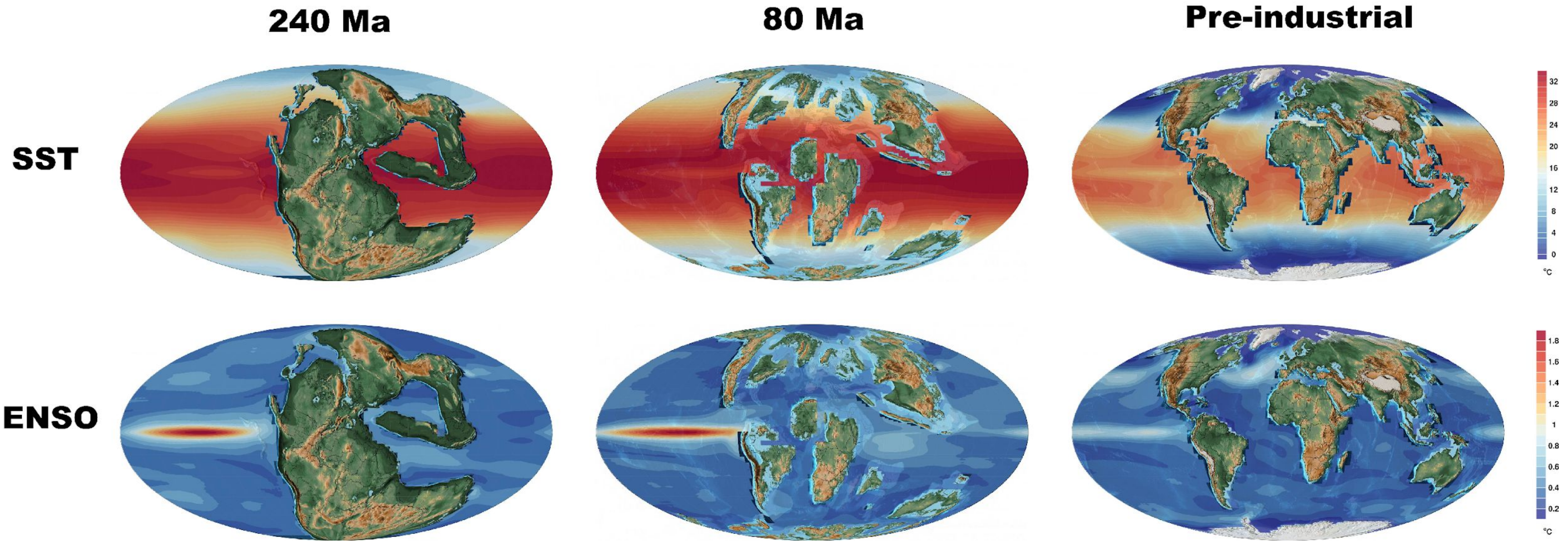

Persistently active El Niño–Southern Oscillation since the Mesozoic

Xiang Li[a,b,1], Shineng Hu[b,1], Yongyun Hu[a,c,*], Wenju Cai[d,e,f,g], Yishuai Jin[d,g], Zhengyao Lu[h], Jiaqi Guo[a], Jiawenjing Lan[a], Qifan Lin[a], Shuai Yuan[a], Jian Zhang[a], Qiang Wei[a], Yonggang Liu[a,c], Jun Yang[a,c], Ji Nie[a,c]

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El Niño–Southern Oscillation in geological periods

- Past climates (different climate mean states, changes in the Pacific width, …) provide a wide range of testbed for ENSO theories.

- Variations in ENSO could have consequential impacts on climate change in the geological past.

RESEARCH

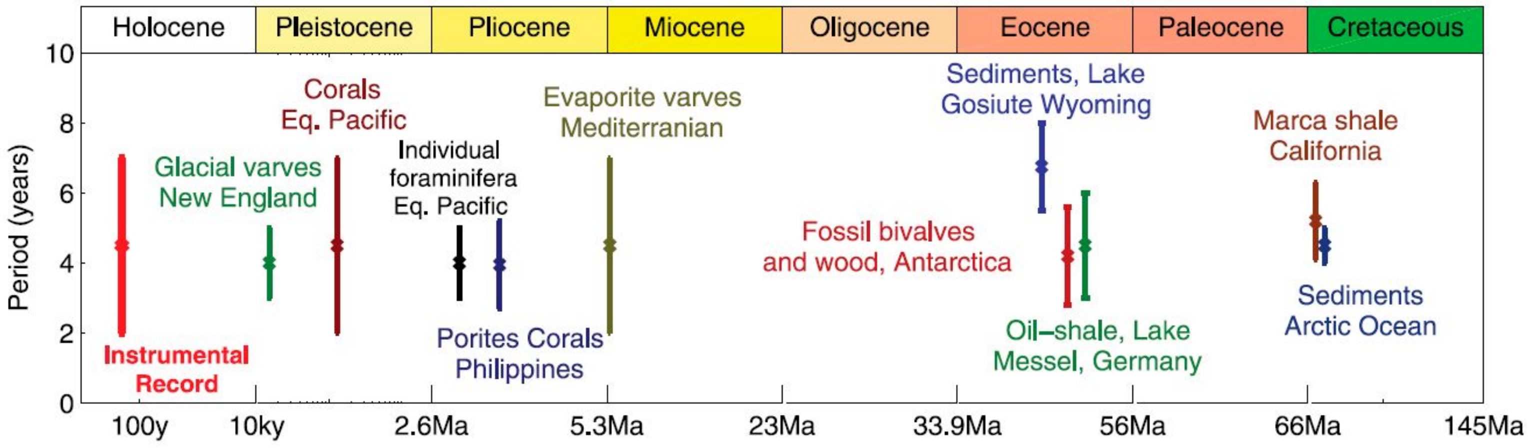
MASS EXTINCTIONS

Mega El Niño instigated the end-Permian mass extinction

Yadong Sun[1,2]*†, Alexander Farnsworth[3,4]†, Michael M. Joachimski[2], Paul B. Wignall[5], Leopold Krystyn[6], David P. G. Bond[7], Domenico C. G. Ravidà[8], Paul J. Valdes[3,4]

