Boundary condition dependency of temperature responses to CO_2 forcing during the late Pliocene

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PlioMIP2 and single forcing experiments

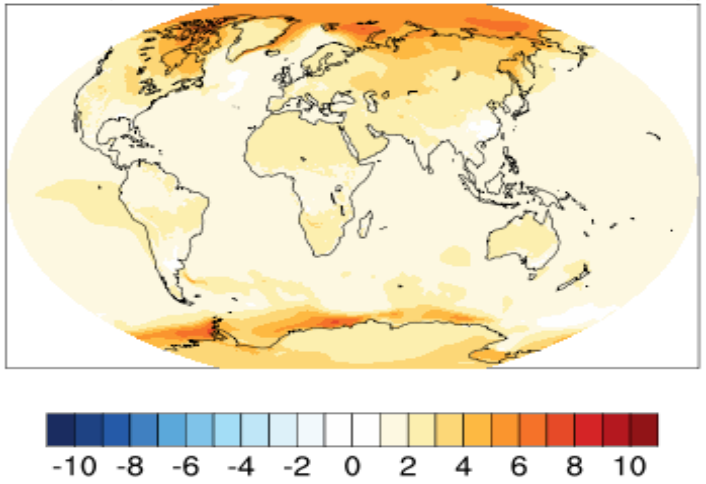
- PlioMIP2 baseline: Pliocene Model Intercomparison Project II
  - Targeting mid-Piacenzian (3.205 Ma)
    - 400 ppm CO_2, mid-Pliocene boundary conditions (Dowsett et al., 2016)
  - NCAR participation with CCSM4, CESM1.2 and CESM2 (Feng et al., 2019, JAMES)
- PlioMIP2 single forcing experiments with CESM2 (Feng et al., 2022, Nat. Comm.)
  - Pliocene vegetation & ice sheet changes
  - Pliocene topography and bathymetry
  - CO_2 only

Boundary condition dependency of temperature responses

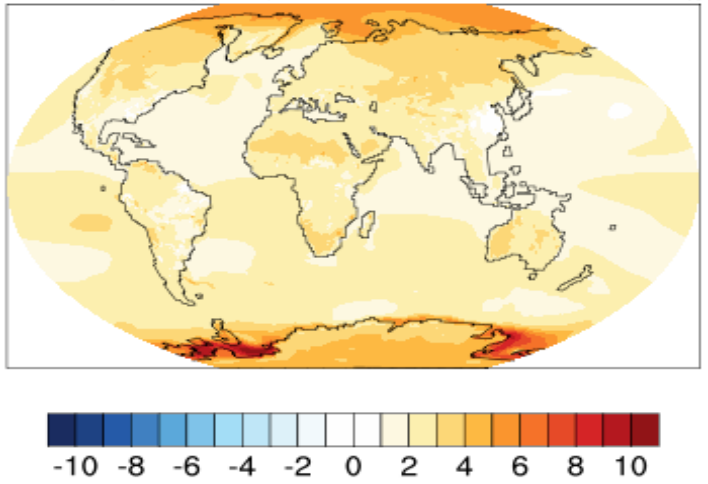
New results from the single forcing experiments

- Warming from 284.7 ppm CO_2 to 400 ppm is 18% greater with Pliocene boundary conditions compared to PI boundary conditions
- Translating to **~0.8K** difference in Equilibrium Climate Sensitivity
- *Notice the similarity in the warming pattern.*

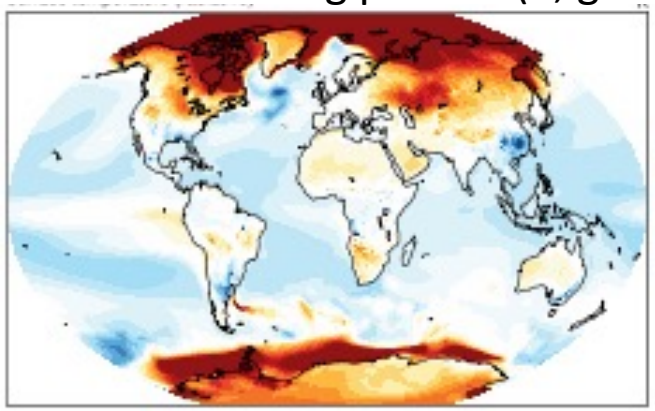
TS (400 ppm – 280 ppm, K, PI)

