

Supplementary materials for

A snow-jet bridging mechanism driving the Afro-Asian summer monsoon precipitation dipole

Chao Zhang^{1,2,*} and Anmin Duan^{1,*}

¹Center for Marine Meteorology and Climate Change, State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen 361005, China

²Marine Biogeochemistry Division, GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel 24148, Germany

Corresponding authors: chaozhang@xmu.edu.cn (C.Z.) and amduan@xmu.edu.cn (A.D.)

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Supplementary Text

Temporal persistence of the leading TPS mode across summer monsoon months

We apply Empirical Orthogonal Function (EOF) analysis to identify the dominant mode of Tibetan Plateau snow cover (TPS) and its temporal persistence. The leading EOF mode (EOF1) shows that snow cover anomalies over the eastern and western plateau exhibit opposite signs in May and October (Fig. S1a, f). In contrast, from June to September (summer monsoon months), the EOF1 pattern displays a spatially coherent structure (Fig. S1b, e), indicating that TPS anomalies tend to vary in phase across the entire plateau during the summer monsoon season.

The first principal component (PC1) of TPS in May shows a weak correlation with the PC1 in June ($R^2 = 0.08$; Fig. S2a). Similarly, the PC1 in October is weakly correlated with that in September ($R^2 = 0.01$; Fig. S2e). This reflects the strong seasonal transitions at the boundaries of the monsoon season^{1,2}. By comparison, significant correlations are observed among the summer monsoon months themselves (June–July: $R^2 = 0.25$; July–August: $R^2 = 0.49$; August–September: $R^2 = 0.22$; all $p < 0.05$; Fig. S2b–d), reflecting persistent TPS fluctuations throughout this period.

Given this temporal consistency, we focus on the summer monsoon mean TPS. Its EOF1 pattern (Fig. S1g) matches that of each individual month (Fig. S1b–e), and the PC1 of the summer monsoon mean is highly correlated with each monthly PC1 ($R^2 = 0.41, 0.69, 0.64, 0.40$ for June–September, respectively; all $p < 0.001$; Fig. S3). This confirms that the summer monsoon mean EOF1 and PC1 well represent the dominant mode of TPS variability during the summer monsoon months. The observed temporal persistence suggests that TPS anomalies exert sustained thermal forcing on the atmosphere, underscoring the importance of examining their impacts on tropical circulation and Afro-Asian summer monsoon precipitation.

