Connecting warming patterns of the paleo-ocean to our future

Xiaoqing Liu[1] (liuxiaoqingdiy@tamu.edu), Lei Wang[2], Matthew Huber[2], Yi Ge Zhang[1]

[1]Department of Oceanography, Texas A&M University; [2]Department of Earth, Atmospheric and Planetary Sciences, Purdue University

1. Introduction

- **Significance**: establishing the spatial pattern of ocean surface warming is important for regional climate changes; constraining its associated pattern effect is crucial to accurately predicting the future climate sensitivity.
- **Challenge**: different models generate different spatial pattern of ocean surface warming[1].
- **Objective**: reconstruct the warming pattern of the past greenhouse climates based on the compilation of sea surface temperature (SST) over the past 10 million years (Myr) (Figure 1).

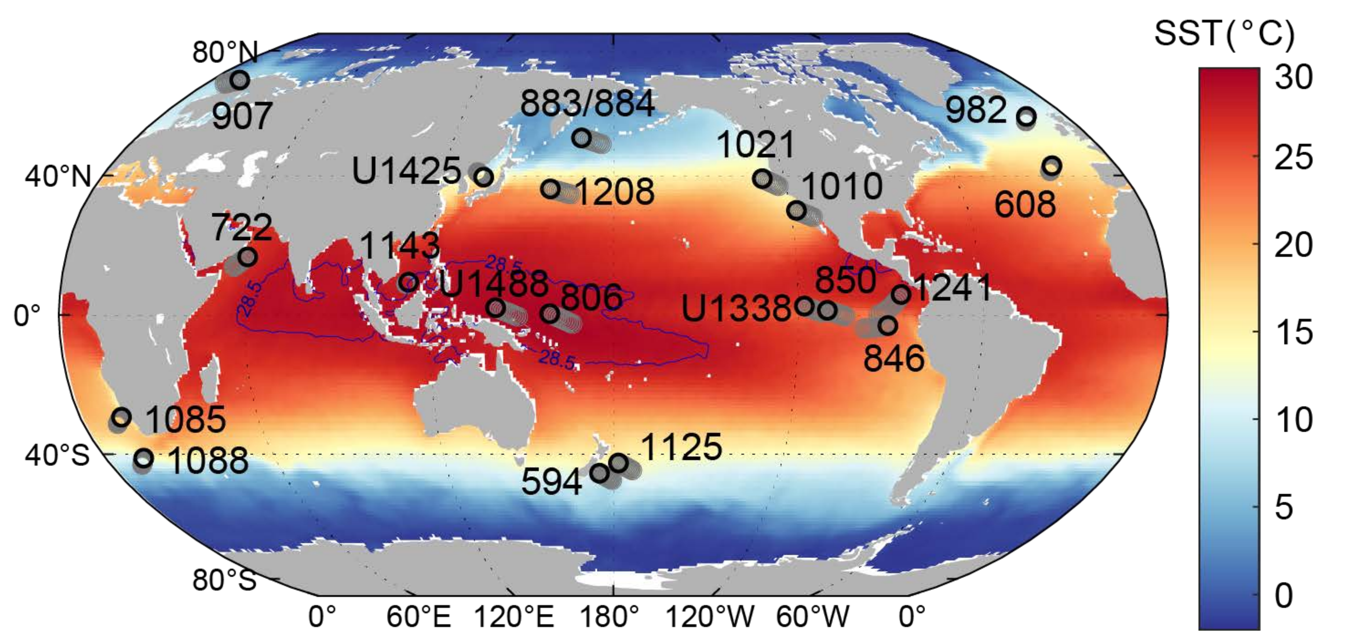

Figure 1 | ODP/IODP Sites used in this study. Gray circles at each site represent paleo-locations of the past 10 Myr at a 1-million-year window and black circles indicate present locations. Blue contour lines indicate the 28.5°C isotherm that defines the modern Western Pacific Warm Pool (WPWP).

2. A new method to define the warming pattern

- **Benchmark**: the 10-Myr SST record from the Western Pacific Warm Pool (WPWP) (Figure 2a).
- **A regression-based technique**: SST records of non-WPWP regions are ordinated by the WPWP SST (Figure 2b).
- **Amplification factor**: the regression slope
- Our new approach **removes time variations in SSTs** and allows past climates directly compared with recent and future climates.

