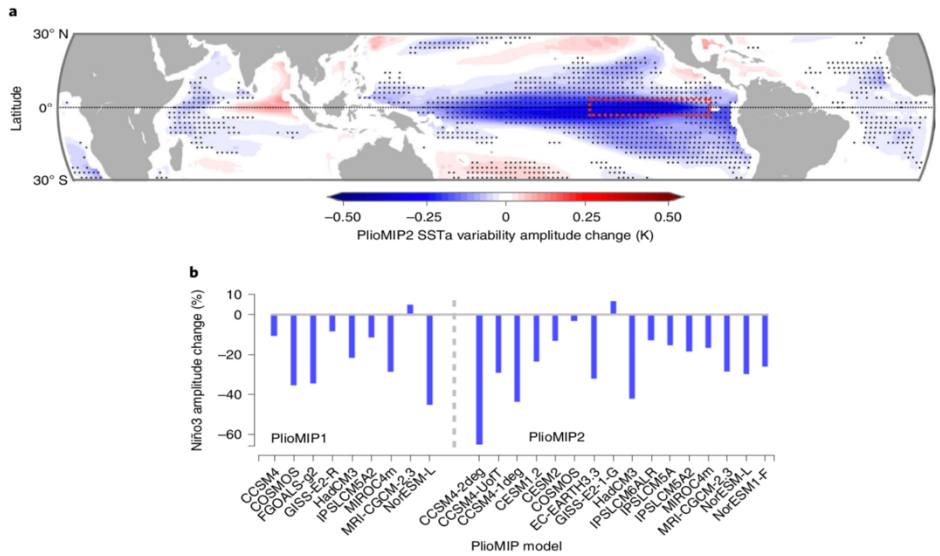

Fig. 1 | Simulated mid-Pliocene tropical variability changes. a, Multimodel mean change in the amplitude (standard deviation) of SST anomaly (SSTa) variability in the PlioMIP2 models (see Extended Data Fig. 1 for PlioMIP1 models). SST anomaly is obtained through removing the mean seasonal cycle. Stippling indicates locations where there is significant model agreement (at least 70%) in the sign of the change. **b**, Change in the amplitude (standard deviation) of the Niño3 time series in each PlioMIP model. Red box in the eastern Pacific in **a** indicates the Niño3 region. Map created using the Basemap library for Python.