Supplementary Figures

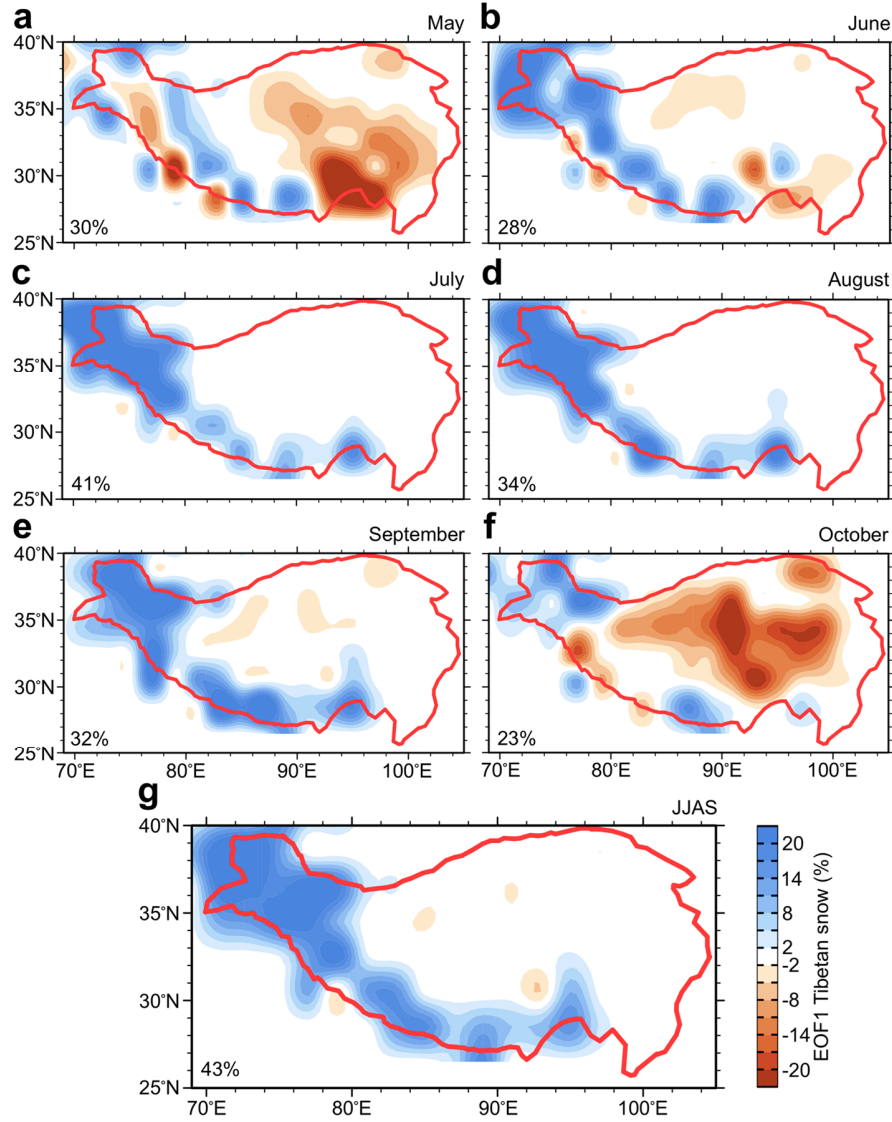


Figure S1. Consistent leading mode of TPS during the summer monsoon season. (a–f) Spatial patterns of the first Empirical Orthogonal Function (EOF1) mode for Tibetan Plateau snow cover in each month from May to October (1979–2023). (g) Spatial pattern of EOF1 for the June–September mean Tibetan Plateau snow cover (TPS) over 1979–2023. The percentage value in each panel indicates the variance explained by the EOF1 mode. Data sources: NOAA satellite snow cover.

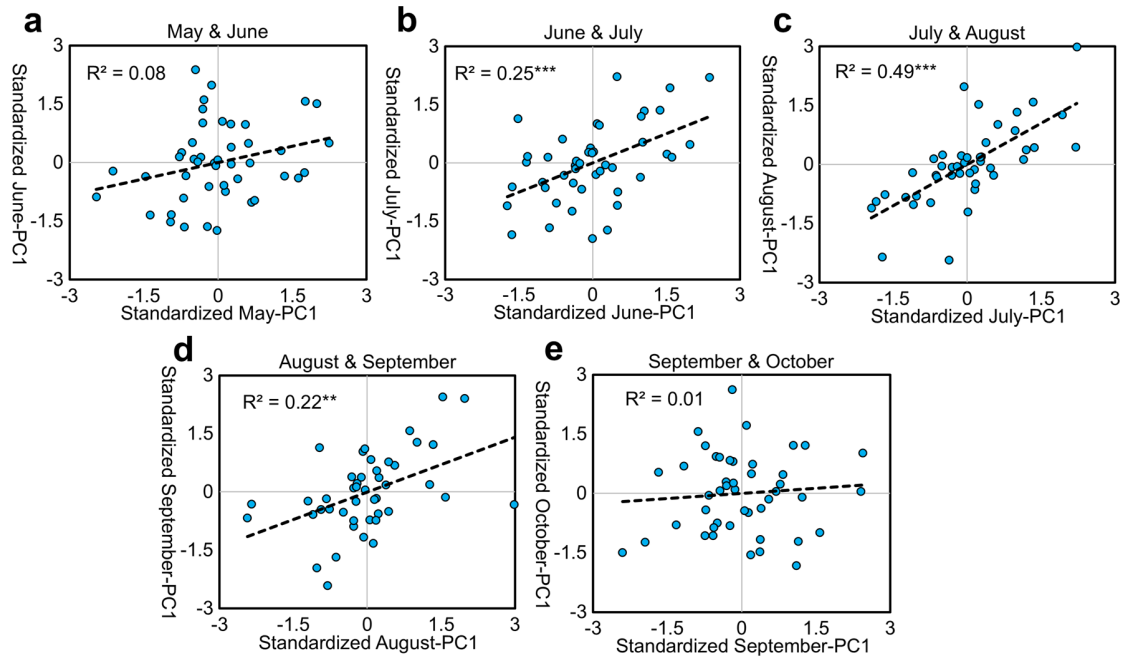


Figure S2. Consistent temporal variability of the TPS first principal component (PC1-TPS) from June to September. Scatters plots illustrate the relationship of PC1-TPS between consecutive months: (a) May and June, (b) June and July, (c) July and August, (d) August and September, and (e) September and October. Each panel shows the coefficient of determination (R^2). Significance levels are denoted by ** for $p < 0.05$ and *** for $p < 0.01$. All correlations are calculated at the interannual scale. Data sources: NOAA satellite snow cover.