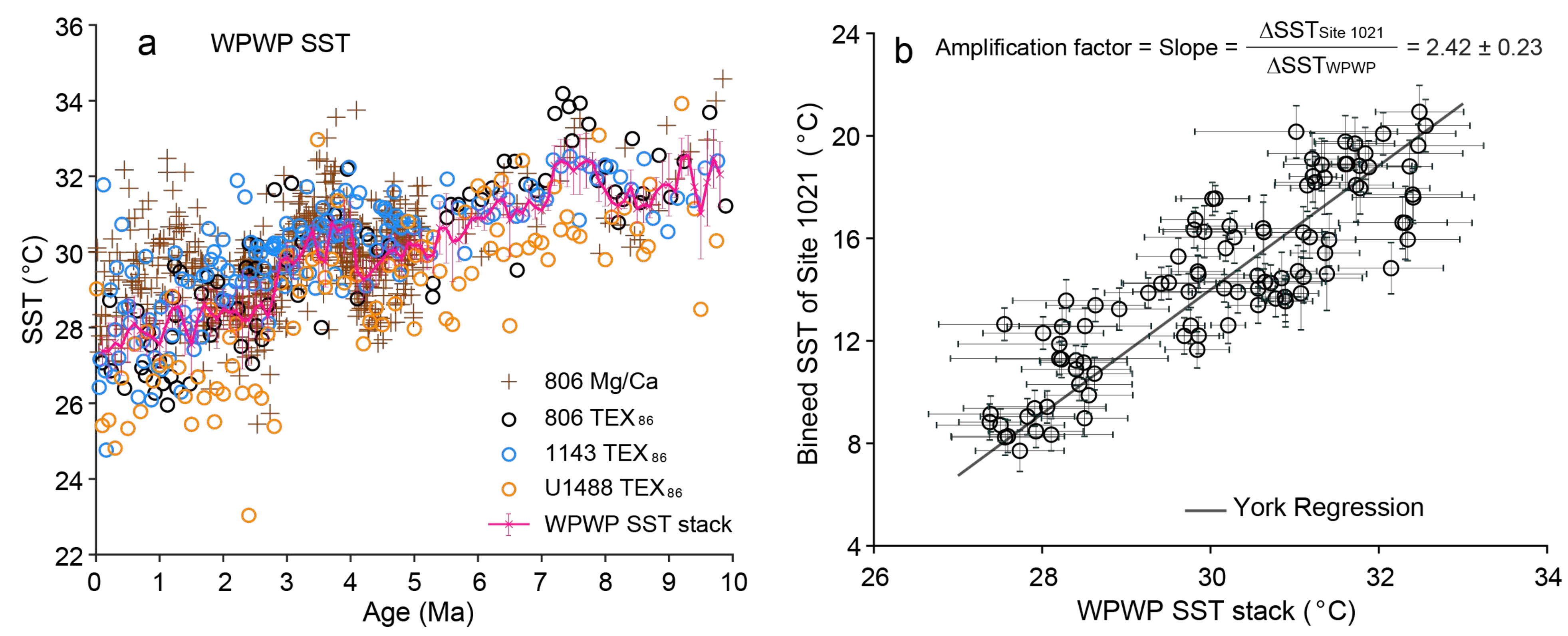

Figure 2 | Calculating amplification factor for any specific site over the WPWP. a, SST of the WPWP over the past 10 Myr. Warm Pool SST stack (pink line) was calculated using TEX_{86}-SST from Sites U1488[2], 806 and 1143[3] and seawater Mg/Ca-adjusted Mg/Ca-SST from Site 806[2]. b, determining the amplification factor for Site 1021. $U^{K'}_{37}$-SSTs[4] were binned over 200 kyr, with 50% overlap. Error bars indicate 1σ, and the black line represents York Regression[5] considering errors in bivariate data. The p-value for the regression slope is 4×10^{-37}, suggesting the linear relationship is statistically significant.