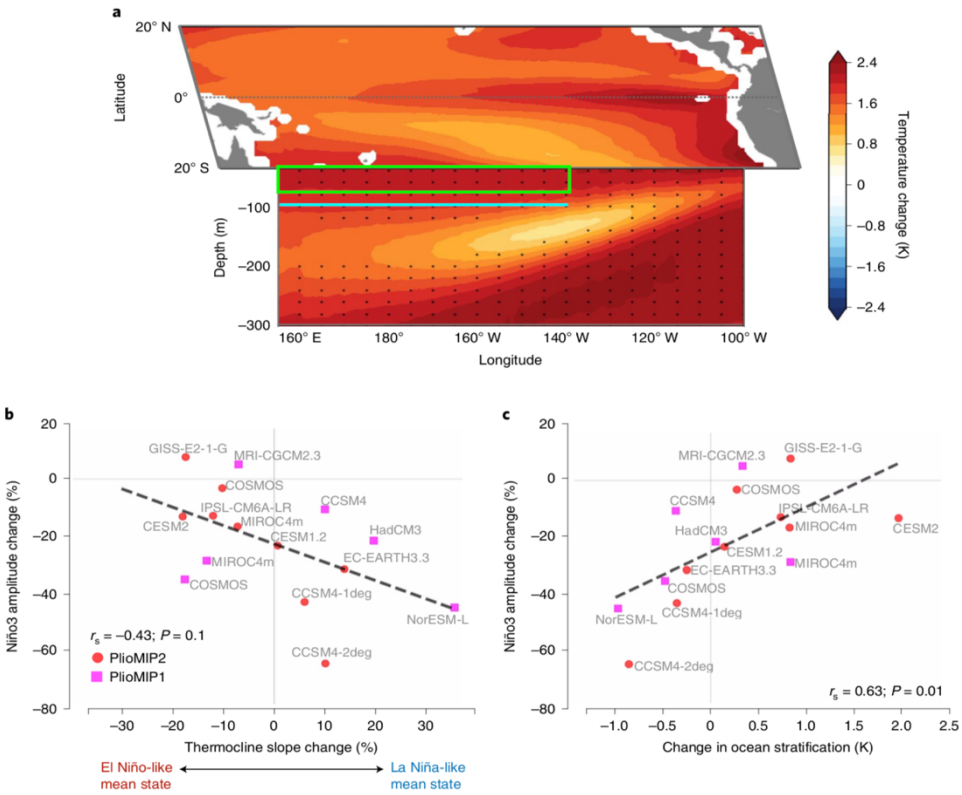

Fig. 2 | Equatorial Pacific Ocean changes. a, PlioMIP2 multimodel mean change in surface tropical and subsurface equatorial Pacific temperatures. The vertical profile is averaged between 5° S and 5° N. Stippling indicates significant change at the 95% level (in the SST panel, the entire basin-wide warming is significant at the 95% level). **b**, Intermodel relationship between the change in the thermocline slope between the eastern and western Pacific (Methods) and the change in the Niño3 amplitude. **c**, Intermodel relationship between the change in ocean stratification and the change in Niño3 amplitude. Ocean stratification was measured as the difference between the average temperature in the top 75 m (green box in **a**) and that at 100 m (blue line in **a**) between 150° E and 140° E.