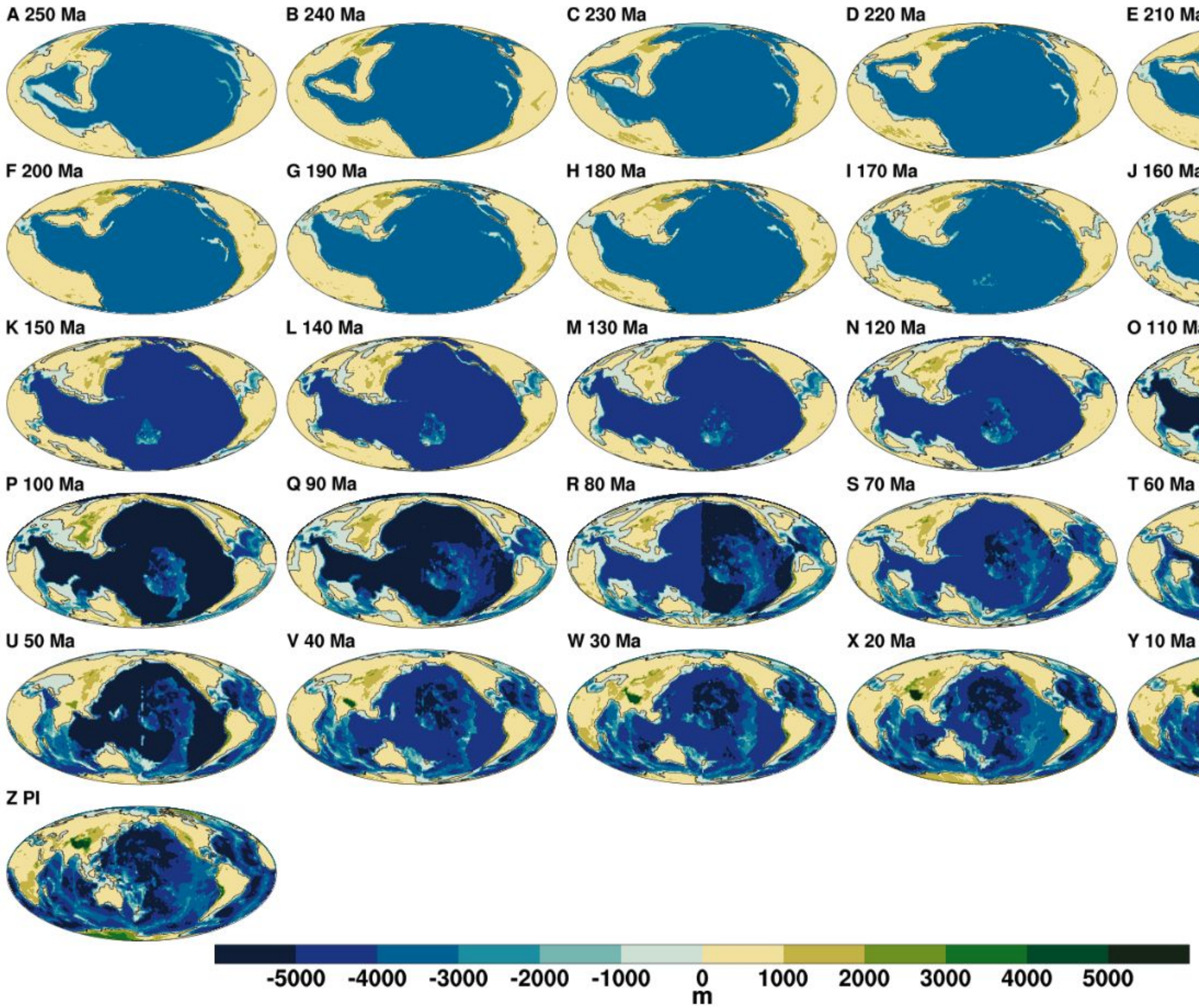
- The geological history of ENSO remains intricate.

- ENSO variability may have been a salient feature of the Earth's climate system for tens of millions of years.



Manucharyan and Fedorov, 2014

The evolution of the Pacific Ocean in the past 250 million years



- Due to tectonic dynamics, modern global oceans are originated from the huge Panthalassa Ocean 250 Myr ago.
- Panthalassa is also referred to as the Paleo-Pacific or Proto-Pacific because the Pacific Ocean is a direct continuation of Panthalassa.

Questions:

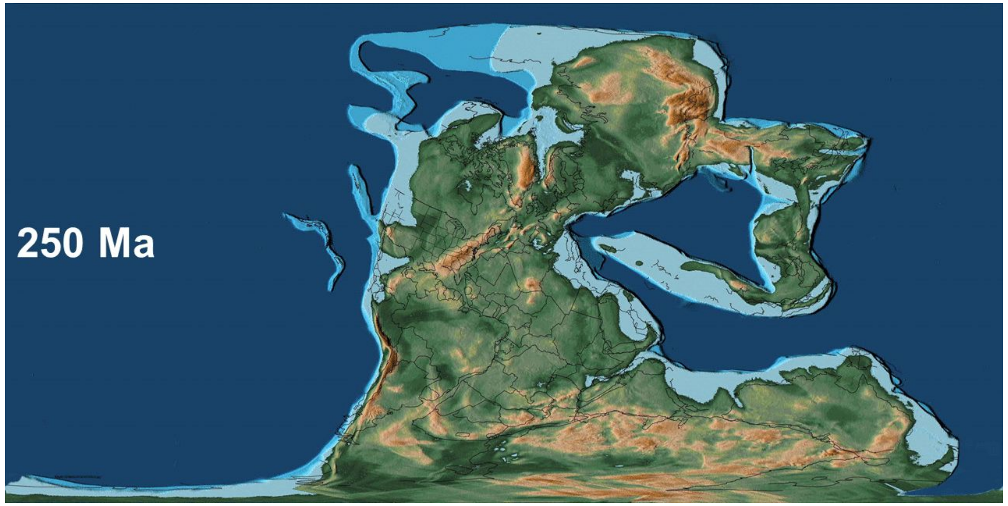
In the past 250 million years,

- How does the equatorial Pacific ocean-atmosphere mean state change?
- Does ENSO remain active?