3. Warming pattern comparison: paleo-results *vs* model simulations

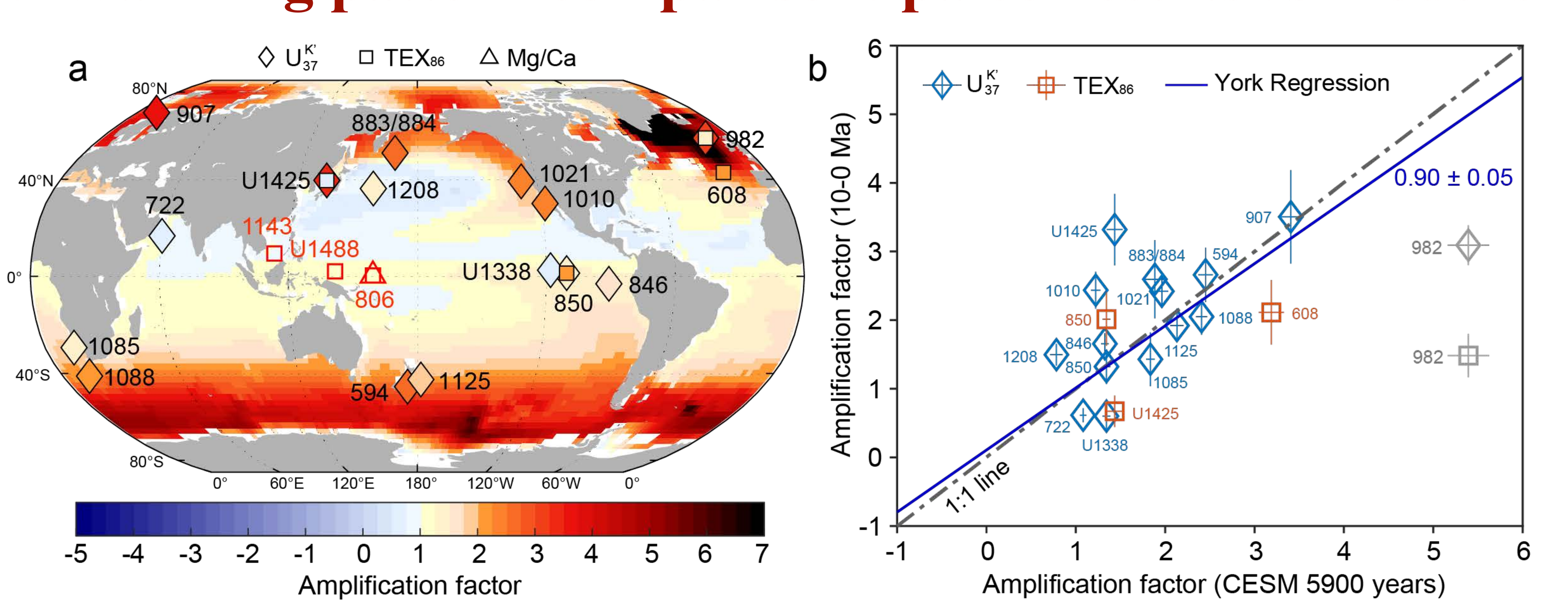

Figure 3 | Comparing amplification factors between the last 10-Myr geological data and CESM model simulations. a, map shows the model-derived warming patterns of the global ocean. Amplification factors were determined by analyzing SST outputs from CESM 1.0.4 run with abrupt atmospheric CO_2 quadrupling above pre-industrial levels[6]. Filled diamonds and squares indicate 10-Myr amplification factors derived from $U^{K'}_{37}$ and TEX_{86}-based SSTs, respectively. b. comparison between model-derived amplification factors and proxy-derived results of past 10 Myr.

For **CESM**, amplification factors at 15 out of 16 studied locations are similar (Figure 3).

