Polar Amplification Over A Wide Range Of Warming In The Community Earth System Models (CESMs)

Jiang Zhu (jiangzhu@ucar.edu), Bette L. Otto-Bliesner | NSF NCAR

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1. Motivation

- Paleoclimate data suggests equable past warm climates with high global mean surface temperatures (GMSTs) & low equator-to-pole gradient (Figure 1 gray boxes for the early Eocene, the warmest climate in the past 60 million years).
- CESM family models simulate divergent Eocene GMSTs at the same atmospheric CO2 but the equator-to-pole gradient converges at the same GMST.
- Potential implications on the polar amplification (PA)
  - PA exists for ice-free climates without involving ice-related mechanisms;
  - PA is weaker for warm, ice-free climates, implying the importance of ice-related mechanisms;
  - Converging equator-to-pole gradient in the GMST space suggests that large-scale processes determine PA (not the details of atmospheric parameterizations).
- ***Objective: to examine these issues in simpler simulations over wider GMSTs***

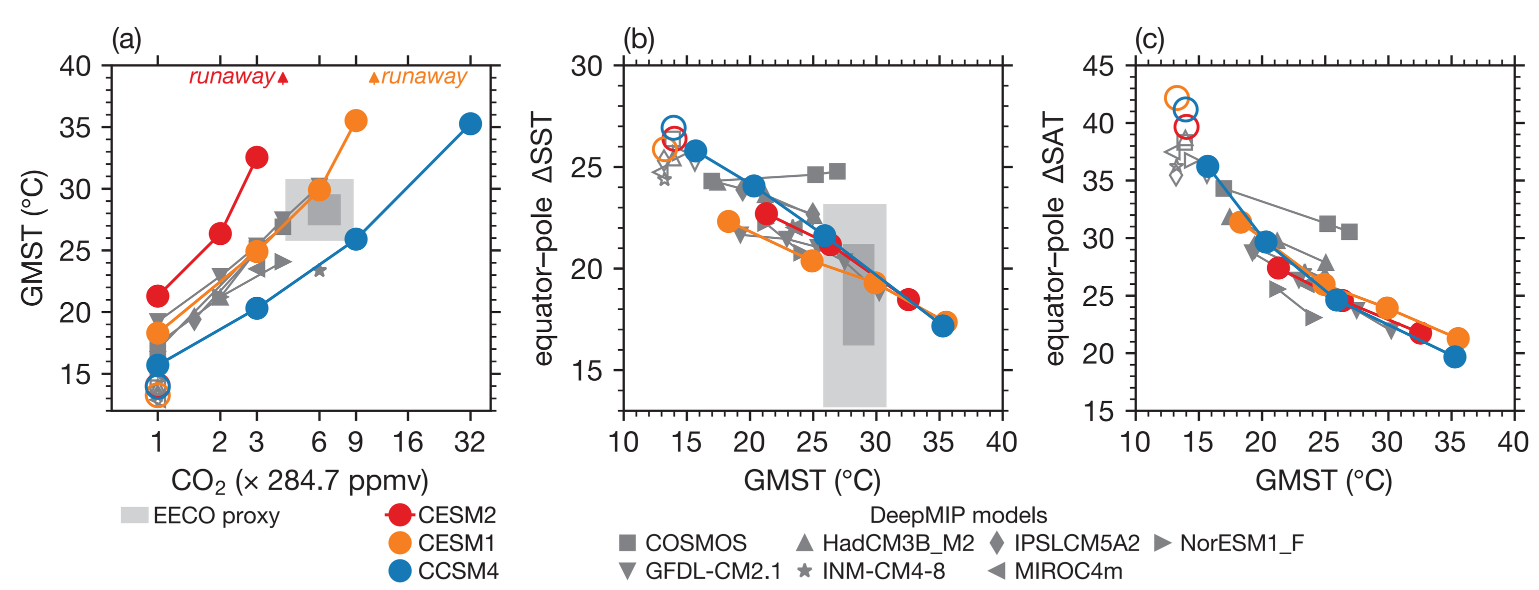

Figure 1. (a) The early Eocene GMST as a function of atmospheric CO2 based on proxy estimates (gray boxes) and model simulations (filled markers) using CESM2 (red), CESM1 (orange), and CCSM4 (blue). For reference, the PI simulations are shown as open markers. (b) The same as panel a but for the equator-to-pole SST difference, defined as the tropical (30°S–30°N) SST minus that of the high latitudes (60°S/N poleward). (c) The same as panel b but for the equator-to-pole difference in surface air temperature. From *Zhu et al., in press, Annu Rev Earth Planet Sci*