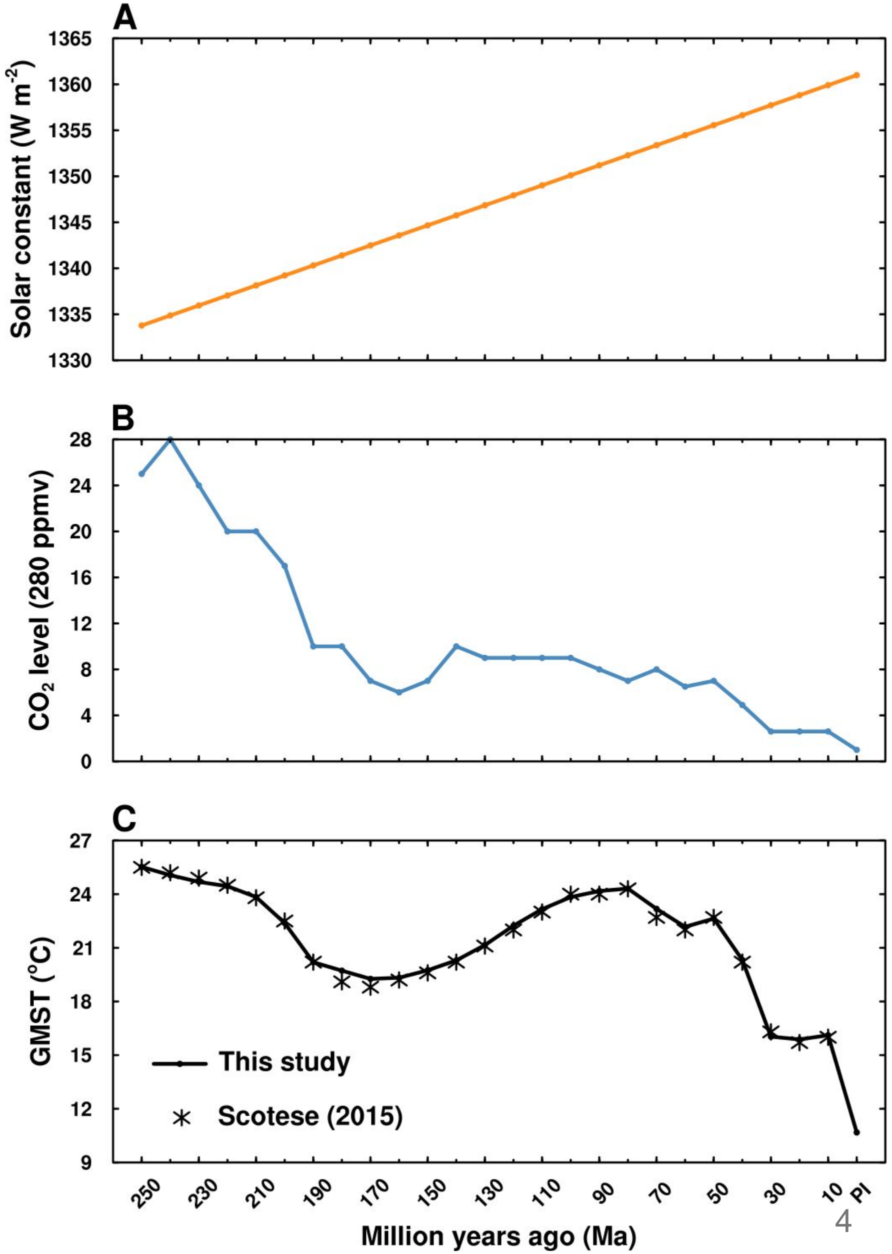
26 time-slice climate simulations for the past 250 million years using CESM1.2.2

Paleogeography

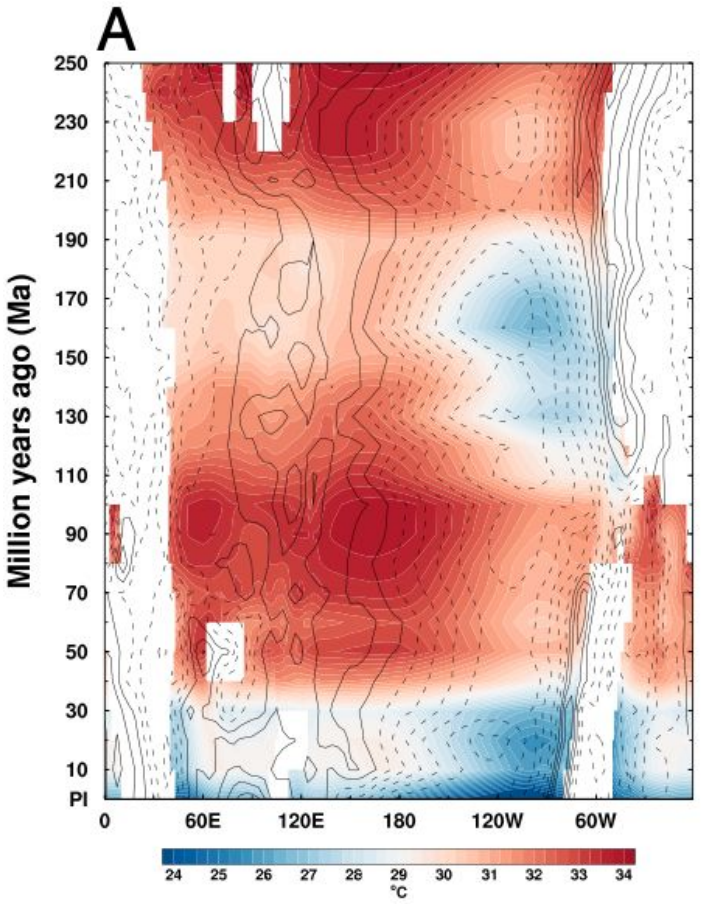
Scotese and Wright, 2018

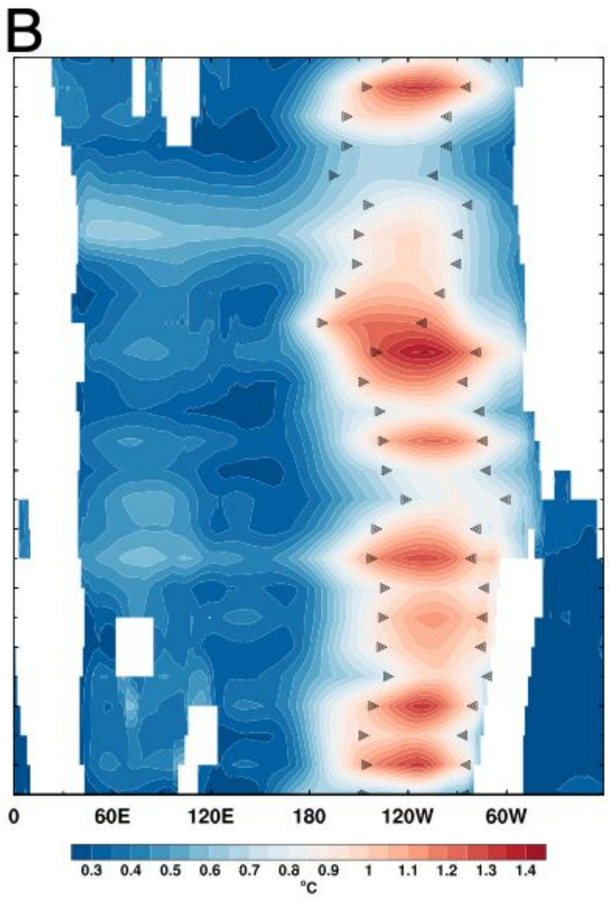


Model and experimental set-ups	
Model	CESM1.2.2, fully-coupled, T31g37
Paleogeography	Scotese and Wright (2018)
Atmospheric CO_2	Inferred from the GMST by Scotese (2015)
Solar irradiance	Linearly increasing following Gough (1981)