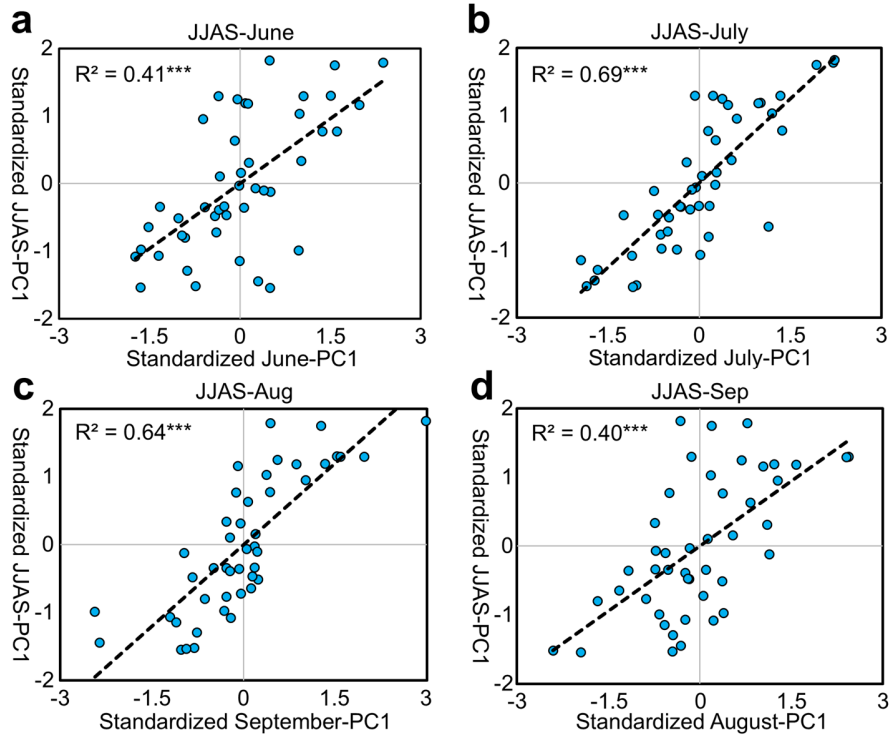


Figure S3. Relationship between the summer monsoon mean PC1-TPS and its monthly components. Scatter plots of June-September mean PC1-TPS versus the corresponding monthly values in (a) June, (b) July, (c) August, and (d) September. The coefficient of determination (R^2) is shown in each panel. Statistical significance is denoted by *** $p < 0.01$. All panels represent interannual correlations. Data sources: NOAA satellite snow cover.