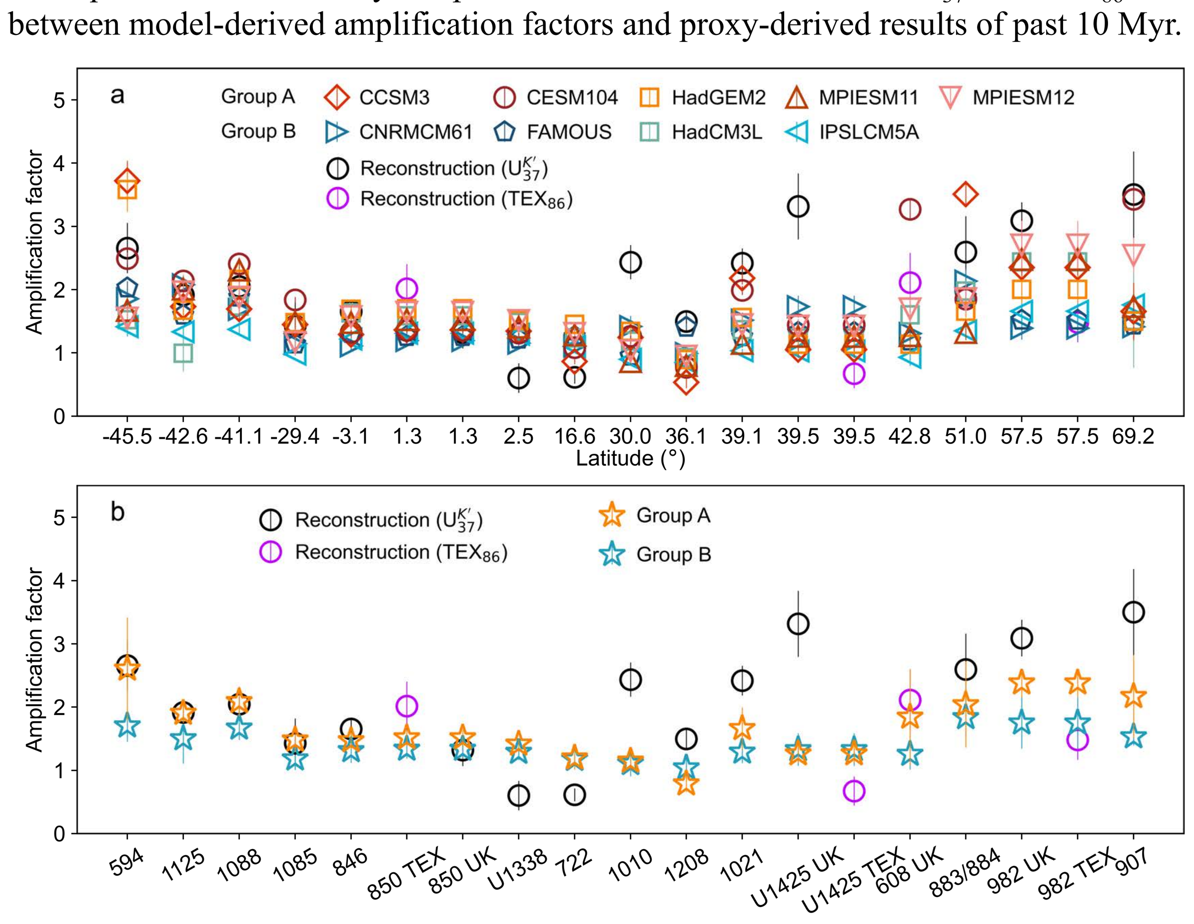

Figure 5 | Comparing amplification factors from the 10-Myr record with those derived from two groups of LongRunMIP models.

- CCSM3, HadGEM2, MPIESM11 and MPIESM12 show a better agreement with the paleo-results than CNRMCM61, FAMOUS, HadCM3L and IPSLCM5A (Figure 4).
- Models inconsistent with paleo-results tend to underestimate mid- an high-latitude amplification (Figure 5).