2. Methods: CESM Simulations

- Community Earth System Model version 2 (CESM2)
- Standard simulations with slab ocean model (SOM)
  - 2° atmosphere with either CAM6, CAM5, or CAM4
  - Preindustrial ocean mixed layer depth & heat flux convergence, & non-CO2 boundary conditions
  - Various levels of atmospheric CO2
- Additional SOM simulations with altered physics
  - PaleoCalibr with two microphysical fixes (1. removing an unphysical limiter on cloud ice number; 2. using shorter microphysical timestep; See Zhu et al., 2022, JAMES, doi:10.1029/2021MS002776)
  - An improved radiation scheme, RTE+RRTMGP, with a wider lookup table and thus more accurate for very warm climates
  - New combinations of atmospheric schemes to avoid the model runaway under high CO2 & warm temperatures (e.g., using the UW moist turbulence scheme in CAM6 & using MG2 in CAM5)

3. Results I: Global Warming and Polar Amplification

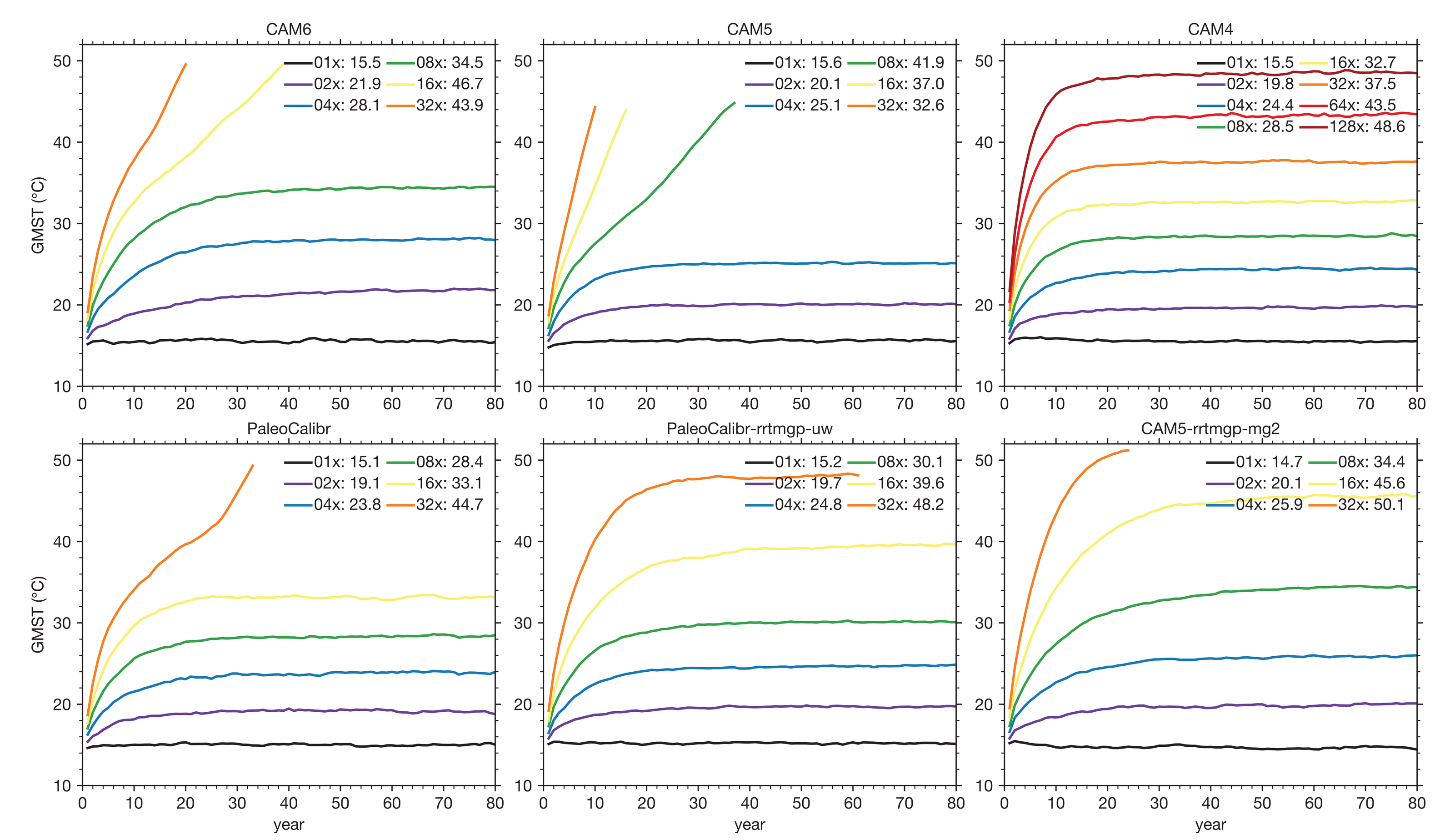

Figure 2. Time series of GMST across a wide range of atmospheric CO2 in the preindustrial-based slab ocean simulations with various combinations of atmospheric physics in the framework of CESM2.

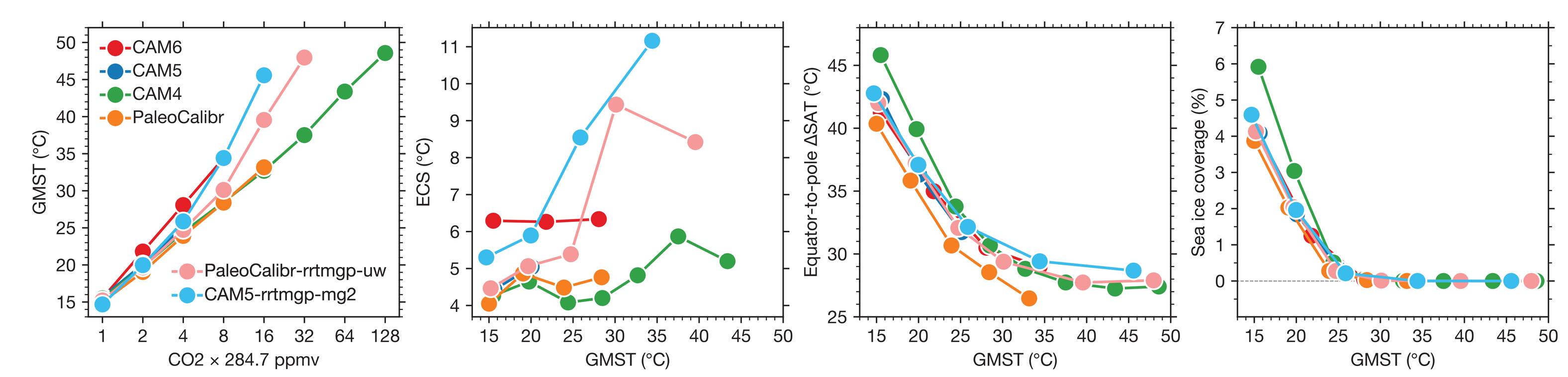

Figure 3. GMST as a function of atmospheric CO2, and equilibrium climate sensitivity (ECS), the equator-to-pole difference in surface air temperature (SAT), and sea ice coverage as a function of GMST in the preindustrial-based slab ocean simulations.