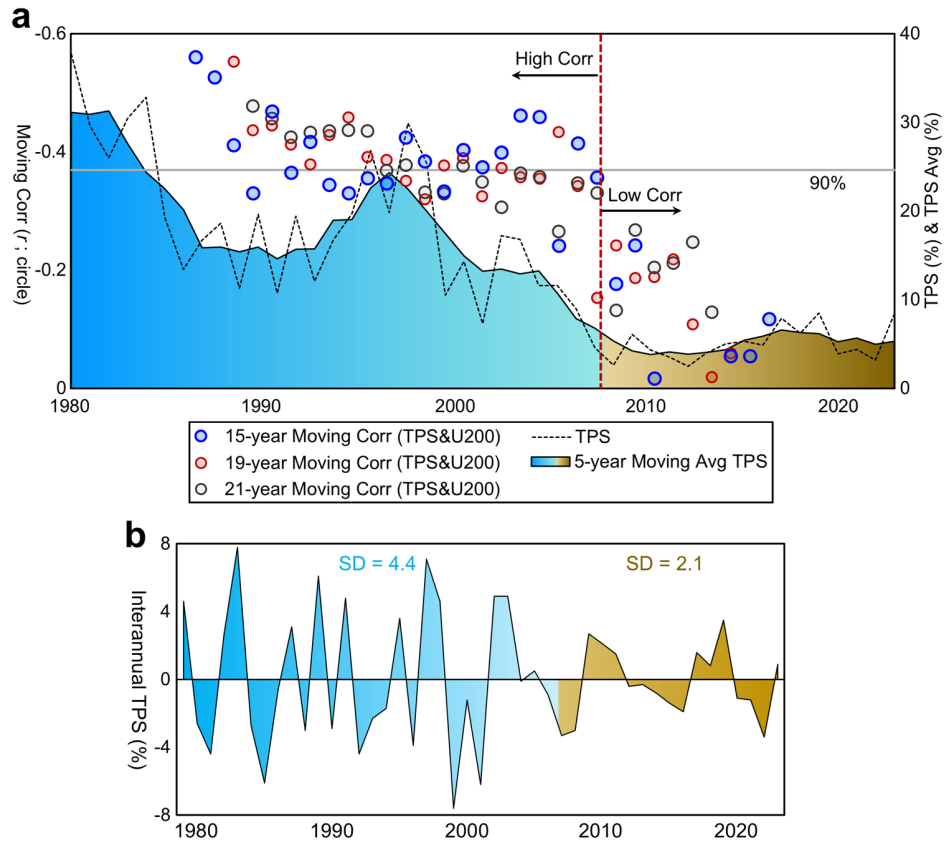


Figure S4. (a) The 15, 19, and 21 years moving correlation (dots) between TPS and TEJ time series on the interannual scale, overlaid with time series of TPS (dashed line) and its 5-year moving mean (colored curve). (b) Time series of interannual variability in TPS.

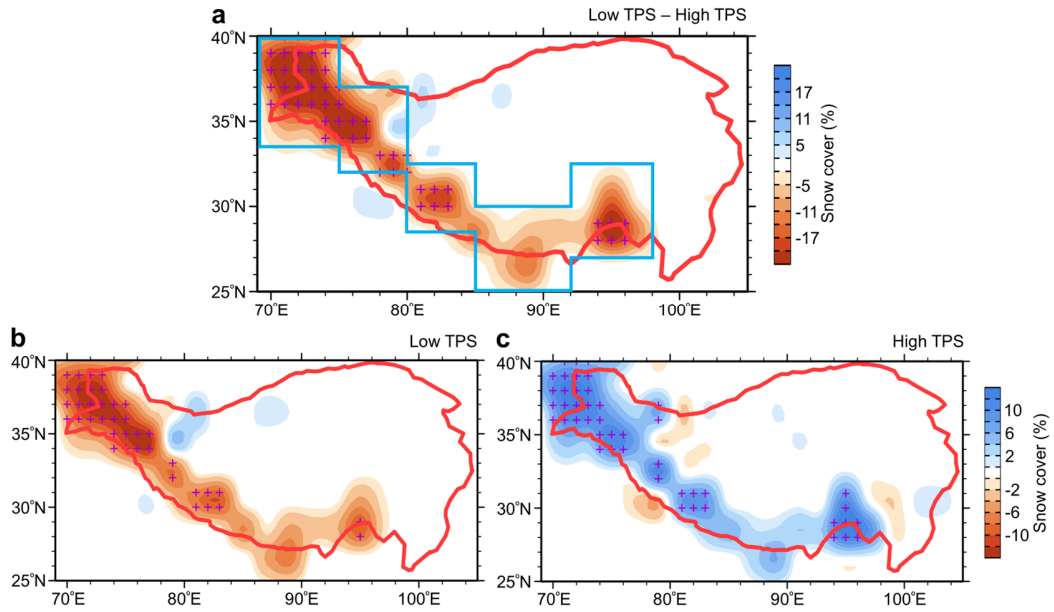


Figure S5. Spatial patterns of summer monsoon TPS anomalies. (a) Composite snow cover anomalies derived as the difference between extreme low-TPS and high-TPS years. The blue boxes mark the TPS hotspot region. (b) Composite snow cover anomalies calculated as the difference between extreme low-TPS years and climatological TPS. (c) As in (b), but for extreme high-TPS years. Plus signs denote regions where anomalies are statistically significant as the 95% confidence level ($p < 0.05$). All analyses are performed at the interannual scale.

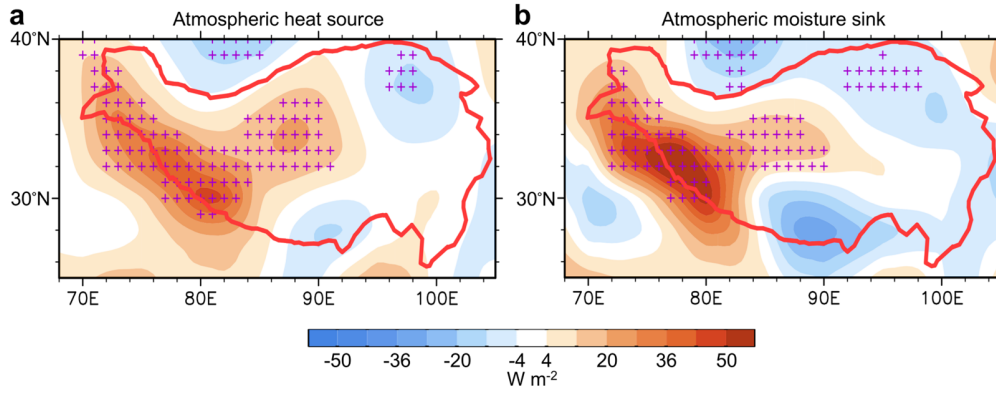


Figure S6. Atmospheric heating anomalies associated with extreme TPS conditions during the summer monsoon season. Composite anomalies of the (a) atmospheric heat source (Q_1) and (b) moisture sink (Q_2), derived from the difference between extreme low-TPS and high-TPS years. Plus signs denote regions where anomalies are statistically significant at the 95% level ($p < 0.05$). All analyses are performed at the interannual scale.