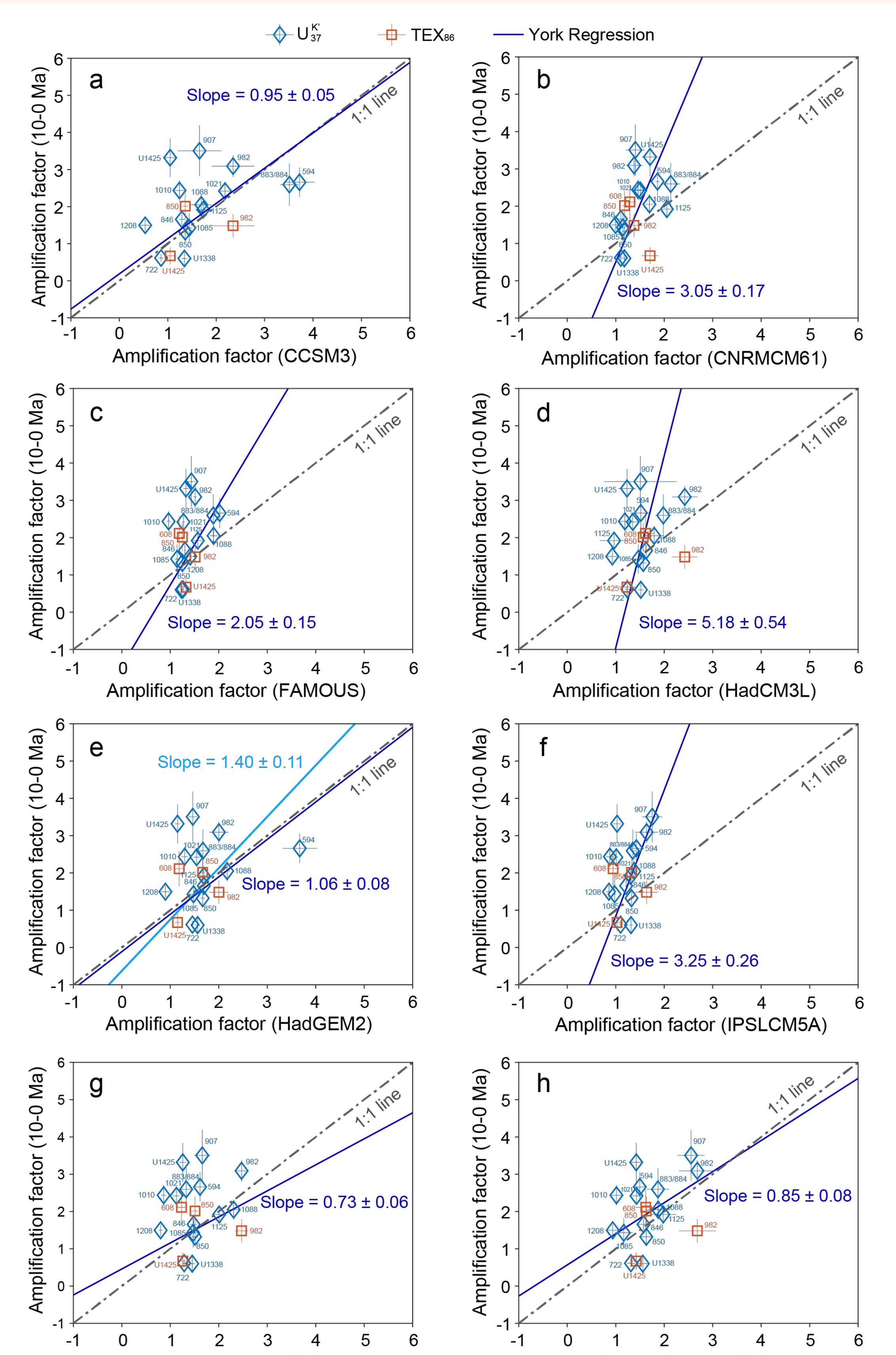

Figure 4 | Comparing amplification factors between the last 10 Myr geological data and other model simulations from LongRunMIP. Symbols are identical to those shown in Figure 3b. Blue lines indicate York Regression using all the data, and the light-blue line in e indicates York Regression excluding the rightmost data point.