Active ENSO during the past 250 million years

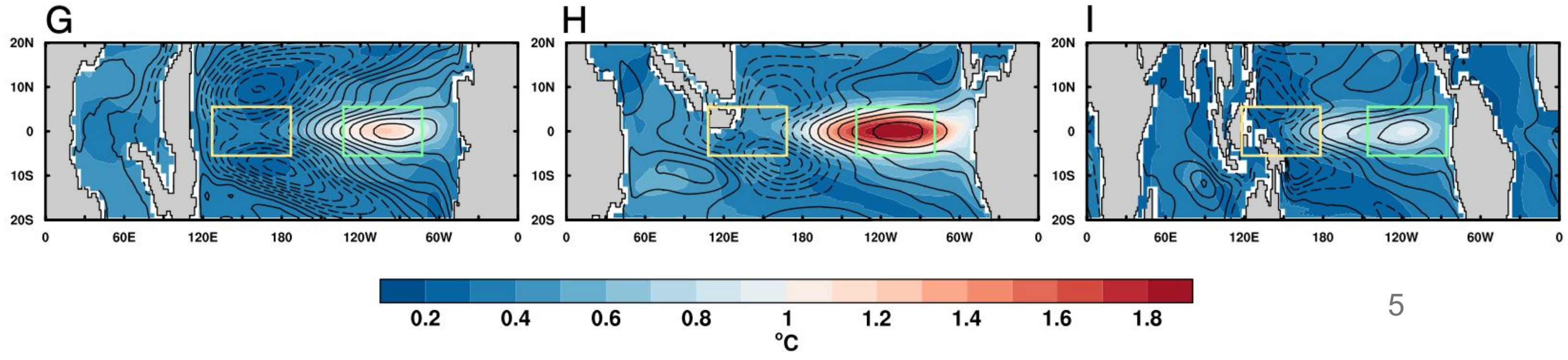




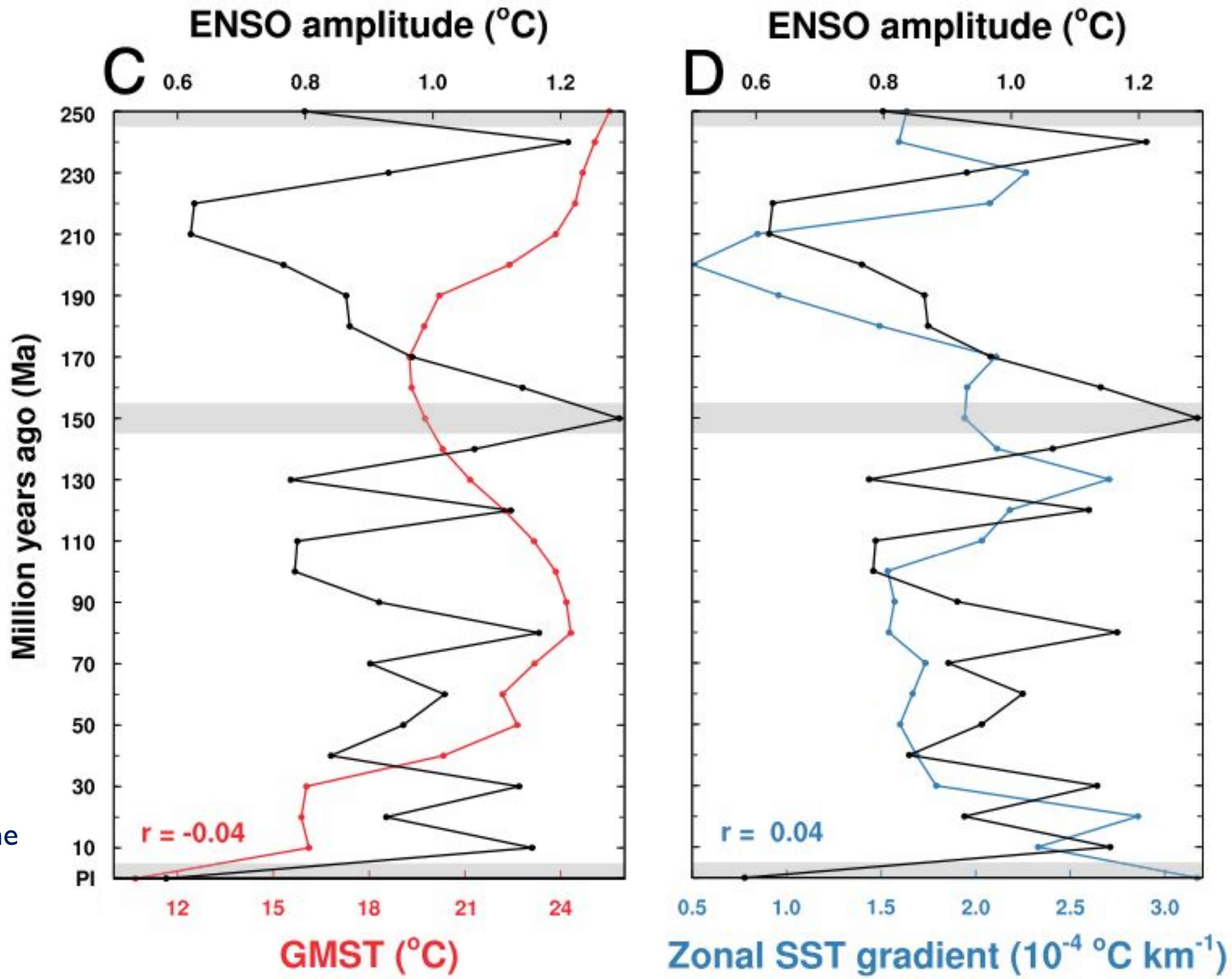
A: Time variation in equatorial SST (shading) and zonal surface winds (contours).
Robust warm pool–cold tongue system with overlying easterly trades

B: Time variation in equatorial SST interannual variability, defined as the SD of SST anomaly
Strongest equatorial SST interannual variability in the eastern Pacific

SST interannual variability (shading) in the tropical ocean at 250 Ma (G), 150 Ma (H), and the PI (I)



No obvious relation between ENSO amplitude and temperature



ENSO amplitude varies by a factor of 2 across the 26 time-slice simulations, ranging from the weakest, 0.6°C for the PI, to the strongest (1.3°C) at 150 Ma.

Linear stability captures 57% of the variations in ENSO amplitude

The Bjerknes linear stability index (BJ index) measures the ENSO's growth rate.