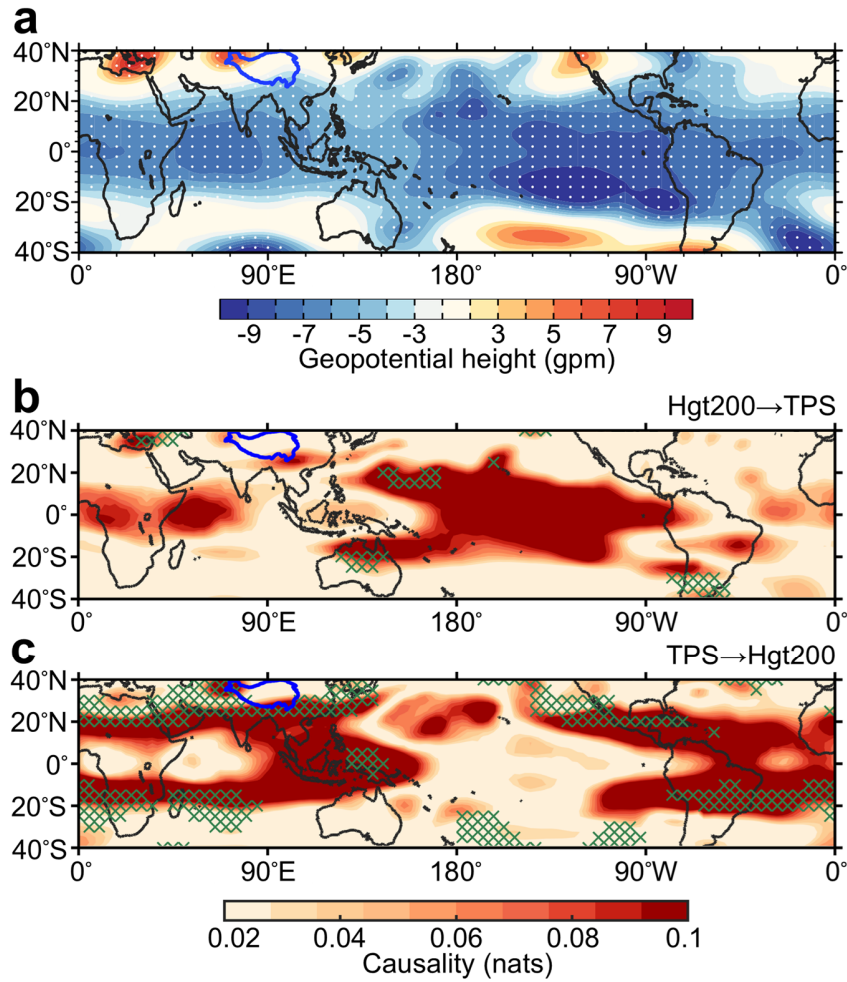


Figure S7. Causality between summer monsoon TPS and tropical geopotential height. (a) Anomalies in the 200 hPa geopotential height field obtained by regressing against the negative PC1-TPS. (b) Causal effect of the 200 hPa geopotential height field on TPS, shown as information flow from the height field to PC1-TPS. (c) Causal effect of TPS on the 200 hPa geopotential height field, shown as information flow from PC1-TPS to the height field. Regions marked with white dots or green crosses are statistically significant at the 95% confidence level ($p < 0.05$). All analyses are conducted at the interannual scale.

