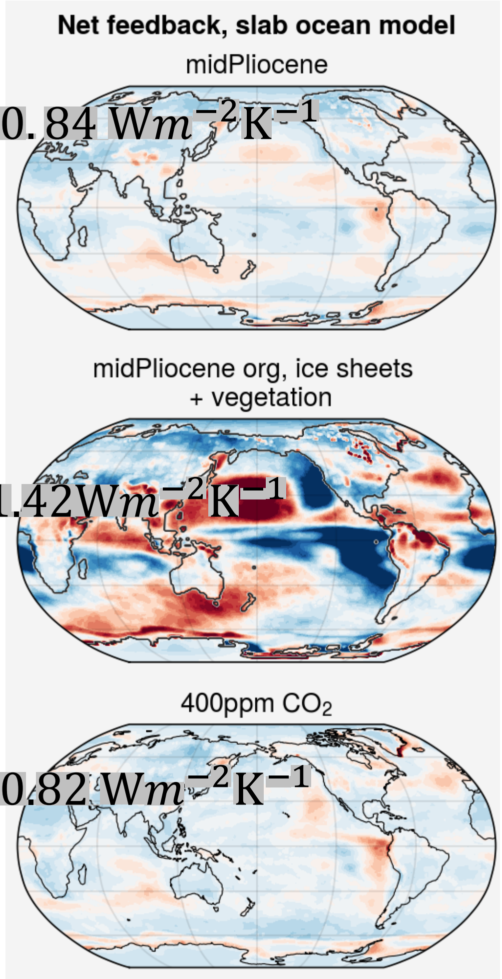
We can isolate the contribution of ocean dynamics to the midPliocene climate through a comparison with respective fully-coupled simulations



Fully coupled simulations show enhanced southward heat transport poleward of 60°S in response to non-CO_2 forcings



Non-CO_2 induced surface cooling leads to substantial difference in the pattern of the global feedback



$\bar{\lambda} = -0.84\ Wm^{-2}K^{-1}$

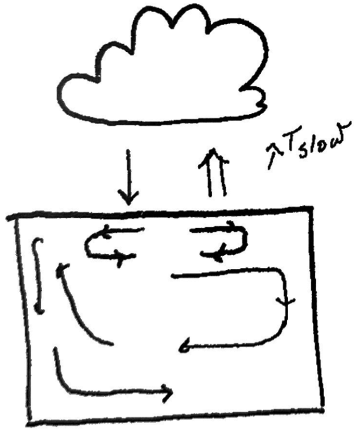
$\bar{\lambda} = -1.42 Wm^{-2}K^{-1}$

$\bar{\lambda} = -0.82\ Wm^{-2}K^{-1}$

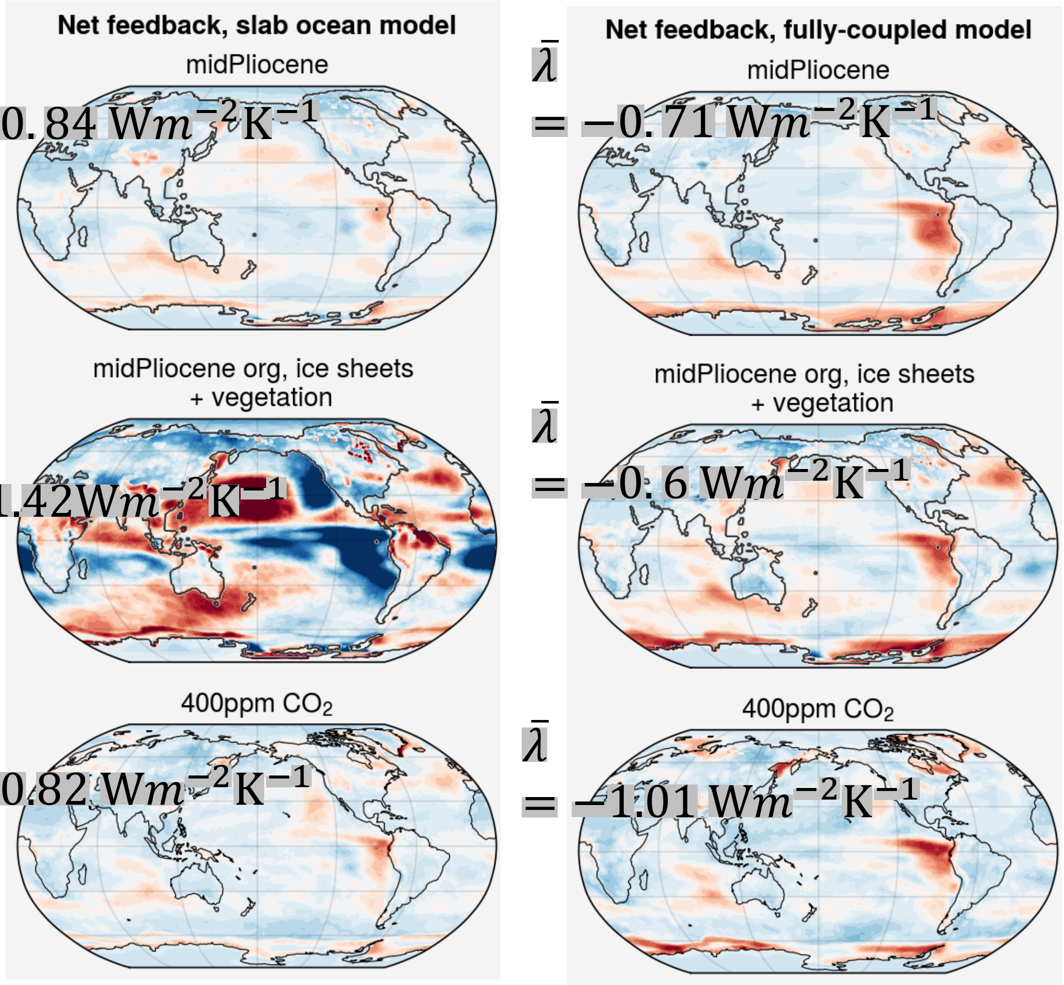
We calculate the global feedback using the standard framework of energy balance:

$$N = F - \lambda T$$

$$\lambda = \frac{N - F}{T}$$



Active ocean dynamics enhance warming and change the spatial pattern of the global feedback



Slab ocean model:

$\bar{\lambda} = -0.84\ Wm^{-2}K^{-1}$

$\bar{\lambda} = -1.42 Wm^{-2}K^{-1}$

$\bar{\lambda} = -0.82\ Wm^{-2}K^{-1}$

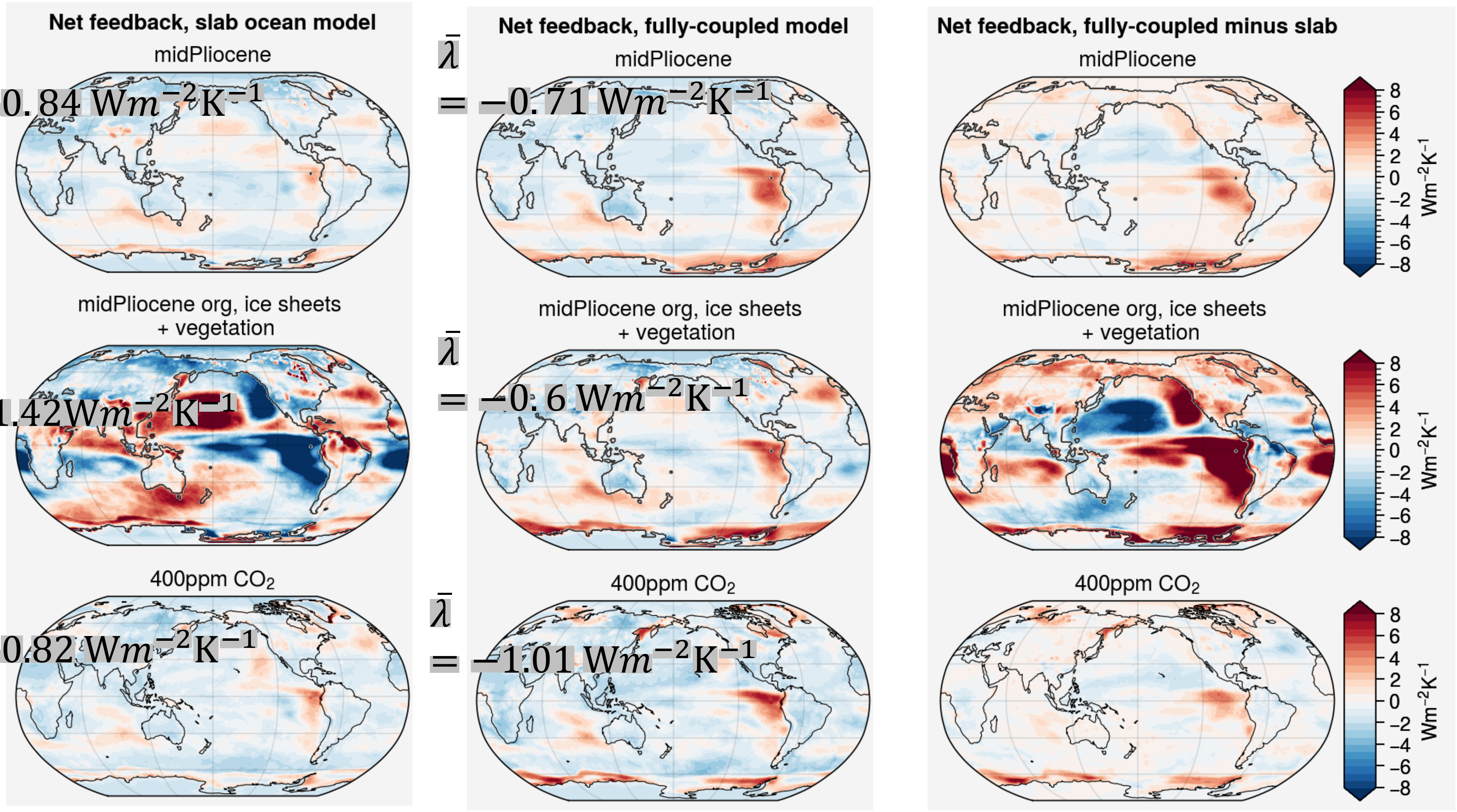
Fully-coupled model:

$\bar{\lambda} = -0.71\ Wm^{-2}K^{-1}$

$\bar{\lambda} = -0.6\ Wm^{-2}K^{-1}$

$\bar{\lambda} = -1.01\ Wm^{-2}K^{-1}$

Active ocean dynamics enhance warming and change the spatial pattern of the global feedback



Slab ocean model:

$\bar{\lambda} = -0.84\ Wm^{-2}K^{-1}$ (midPliocene)

$\bar{\lambda} = -1.42 Wm^{-2}K^{-1}$ (midPliocene org, ice sheets + vegetation)

$\bar{\lambda} = -0.82\ Wm^{-2}K^{-1}$ (400ppm CO_2)

Fully-coupled model:

$\bar{\lambda} = -0.71\ Wm^{-2}K^{-1}$ (midPliocene)

$\bar{\lambda} = -0.6\ Wm^{-2}K^{-1}$ (midPliocene org, ice sheets + vegetation)

$\bar{\lambda} = -1.01\ Wm^{-2}K^{-1}$ (400ppm CO_2)

Fully-coupled minus slab:

$\overline{\Delta\lambda} = 0.13\ Wm^{-2}K^{-1}$ (midPliocene)

$\overline{\Delta\lambda} = 0.82\ Wm^{-2}K^{-1}$ (midPliocene org, ice sheets + vegetation)

$\overline{\Delta\lambda} = -0.19\ Wm^{-2}K^{-1}$ (400ppm CO_2)

→ Accounting for differences between CO_2 and non-CO_2 feedbacks would reduce our estimate of modern-day climate sensitivity

$$\Delta\lambda = \lambda_{CO2} - \lambda_{Pliocene}$$

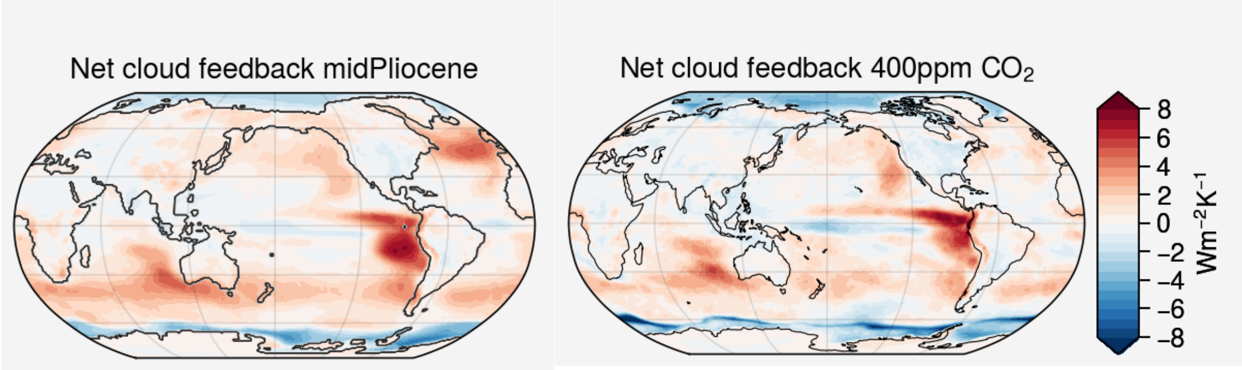
$$\Delta T = \frac{-\Delta F_{\mathrm{CO2}}\,(1 + f_{\mathrm{CH4}})\,(1 + f_{ESS})}{\lambda}$$