Jin, 1997a; Jin, 1997b; Jin et al., 2006; Kim and Jin, 2010a; Kim and Jin, 2010b; Lübbecke and McPhaden; 2014

$$\mathbf{BJ} = -\left(\frac{\langle \overline{u} \rangle_E}{L_x} + \frac{\langle -2y\overline{v} \rangle_E}{L_y^2} + \frac{\langle \overline{w} \rangle_E}{H_m}\right) - \alpha_s + \mu_a \beta_u \langle -\frac{\partial \overline{T}}{\partial x} \rangle_E + \mu_a \beta_w \langle -\frac{\partial \overline{T}}{\partial z} \rangle_E + \mu_a \beta_h \langle \frac{H(\overline{w})\overline{w}}{H_m} a_h \rangle_E$$

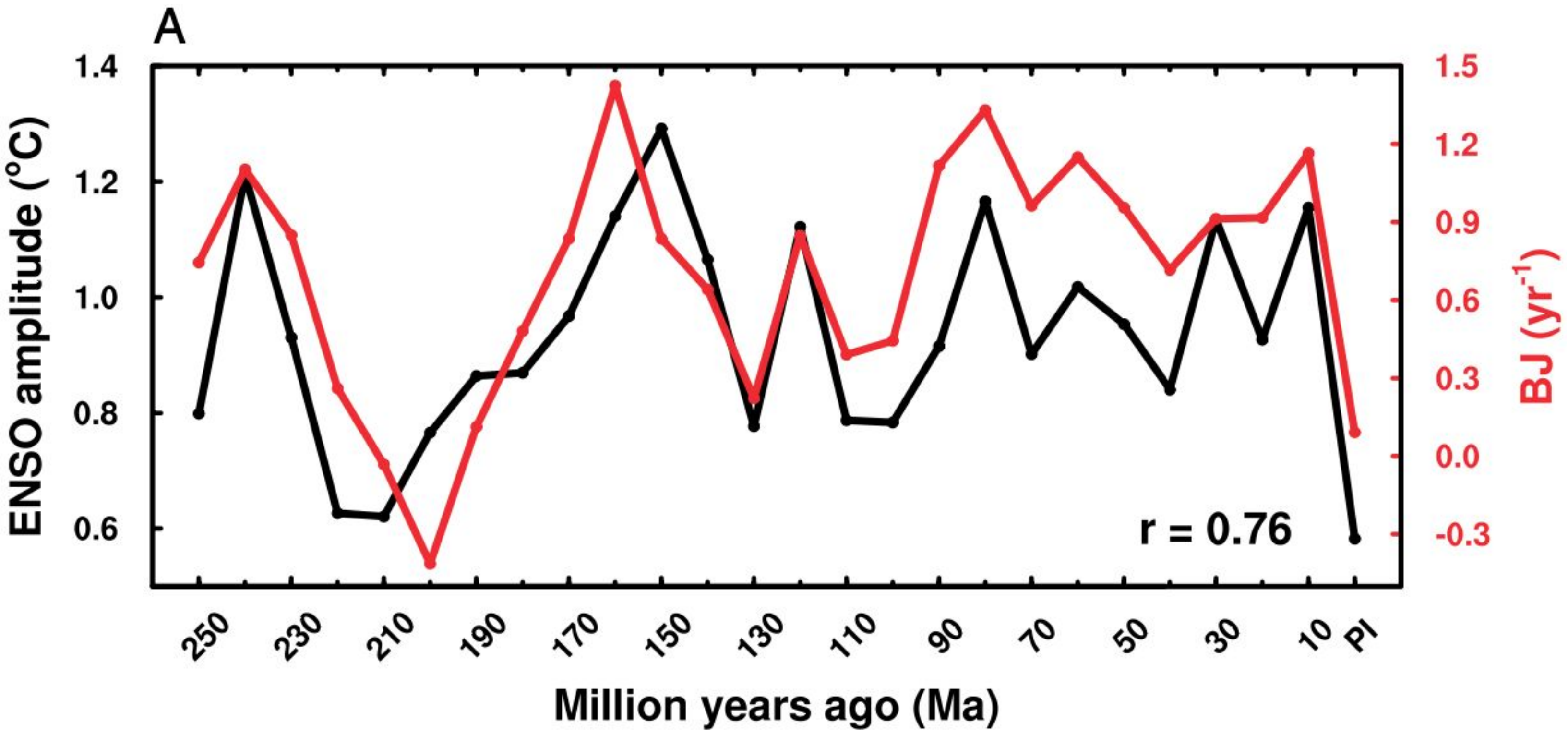
Dynamical damping (DD)

Thermodynamic damping (TD)

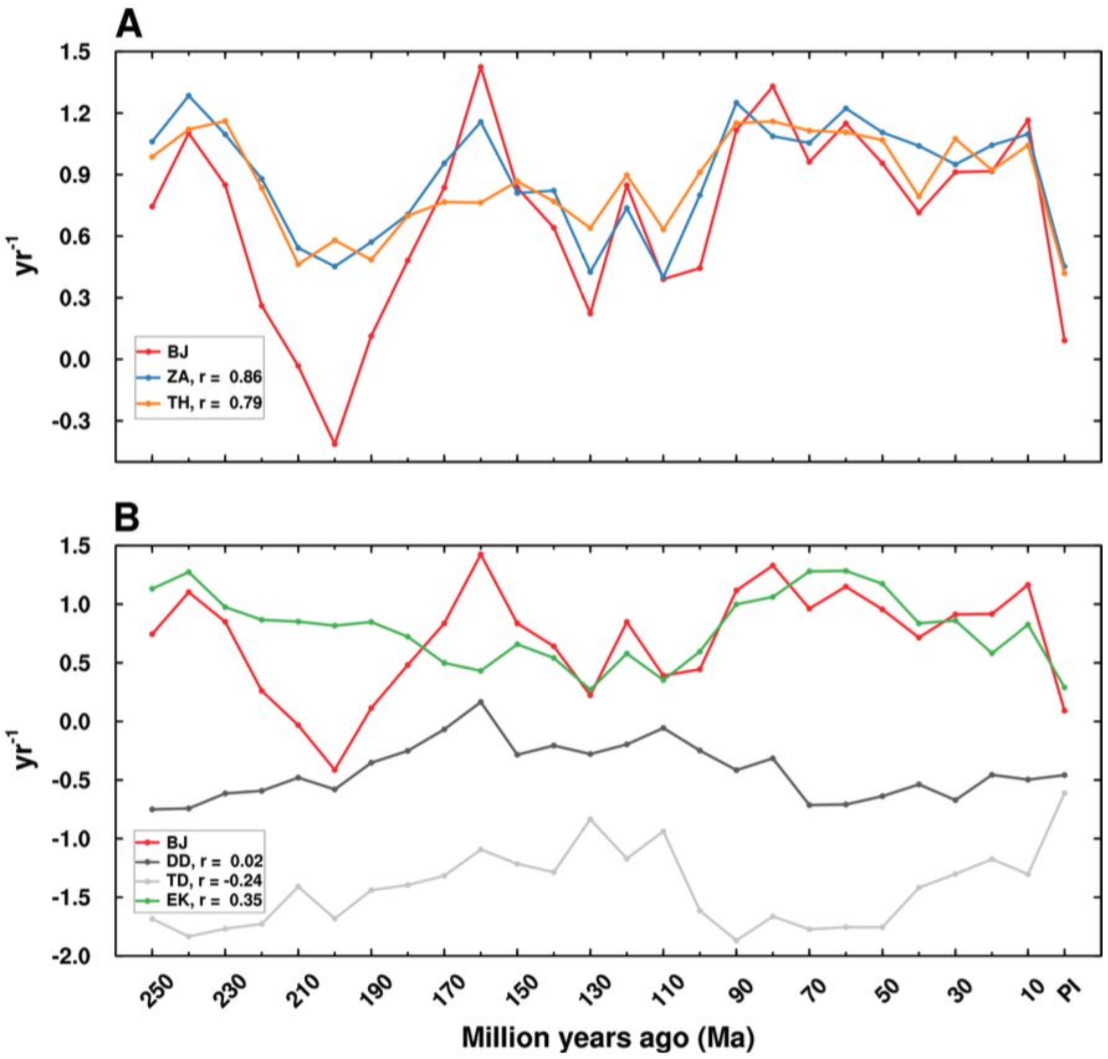
Zonal advective feedback (ZA)