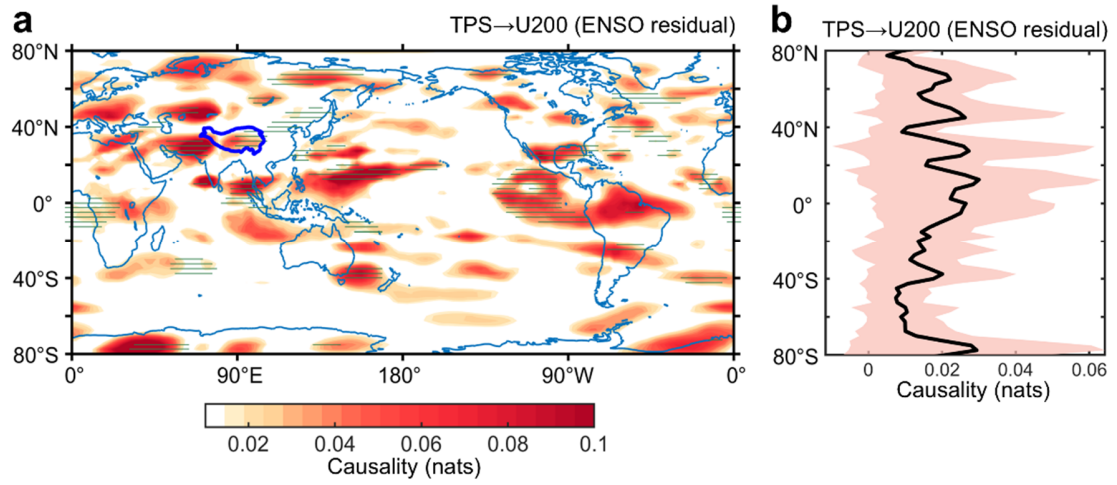


Figure S8. Detecting TPS–U200 causality during the summer monsoon. (a) ENSO-adjusted residual information flow from the leading principal component of TPS to 200 hPa zonal winds (U200) during 1979–2023 (TPS→U200 causality), computed after linearly removing the Niño3 index from both TPS and U200. Stippling denotes statistical significance ($p < 0.05$). (b) Zonal mean of the TPS→U200 causality after linearly removing the Niño3 index, with shading for ± 1 standard deviation. The first principal component of TPS is from EOF analysis of summer monsoon TPS.

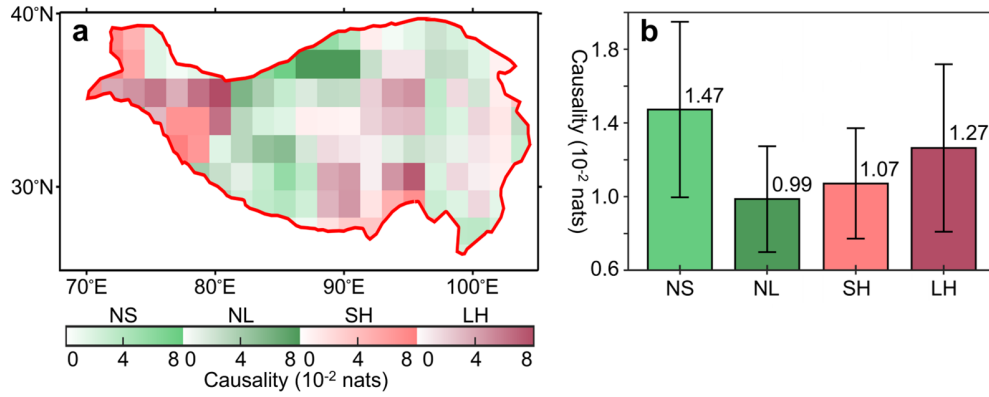


Figure S9. Causal impacts of summer monsoon TPS on atmospheric energy fluxes. (a) Maps of the dominant TPS-to-energy (TPS→energy) causality during 1979-2023, quantified by information flow with the largest magnitude among four energy flux components: net surface shortwave radiation (NS) and longwave radiation (NL), sensible heat (SH), and latent heat (LH). The red contour outlines the Tibetan Plateau. (b) Spatial average TPS→energy causality over the Tibetan Plateau for each energy type, with error bars representing the 95% confidence interval.