In the slab ocean model:

$$\Delta\lambda = -0.86 + 0.84$$
$$= \mathbf{-0.02\ Wm^{-2}K^{-1}}$$

In the fully-coupled model:

$$\Delta\lambda = -1.01 + 0.71$$
$$= \mathbf{-0.30\ Wm^{-2}K^{-1}}$$



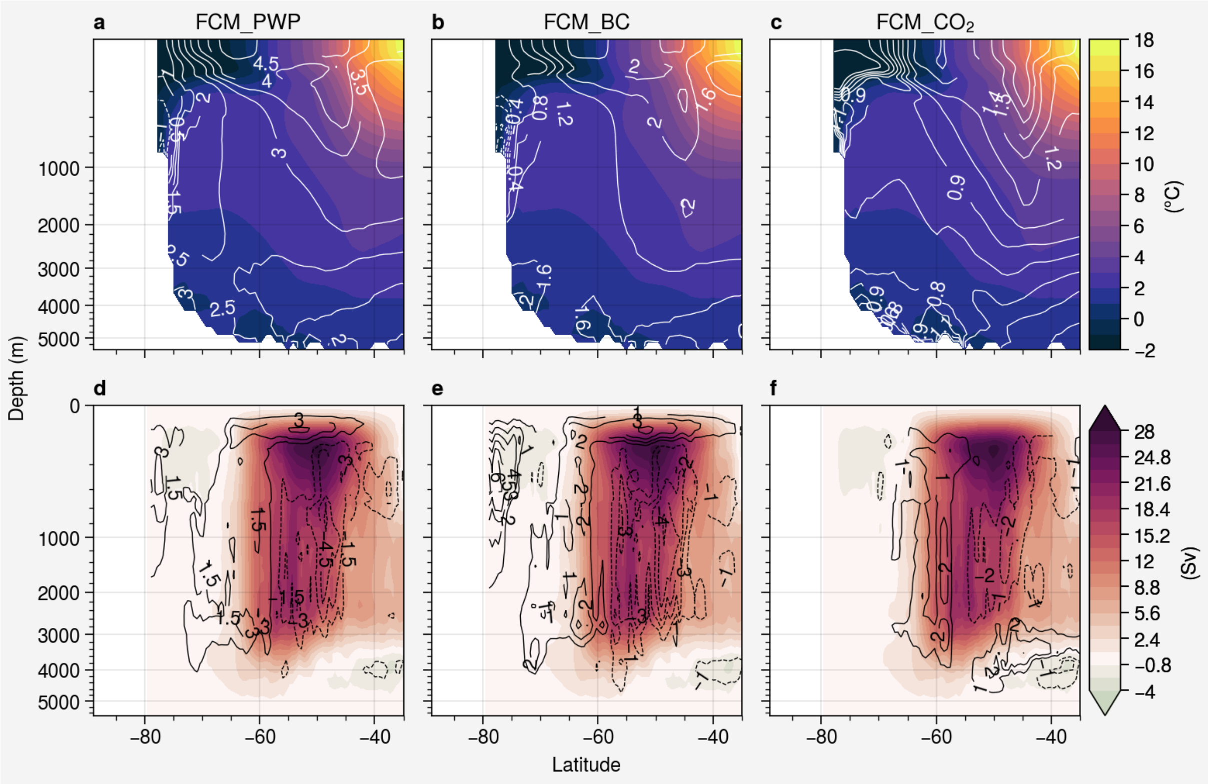
Next steps

To further clarify the role of ocean circulation in warming the Southern Ocean and tropical Pacific in response to non-CO2 (boundary condition) forcing…

An additional slab ocean simulation at PI CO_2 where Q_{flx} is prescribed to match the fully-coupled midPliocene simulation in the Southern Ocean south of 65°S

Supplementary

Fully coupled ocean shows enhanced surface warming; southward shift and shoaling of Southern Ocean overturning



Southern Ocean temperatures and meridional overturning circulation, with anomalies. (a-c) preindustrial ocean temperature profiles for the West Antarctic shelf (averaged over 180-360°E), with temperature anomalies as white contours. (d-f) Preindustrial meridional overturning circulation (MOC) for the global ocean south of 40S, with anomalies as black contours.

Supplementary