4. Warming pattern comparison: paleo-results *vs* recent observations

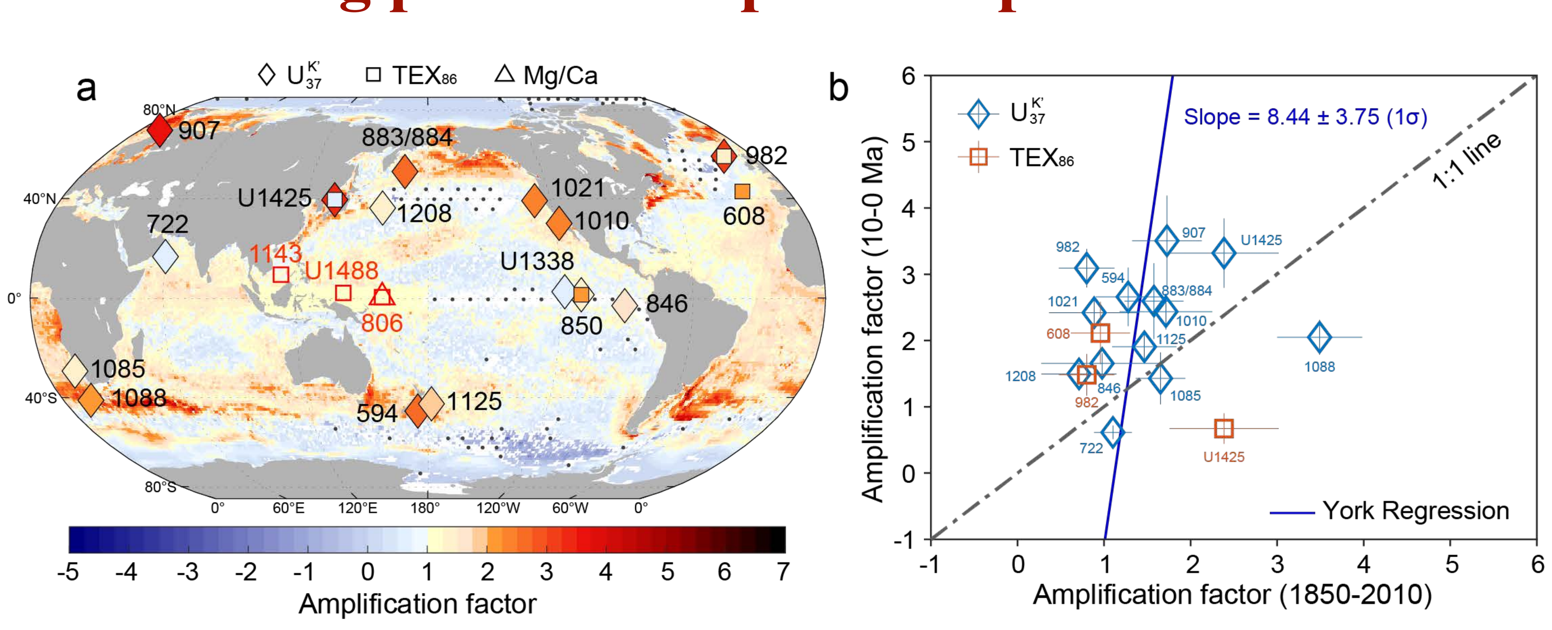

Figure 6 | Comparing amplification factors between the last 10 Myr and the last 160 years. a, the warming pattern shown on the map. The color of the world's ocean shows amplification factors over 160 years (1850-2010) derived from HadISST2.1. Stippling on the white space indicates that the amplification factor is not available at some grid point since its SST does not have a significant linear relationship with the WPWP SST at a 5% significance level. b, comparing amplification factors between the recent 160-year and the past 10-Myr results with a cross plot. For grid points nearest to the paleo-locations of Sites 850 or 1338, their averaged SST from 1850 to 2010 does not have a significant linear relationship with the WPWP SST (p-value > 0.05), and thus Sites 850 and 1338 are not included in the cross plot (b).

Amplification factors derived from the past 10 Myr are mostly larger than those from the recent 160 years (Figure 6).

5. Conclusion and implication

- We identified a nearly stationary pattern of warming similar to that shown in some equilibrated model simulations under high CO_2 conditions.
- These data help us to define an "equilibrium" warming pattern, illuminating our potential future path of the "pattern effect".

Selected References

1 Dong Y. et al., *Journal of Climate* 32, 5471–5491 (2019).
2 Liu X. et al., *Nature Communications*, In Review.
3 Zhang, Y.G. et al., *Science* 344, 84–87 (2014).
4 Herbert, T.D. et al., *Nature Geosciences*. 9, 843-847 (2016).
5 York D. et al., *American Journal of Physics* 72, 367–375 (2004).
6 Rugenstein, M. et al. *Bulletin of the American Meteorological Society* 100, 2551–2570 (2020).

Acknowledgement we thank Ping Chang and Andrew Dessler for helpful discussions and advice.