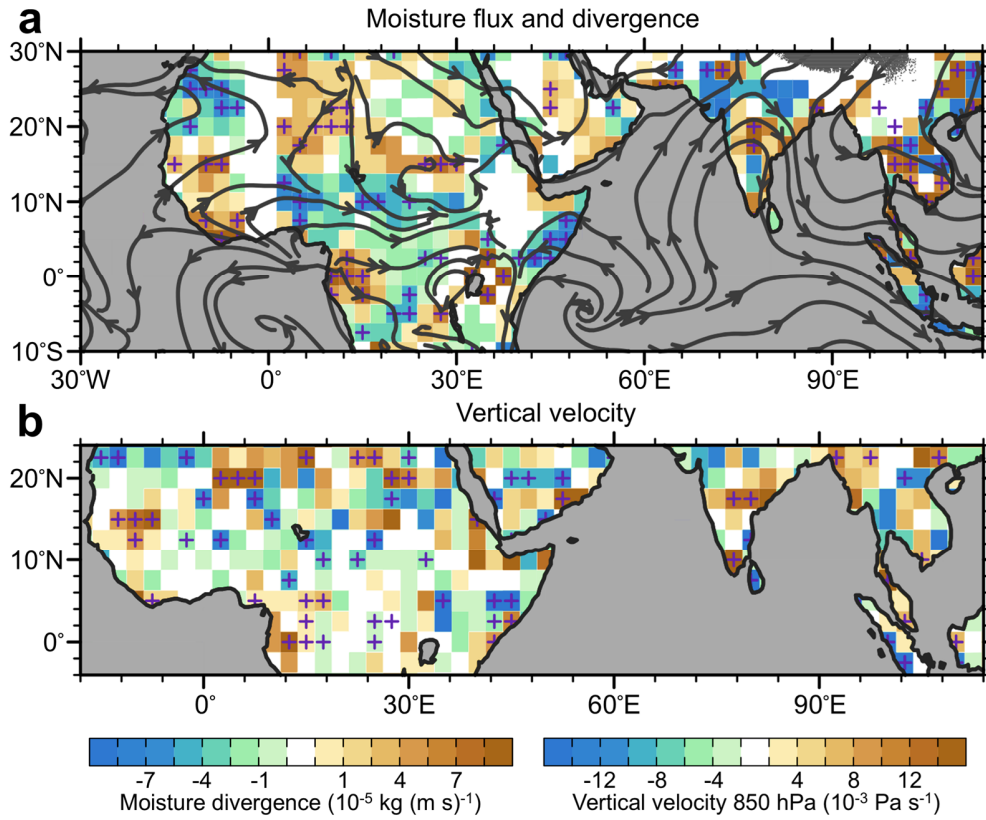


Figure S10. Moisture and vertical motion processes associated with reduced TPS during the summer monsoon. (a) Composite difference in vertically integrated moisture divergence (surface to 850 hPa; shading) and water vapor flux between extreme low- and high-TPS years from ERA5, with extreme Niño 3 events removed. Stippling indicates significant moisture anomalies ($p < 0.05$). (b) As in (a), but for 850 hPa vertical velocity (omega).

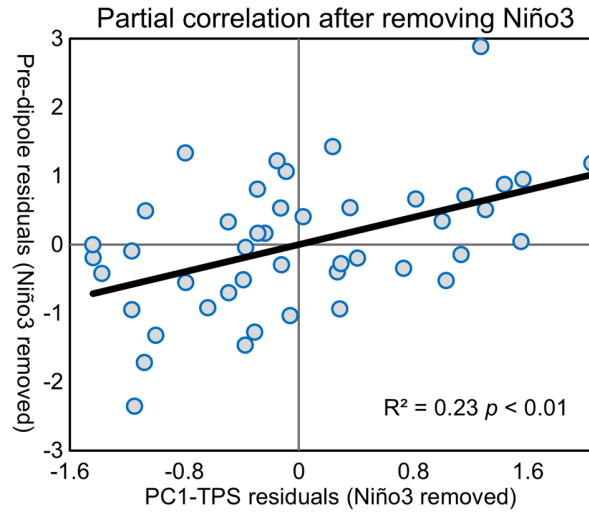


Figure S12. Scatter plot of the residuals of PC1-TPS against those of the Pre-dipole index after removing the linear effect of Niño3. The solid line represents the least-squares linear fit, and the partial correlation coefficient and its significance level are given. Pre-dipole index is the standardized interannual difference between precipitation over (South Asia; 73°–80°E, 9°–19°N) and (Tropical Africa; 10°–35°E, 0°–10°N). Both the Pre-dipole and the PC1-TPS indices were standardized and filtered to retain only year-to-year variability (with decadal signals removed by detrending and applying a 8-year high-pass filter). Each of the precipitation dipole and PC1-TPS indices was regressed against Niño 3, and the residuals were retained; the Pearson correlation between the two residual series then gives the partial correlation coefficient.