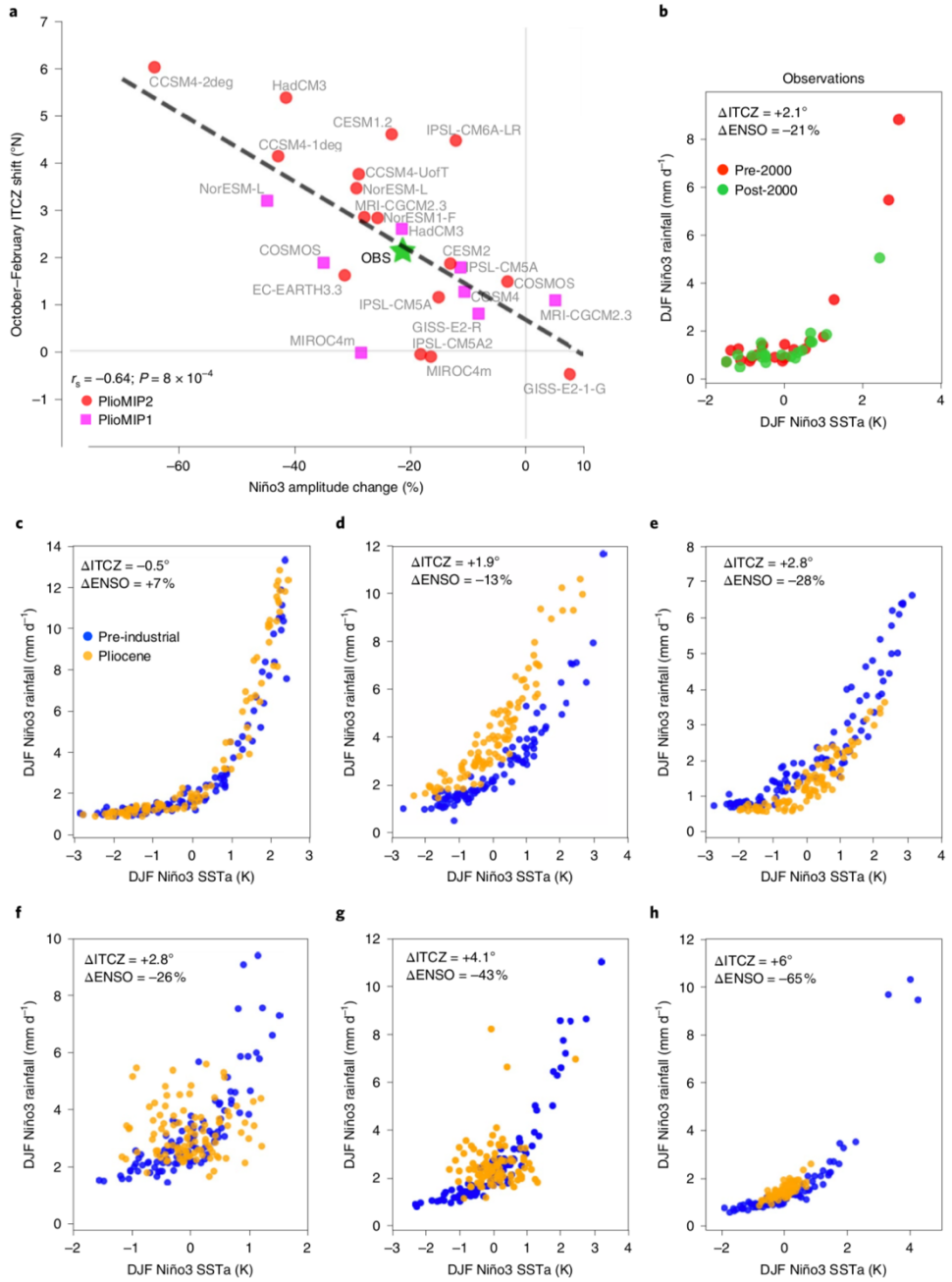

Fig. 3 | ITCZ–ENSO relationship. a, PlioMIP2 intermodel relationship between the change in the Niño3 amplitude and mean ITCZ shift from October to February. Green star indicates values obtained from observations by comparing periods 1979–1999 and 2000–2020. The correlation coefficient was evaluated considering PlioMIP models only. **b**, Relationship between December–January–February (DJF) Niño3 SST anomalies and DJF Niño3 rainfall for the period pre-2000 (red) and post-2000 (green). **c**–**h**, As in **b** but for selected PlioMIP models that correctly simulate nonlinear ENSO characteristics (Methods): GISS-E2-1-G (**c**), CESM2 (**d**), MRI-CGCM2.3 (e), NorESM1-F (**f**), CCSM4-1deg (**g**) and CCSM4-2deg (**h**). Pre-industrial simulation in blue and Pliocene in yellow.

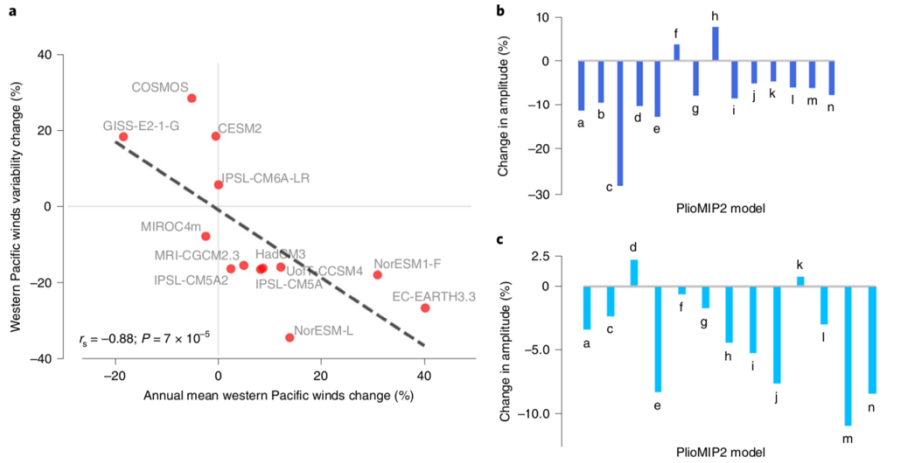

Fig. 4 | Changes to potential ENSO triggers. a, Intermodel relationship between the change in the intensity of the western Pacific trade winds (10° S–10° N; 160° E–150° W) and the amplitude (standard deviation) of its monthly variability. To ideally examine changes in the western wind bursts, we would need high-frequency output, which is not available for the PlioMIP models. **b**, Change in the amplitude (standard deviation) of the SPMM time series, defined as the mean SST anomaly between 15° S and 25° S and between 110° W and120° E. **c**, Change in the amplitude (standard deviation) of the meridional wind variability over the SHB region (10° S–30° S; 140° E–170° E). PlioMIP2 models in **b** and **c**: a, CCSM4-UofT; b, CCSM4-2deg; c, CESM2; d, COSMOS; e, EC-EARTH3.3; f, GISS-E2-1-G; g, HadCM3; h, IPSL-CM6A-LR; i, IPSL-CM5A; j, IPSL-CM5A2; k, MIROC4m; l, MRI-CGCM2.3; m, NorESM-L; n, NorESM1-F.