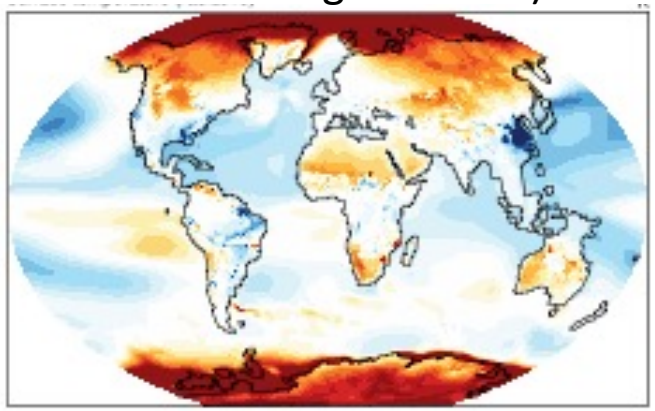


TS (400 ppm – 280 ppm, K, Pliocene)



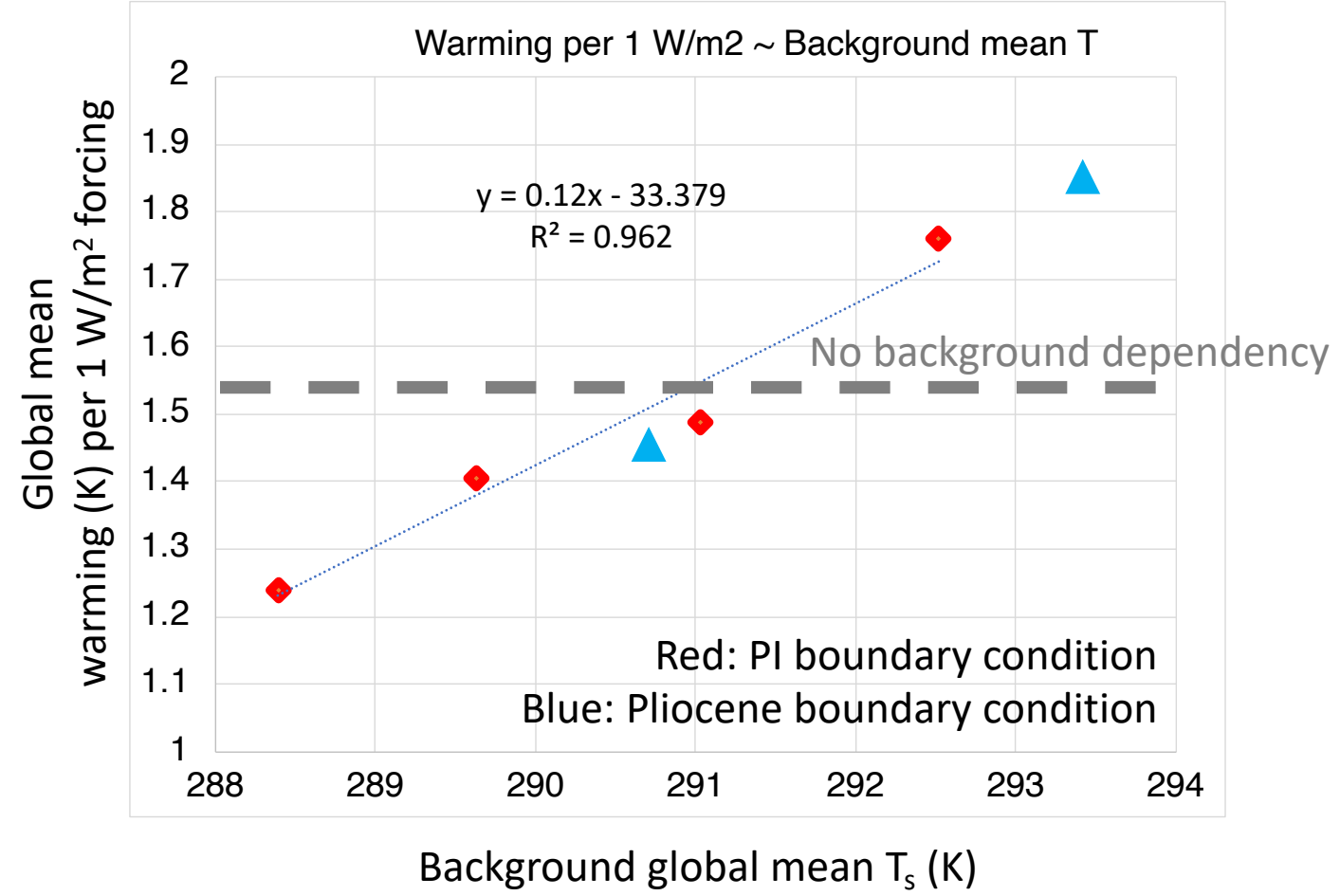
SST warming pattern (K, global mean warming removed)





