Boundary condition dependency of temperature responses to CO₂ 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 CO₂, 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
 - CO₂ only

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Special Collection

Increased Climate Response and Earth System Sensitivity From CCSM4 to CESM2 in Mid-Pliocene Simulations

Special Section: Ran Feng¹, Bette L. Otto-Bliesner², Esther C. Brady², and Nan Rosenbloom² Community Earth System Model version 2 (CESM2)

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Past terrestrial hydroclimate sensitivity controlled by Earth system feedbacks

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Boundary condition dependency of temperature responses

New results from the single forcing experiments TS (400 ppm – 280 ppm, K, PI) TS

- Warming from 284.7 ppm CO₂ 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)







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 CO₂ from 284.7 ppm to 590.6 ppm to reflect ~1 W/m² incremental increase of CO₂ from 0 to 4 W/m²
 - 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 $1W/m^2$



Background global mean T_s (K)

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/m², 7.35K warming with the linear model
 - 9.15K warming with the non-linear model



 ΔT_s (K)

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, $\frac{\Delta R_{TOA}''}{2} < 0$, λ 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/m² linear increase of *F*, *calculate*
 - Δ*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 \rightarrow enhanced positive longwave feedback





F (W/m²)

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 CO₂) with background climate warmth due to non-linearity in net response parameter
- Perhaps provides an explanation for warm climates with moderately elevated CO₂?
 - Mid-Miocene? (Kürschner et al., 2008 PNAS; Rea et al., 2020 Ann. Rev. Ear. Pla.)

Thanks for your attention!