Ekman upwelling feedback (EK)

Thermocline feedback (TH)



Zonal advective feedback and thermocline feedback are dominant factors

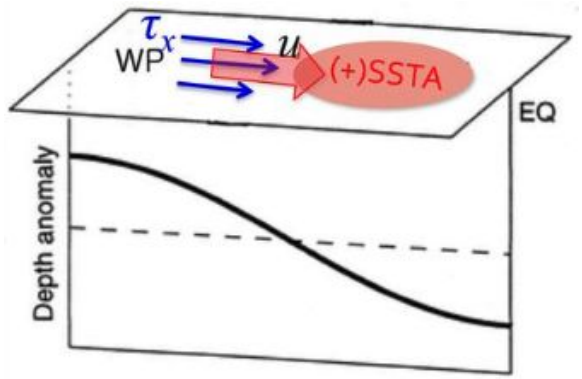


Zonal advective feedback (ZA)

$$\mu_a \boxed{\beta_u} \langle -\frac{\partial \bar{T}}{\partial x} \rangle_E$$

$$[\tau_x] = \mu_a \langle T \rangle_E$$

$$\langle u \rangle_E = \boxed{\beta_u} [\tau_x] + \beta_{uh} \langle h \rangle_w$$



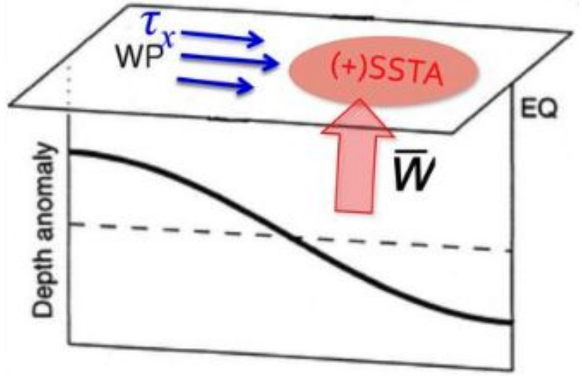
Thermocline feedback (TH)

$$\mu_a \boxed{\beta_h} \langle \frac{H(\bar{w})\bar{w}}{H_m} a_h \rangle_E$$

$$[\tau_x] = \mu_a \langle T \rangle_E$$

$$\langle h \rangle_E - \langle h \rangle_w = \boxed{\beta_h} [\tau_x]$$

$$\langle H(\bar{w}) T_{sub} \rangle_E = a_h \langle h \rangle_E$$



Zonal advective feedback and thermocline feedback are dominant factors

Zonal advective feedback (ZA)

$$\mu_a \beta_u \langle -\frac{\partial \overline{T}}{\partial x} \rangle_E$$

$$\langle u \rangle_E = \beta_u [\tau_x] + \beta_{uh} \langle h \rangle_w$$

β_u: response of surface zonal current to wind forcing

Thermocline feedback (TH)

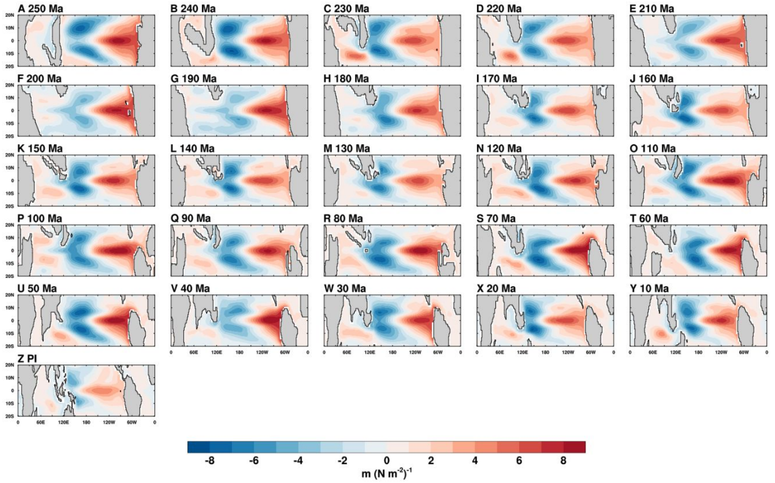
$$\mu_a \beta_h \langle \frac{H(\overline{w})\overline{w}}{H_m} a_h \rangle_E$$

$$\langle h \rangle_E - \langle h \rangle_w = \beta_h [\tau_x]$$

β_h: response of zonal slope of the equatorial thermocline to wind forcing

The changes in β_u is linked with that of β_h.