Dependency on boundary condition can be explained by dependency on background warmth

- Mixed layer ocean experiments at 1° resolution with CESM2
  - With Preindustrial boundary conditions and ocean heat flux
    - 5 different levels of CO_2 from 284.7 ppm to 590.6 ppm to reflect ~1 W/m^2 incremental increase of CO_2 from 0 to 4 W/m^2
  - With Pliocene boundary conditions and ocean heat flux
    - 284.7 ppm, 400 ppm, 569.4 ppm
    - Scaled to reflect incremental increase of CO_2 forcing equivalent to 1W/m^2



What causes this dependency of temperature response on background warmth?

Review of the energy balance model and ECS

- Energy balance model of TOA radiative responses (ΔR_{TOA}) to forcing F at a TOA radiative imbalance N:

$$N = F - \Delta R_{TOA}$$

- Taylor expansion of radiative responses as a function of surface warming (e.g., Roe et al., 2009, Ann. Rev. Ear. Pla.):

$$\Delta R_{TOA} = \Delta R_{TOA}{}' \Delta T_s + \frac{\Delta R_{TOA}{}''}{2} \Delta T_s{}^2 + \cdots$$

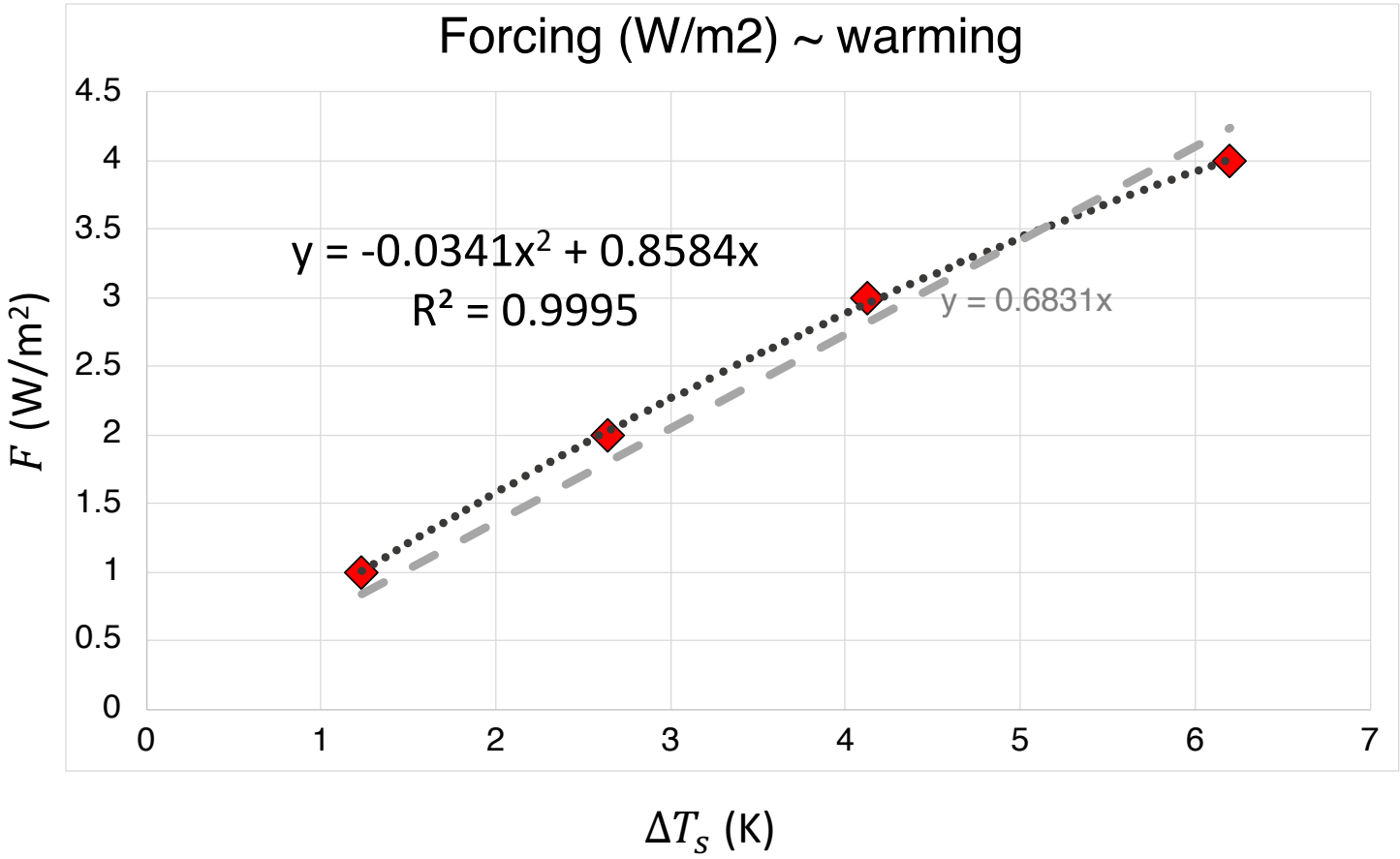
- Keep the first-order term of Taylor series:

  $\Delta R_{TOA} \approx \Delta R_{TOA}{}' \Delta T_s$, and $N = F - \Delta R_{TOA}{}' \Delta T_s$ (Gregory et al., 2004, GRL)

- At equilibrium after a doubling of CO_2, $F = \Delta R_{TOA}{}' \Delta T_s$, ΔT_s is the ECS.

Is the first order approximation good enough for CESM2?

- Probably not…
- Deviations can be large for warm climates
  - With forcing at 5 W/m^2, 7.35K warming with the linear model
  - 9.15K warming with the non-linear model



Potential source for the dependency on background warmth

- Based on CESM2 results, keep the second order term of the Taylor series:

$$F = \Delta R_{TOA} \approx \Delta R_{TOA}{}' \Delta T_s + \frac{\Delta R_{TOA}{}''}{2} \Delta T_s{}^2$$

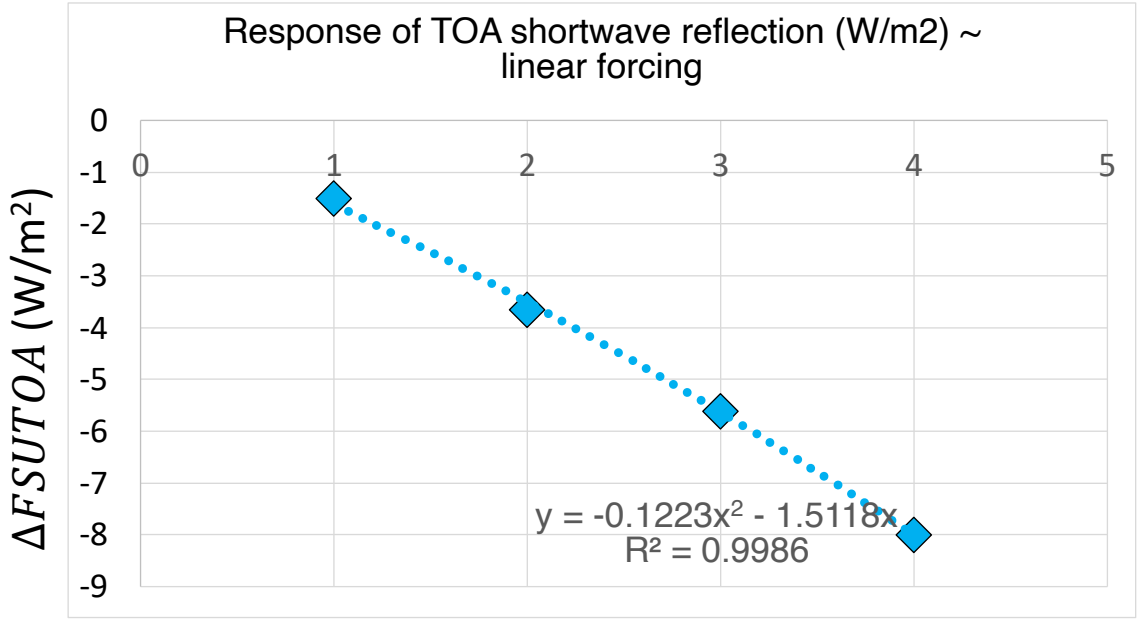
- Following the definition of net response parameter:

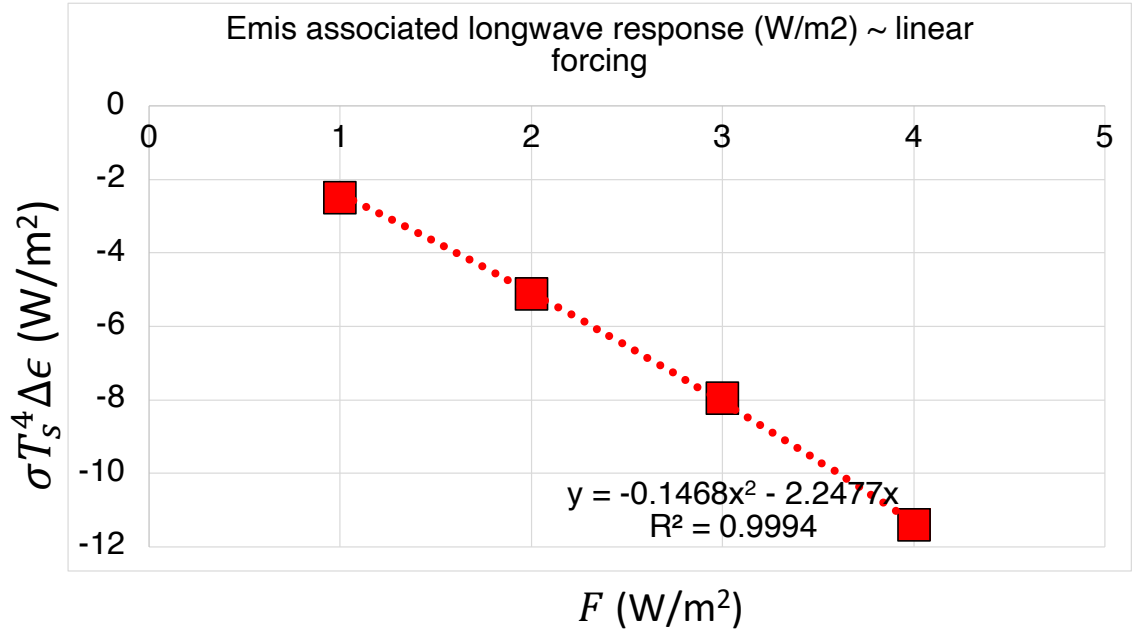
$$\frac{\Delta R_{TOA}}{\Delta T_s} = \lambda(\Delta T_s) \approx \Delta R_{TOA}{}' + \frac{\Delta R_{TOA}{}''}{2} \Delta T_s$$

- For CESM2, $\frac{\Delta R_{TOA}{}''}{2} < 0$, ***$\lambda$ decreases with warming.*** *Given that* $F = \lambda(\Delta T_s)\Delta T_s$, ***increasing background warmth increases climate sensitivity.***

The rise of λ *non-linearity*

- For every W/m^2 linear increase of *F, calculate*
  - $\Delta FSUTOA$: *TOA reflected shortwave*
  - $\Delta\epsilon$*: changes in planetary emissivity*
- $\Delta FSUTOA \sim F(\Delta R_{TOA})$
  - **decrease with increasing forcing → enhanced positive shortwave feedback**
- $\sigma T_s^4 \Delta\epsilon \sim F(\Delta R_{TOA})$
  - $\sigma T_s^4 \Delta\epsilon$ **decrease with increasing forcing → enhanced positive longwave feedback**





Implications to paleoclimate

- Estimating ECS from past climate is perhaps less useful than estimating the net response parameter
  - ECS varies **continuously (not just at high CO_2)** with background climate warmth due to non-linearity in net response parameter
- Perhaps provides an explanation for warm climates with moderately elevated CO_2?
  - Mid-Miocene? (Kürschner et al., 2008 PNAS; Rea et al., 2020 Ann. Rev. Ear. Pla.)

Thanks for your attention!