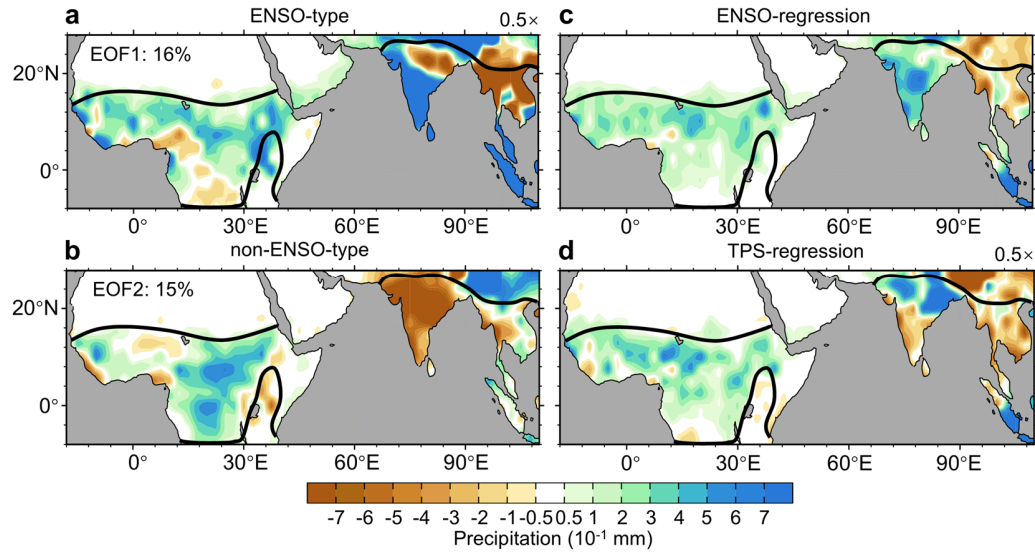


Figure S13. Dominant modes of Afro-Asian summer monsoon precipitation. (a) First mode and (b) second mode derived from EOF analysis. The numbers in the panels represent the percentage of total variance explained by each mode. (c) Summer monsoon precipitation anomalies derived from regression onto the Niño 3 index (multiplied by -1). (d) As in (c), but for the PC1-TPS (multiplied by -1). The number in the top-right corner of the panel indicates the scaling factor by which the values in the spatial map should be multiplied. The solid black lines denote the summer monsoon domain³.

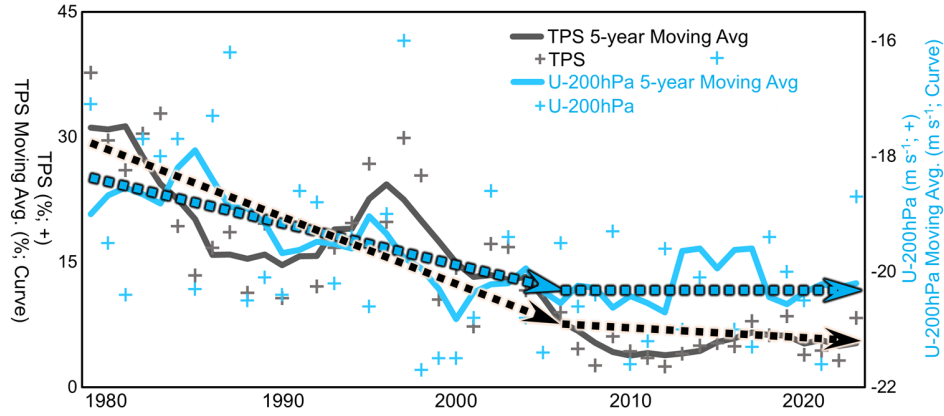


Figure S14. Temporal evolution of summer monsoon TPS and TEJ. Time series of TPS (black +) and TEJ (blue +), averaged over the TPS hotspot (boxes in Fig. S5a) and the TEJ core region (45°E-90°E; 0°-15°N), respectively. Their 5-year running means are shown as solid black curve and blue curve. Arrows schematically illustrate the corresponding trends.

Supplementary Table S1. Extreme TPS years selected for composite analysis.

Period	Extreme low-TPS years	Extreme high-TPS years
1979-2006	1980 (-1.1), 1981 (-1.3), 1985 (-1.5), 1988 (-1.1), 1990 (-1.2), 1992 (-1.5), 1996 (-1.0), 1999 (-1.6), 2001 (-1.6)	1979 (1.3), 1982 (1.3), 1983 (1.8), 1987 (1.0), 1989 (1.8), 1991 (1.8), 1995 (1.3), 1997 (1.2), 1998 (1.3), 2002 (1.2), 2003 (1.2)
2007-2023	2008 (-1.0)	2019 (1.0)

Note: Extreme years are identified based on the standardized PC1-TPS being ≤ -1.0 or $\geq +1.0$ standard deviations. Values in brackets are the standard deviation of the standardized PC1-TPS.

Supplementary References:

1. Hill, S. A., *et al.* More extreme Indian monsoon rainfall in El Niño summers. *Science*. **389**, 1220-1224 (2025).
2. Sun, J., *et al.* Causal pathways underlying global soil moisture–precipitation coupling. *Nat. Commun.* **16**, 8935 (2025).
3. Jianping, L. & Qingcun, Z. A new monsoon index and the geographical distribution of the global monsoons. *Adv. Atmos. Sci.* **20**, 299-302 (2003).