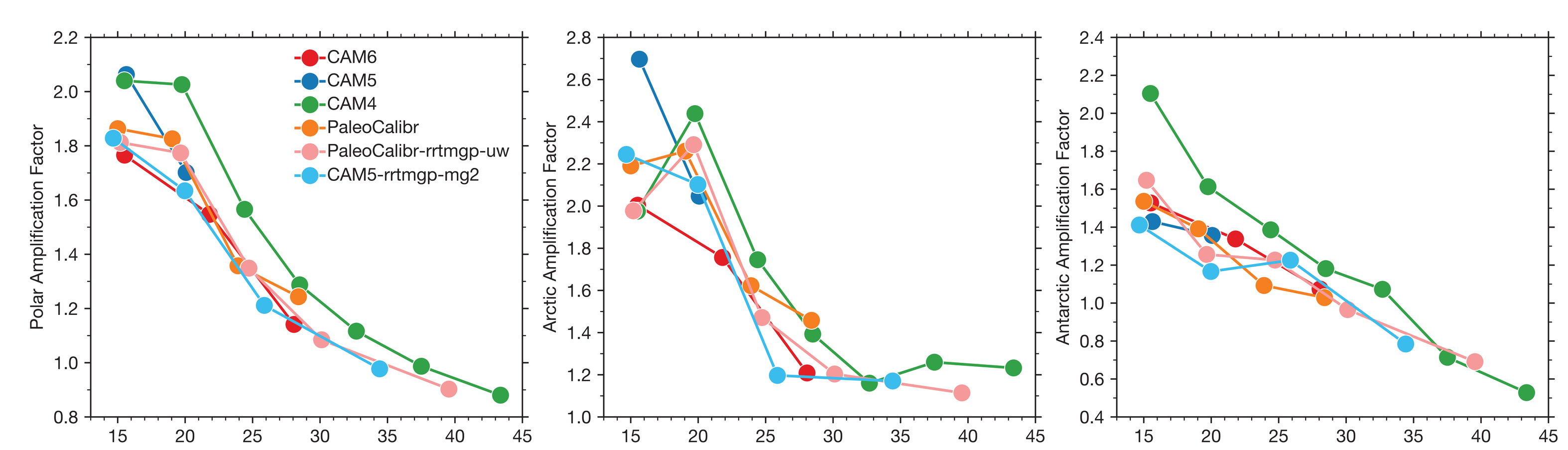

Figure 4. Polar (60°S/N poleward), Arctic (60–90°N), and Antarctic (90–60°S) amplification factors (regional warming divided by ΔGMST) as a function of GMST in the simulations.

- Simple SOM simulations cover a wide range of GMST & atmospheric physics.
- Sea ice disappears when GMST exceeds ~25°C.
- Equator-to-pole temperature gradient decreases with global warming and saturates for extreme warm climates (GMST > ~35°C).
- Arctic amplification factor decreases rapidly with global warming and reaches a saturation of ~1.1–1.2.
- Antarctic amplification factor decreases with global warming gradually and linearly without an apparent saturation.

4. Results II: Sea Ice and Temperature Profiles

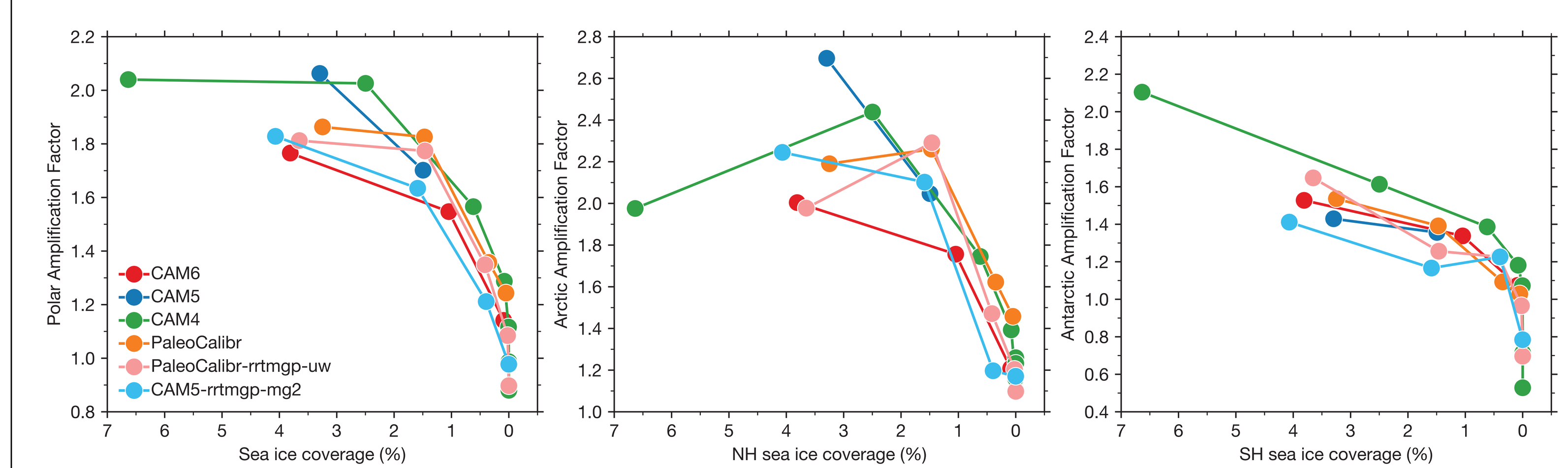

Figure 5. Polar (60°S/N poleward), Arctic (60–90°N), and Antarctic (90–60°S) amplification factors (regional warming divided by ΔGMST) as a function of sea-ice coverage in the simulations.