A local maximum response of positive thermocline anomaly (D') in the eastern equatorial Pacific to an eastward equatorial surface wind forcing (i.e., $\boxed{\beta_h}$) → $\frac{\partial^2 D'}{\partial y^2} < 0$ → $u'_g = -\frac{g'}{\beta} \frac{\partial^2 D'}{\partial y^2} > 0$ → An eastward response of u'_g and thus u' to the eastward surface wind forcing $\boxed{(\beta_u)}$

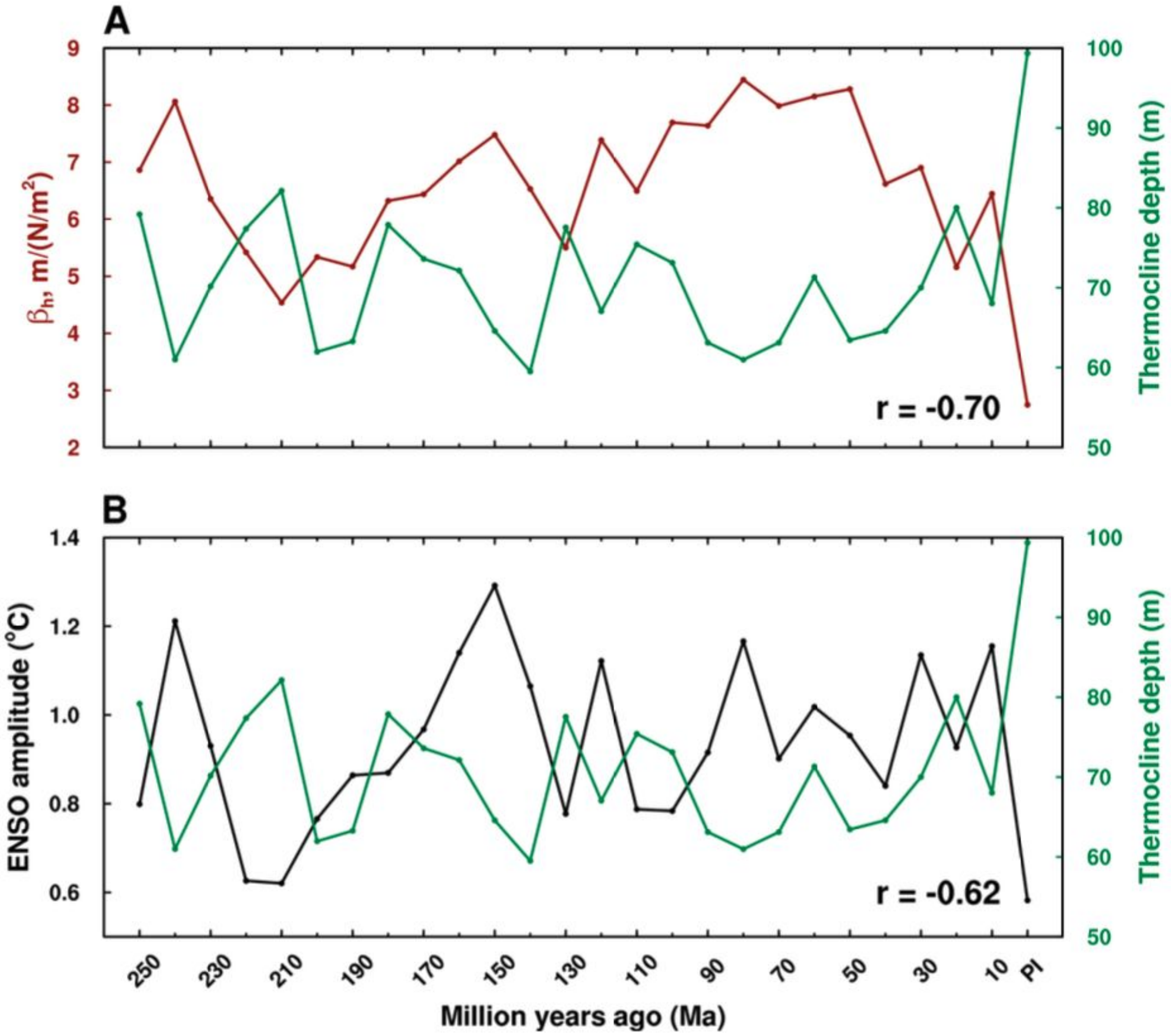


Linear reduced-gravity model in an equatorial β-plane framework (Hirst, 1986; Wang and Weisberg, 1994)

Zonal current anomalies (u') consist of geostrophic (u'_g) and Ekman (u'_e) current anomalies, and u'_e is one order of magnitude smaller than u'_g (Jin, 1997; Jin and An, 1999; Su et al., 2010; Chen et al., 2019).

Modulation of ENSO amplitude by background thermocline depth

β_h: response of zonal slope of the equatorial thermocline to wind forcing



Background thermocline is deeper (shallower)

Shallow-water theory, $g'\frac{\partial D'}{\partial x} \sim \frac{\tau_x'}{\rho D}$ (Neelin, 1991; Jin, 1997; Fedorov and Brown, 2009)

Equatorial thermocline tilt becomes less (more) sensitive to surface wind variations, namely a weaker (stronger) β_h