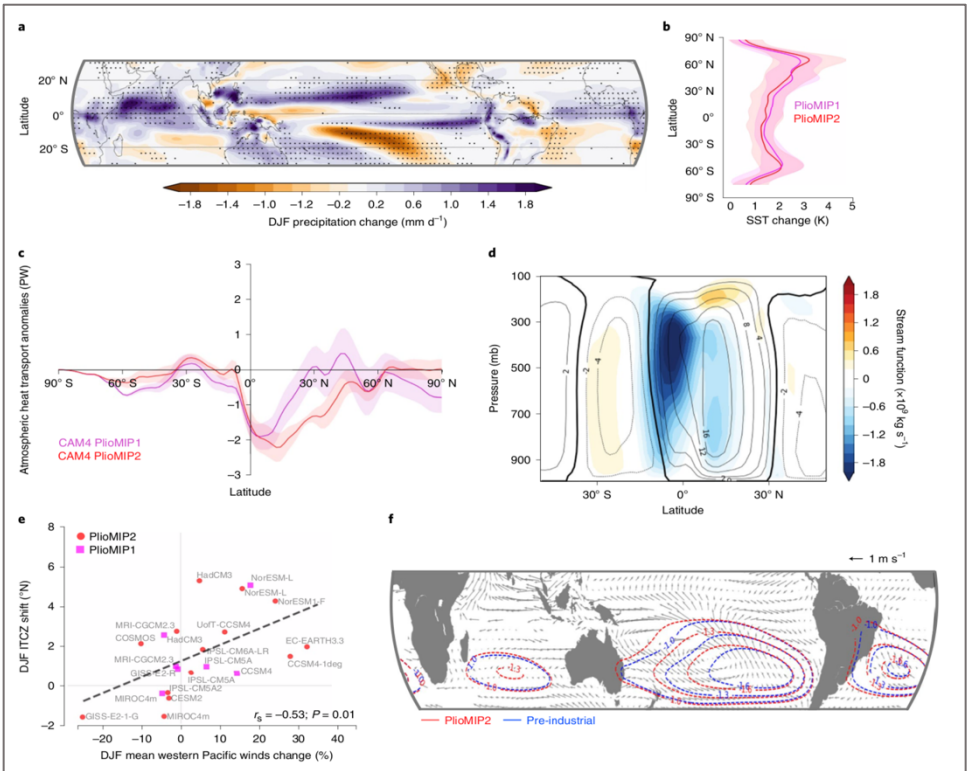

Fig. 5 | Energetic constraints for the ITCZ position. a, DJF precipitation change in the PlioMIP2 models (mPWP minus pre-industrial). Stippling indicates where the change is significant at the 95% level. **b**, Multimodel mean change zonally averaged SST for PlioMIP1 (magenta) and PlioMIP2 (red). Banding indicates standard deviation range. **c**, Cam4: changes in DJF atmospheric energy flux, computed as the residual between the total top-of-the-atmosphere and surface energy fluxes, in the AGCM experiments forced with PlioMIP1 and PlioMIP2 climatological SST and sea ice (Methods). Banding indicates standard deviation range of a five-member ensemble. Negative anomalies in the Northern Hemisphere indicate weakening of the northward heat transport, while negative anomalies in the Southern Hemisphere indicate intensification of the southward heat transport. **d**, CAM4: changes in the meridional stream function in the AGCM experiment forced with PlioMIP2 SST and sea ice. Contours indicate pre-industrial stream function (zero contour in bold). Colours indicate change. **e**, Intermodel relationship between changes in the intensity of the zonal western Pacific trades and ITCZ shift during austral summer. **f**, Changes in low-level (850 hPa) winds and stream function in the PlioMIP2 models. Wind changes are shown only where changes are significant at the 95% level. Maps created using the Basemap library for Python.

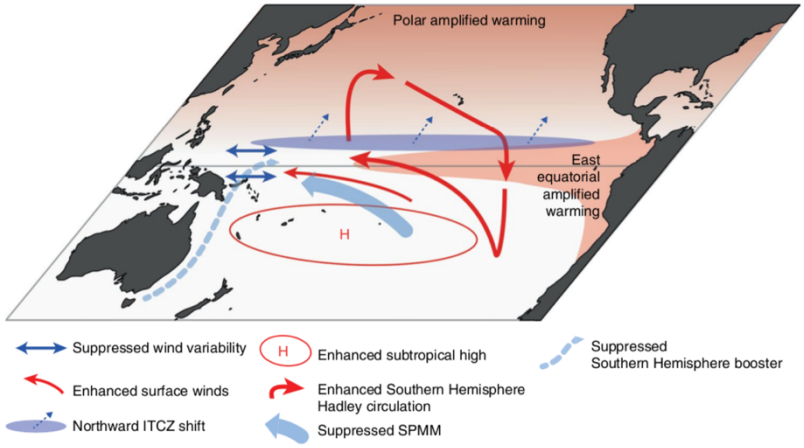

Fig. 6 | Schematic of the drivers of suppressed ENSO activity in the mPWP. A northward ITCZ shift reduces the probability of occurrence of deep convection in the central-eastern Pacific. Energetic constraints for the ITCZ position indicate that higher rates of warming in the Northern Hemisphere drive a northward ITCZ shift and enhanced Southern Hemisphere Hadley circulation. These changes are also associated with intensified surface subtropical high and western Pacific trades. Enhanced trade winds suppress wind variability in the western Pacific, which is important for El Niño initiation. An intensified subtropical high is thought to impede zonal pressure anomalies across the tropical South Pacific and, thus, suppress the activity of the SPMM and SHB, which are important for the development of strong El Niño events. Map created using MATLAB®.