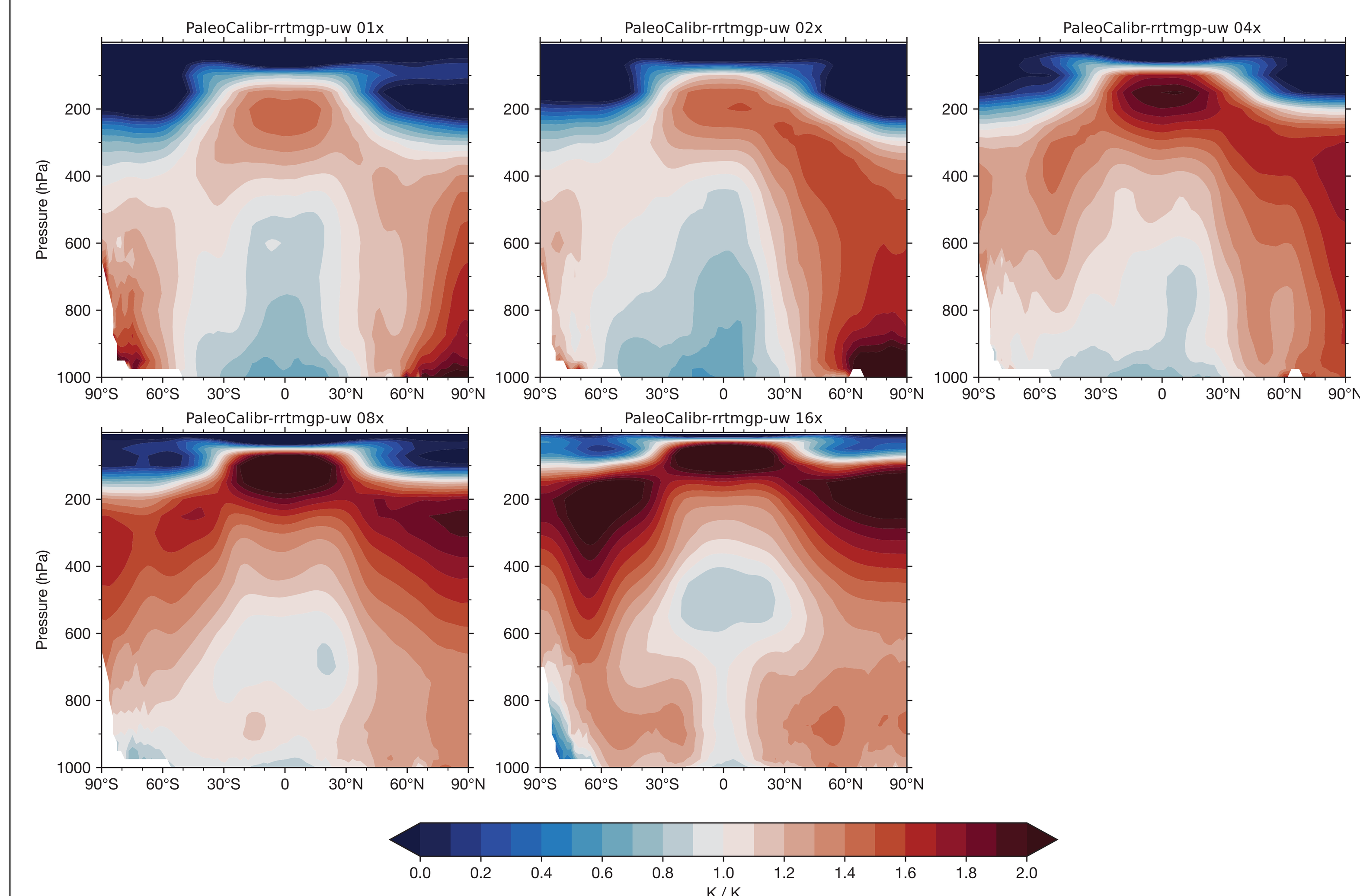

Figure 6. Warming in air temperature scaled by ΔGMST for each CO2 doubling in CESM2 in the configuration of PaleoCalibr-rrtmgp-uw.

- PA exists for ice-free climates.
- Sea-ice coverage in the background climate correlates with the PA factor.
- PA weakens for warm climates, likely due to the disappearing of sea ice & temperature inversion and the initiation of polar convection, i.e., when the polar region warms and becomes similar to the tropics and subtropics.
- Unique structure in temperature response in extreme warm climates.

5. Preliminary Summary

- **Polar amplification (PA) is more prominent for the ice-house climate with sea ice than the hothouse climate.**
- **PA factor decreases with the background temperature, as the sea ice melts away and the temperature inversion disappears. Extreme warm climates may not have PA.**
- **Interesting asymmetry between Arctic and Antarctic.**