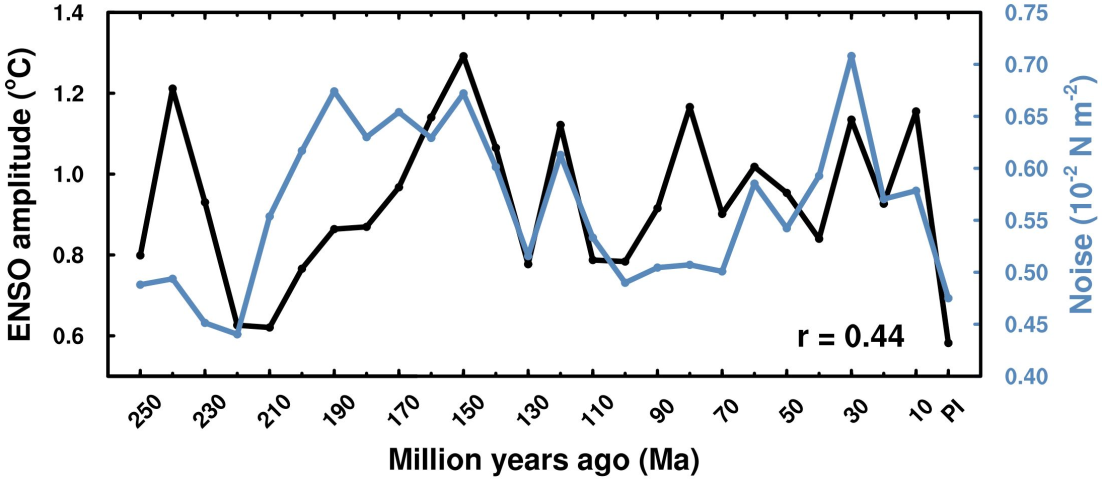
ZA and TH dominated by β_h

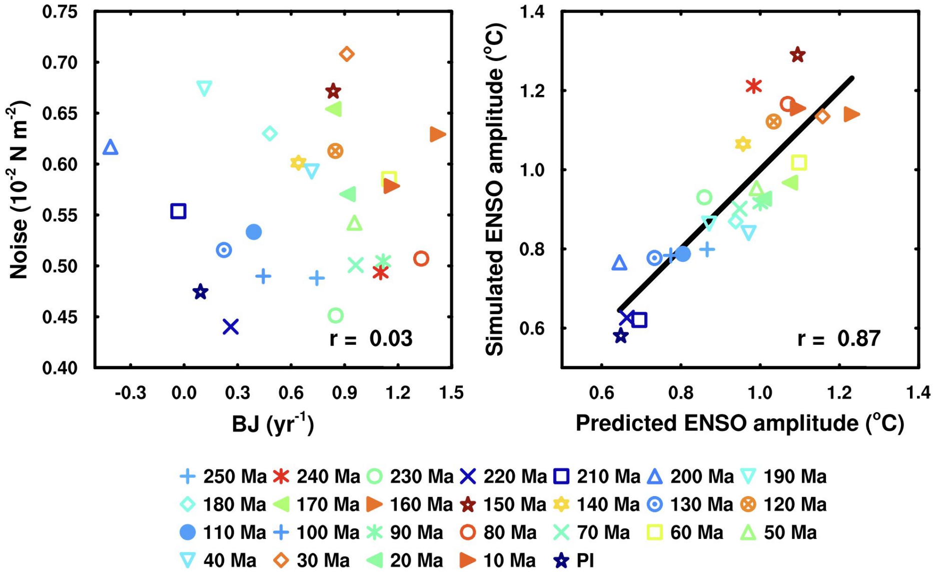
Zonal advective feedback and thermocline feedback are weakened (strengthened)

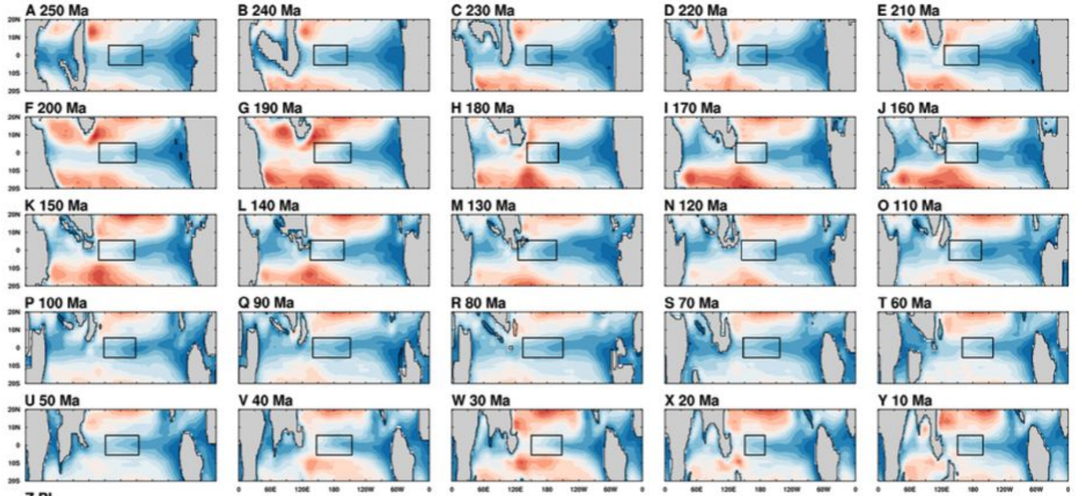
BJ dominated by ZA and TH

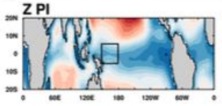
A weaker (stronger) ENSO

Modulation of ENSO amplitude by atmospheric noise

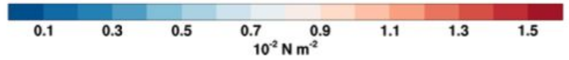








Atmospheric noise: surface zonal wind stress with SST-forced (including ENSO-related) signals removed



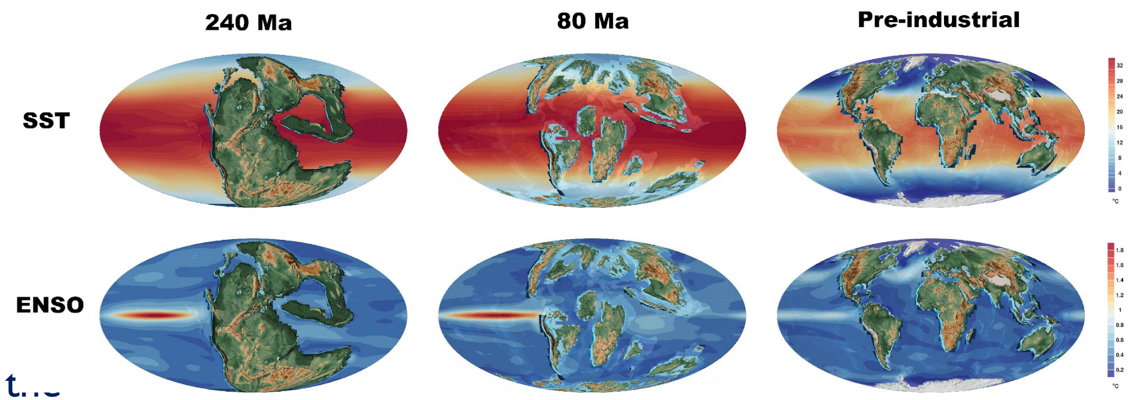
Atmospheric noise and the Bjerknes linear stability are almost completely uncorrelated with each other.

$$ENSO\ amplitude = a \cdot \boldsymbol{BJ} + b \cdot \boldsymbol{noise} + c$$

$$a = 0.31\ ^\circ\mathrm{C} \cdot yr, b = 1.10\ ^\circ\mathrm{C} \cdot (10^{-2}\ N\, m^{-2})^{-1}, c = 0.10\ ^\circ\mathrm{C}$$

The BJ index and atmospheric noise together can explain about **76%** of the variations in ENSO amplitude.

Summary



- A series of 26 coupled time-slice climate simulations forced by paleogeography, atmospheric CO_2 concentrations, and solar radiation for the past 250 Myr are performed, using CESM1.2.2, and analyzed in this study.

- Climate simulations show that ENSO has been a leading mode of tropical sea surface temperature variability in the past 250 Myr but with substantial variations in amplitude across geological periods.

- Our results uncover the geological history of ENSO from a modeling perspective.

- Our findings support the importance of changing ocean vertical thermal structure and atmospheric noise in influencing projected future ENSO change and its uncertainty.

Thanks!

X. Li, S. Hu, Y. Hu, W. Cai, Y. Jin, Z. Lu, J. Guo, J. Lan, Q. Lin, S. Yuan, J. Zhang, Q. Wei, Y. Liu, J. Yang, J. Nie, Persistently active El Niño–Southern Oscillation since the Mesozoic, Proc. Natl. Acad. Sci. U.S.A. 121 (45) e2404758121, https://doi.org/10.1073/pnas.2404758121 (2024).