

Teleconnections among tipping elements in the Earth system

In the format provided by the
authors and unedited

- Robust strongly localized planetary impact pattern of the ARA during ENSO period
- Propagation pathway of the teleconnection between the ARA and West Antarctic
- Figs. S1 to S18
- Tables. S1 to S2

I. ROBUST STRONGLY LOCALIZED PLANETARY IMPACT PATTERN OF THE ARA DURING ENSO PERIOD

In order to confirm the strongly localized planetary impact pattern of the ARA is robust during ENSO period, we constructed a sequence of networks based on successive windows of lengths of 1 year, with a sliding window 1 month. We defined N^m as the number of nodes influenced by the ARA, C^m as the average in-weights per node, which is given by following:

$$C^m = \sum_{i \in \text{ARA}} \sum_{j \notin \text{ARA}} A_{i,j}^m |C_{i,j}^m(\sigma_0)| / N^m \quad (1)$$

where m stands for the month. Similarly, we defined W^m as the average in-strengths per node:

$$W^m = \sum_{i \in \text{ARA}} \sum_{j \notin \text{ARA}} A_{i,j}^m |W_{i,j}^m| / N^m \quad (2)$$

Considering the heterogeneity of temperature rise in ARA, we find that the in-degree of nodes outside the ARA are not always equal to zero. Therefore, here we chose a series of percentiles (20%, 30%, 40%, 50%) of 1374 (the total number of nodes in ARA) as thresholds. If the node's in-degree is lower than the above threshold, we consider this node does not be influenced by ARA.

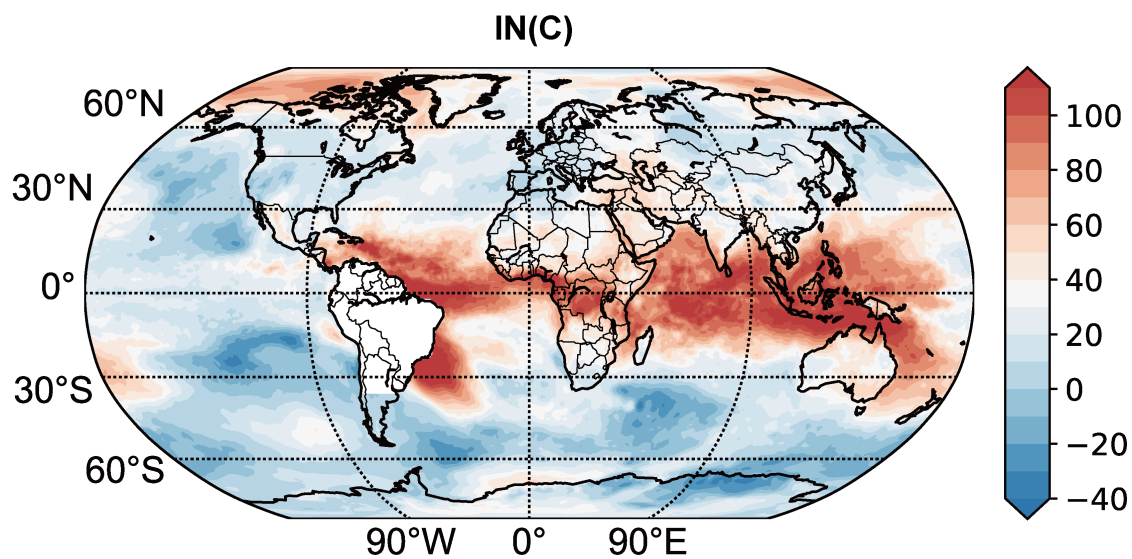
Fig. S3 shows the 3-month running average of N^m , C^m and W^m under various thresholds. We find that the strongly (higher C and W) localized (lower N^m) planetary impact pattern of the ARA is robust during ENSO periods. In contrast to non-ENSO periods, these stronger in-weighted activities are found to be concentrated in very localized areas, whereas a large fraction of the globe is not influenced by the events.

II. PROPAGATION PATHWAY OF THE TELECONNECTION BETWEEN THE ARA AND WEST ANTARCTIC

The accelerating and persistent mass loss in the Antarctic Ice Sheet, especially the West Antarctic Ice Sheet (WAIS), bring huge uncertainties in predicting and projecting a future sea-level rise in this and upcoming centuries. Model studies and palaeo-evidence [1] support that the widespread collapse of WAIS is a ‘low likelihood high impact’ event, and some regions of the ice sheet may reach tipping points with a warming climate [2]. In this study, the high intensity of the nodes within WAIS in Fig. 3b indicates the existence of stable negative teleconnection between these two well-known tipping elements, ARA and WAIS. The potential propagation paths for this teleconnection with various datasets have been shown in Fig. S11. The path length is close to ten thousand kilometers (the great-circle distance between the ARA and West Antarctic is about six thousand kilometers). We find that the path can be explained by the steady and strong ocean currents and westerly winds near the West Antarctic area. This implies that the transportation of substances, like dust and carbonaceous aerosols, is likely to cause this teleconnection. This hypothesis is supported by Antarctic pollution studies [3] where the increased dust mobility in ARA caused by overgrazing and deforestation has a certain impact on West Antarctic pollution. Besides TP and WAIS, the paths of two more locations that show high impact signals from ARA have been considered in Fig. S12.

-
- [1] Feldmann, J. & Levermann, A. Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences* **112**, 14191–14196 (2015).
 - [2] Pattyn, F. & Morlighem, M. The uncertain future of the Antarctic Ice Sheet. *Science* **367**, 1331–1335 (2020).
 - [3] McConnell, J. R., Aristarain, A. J., Banta, J. R., Edwards, P. R. & Simoes, J. C. 20th-century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America. *Proceedings of the National Academy of Sciences* **104**, 5743–5748 (2007).

a



b

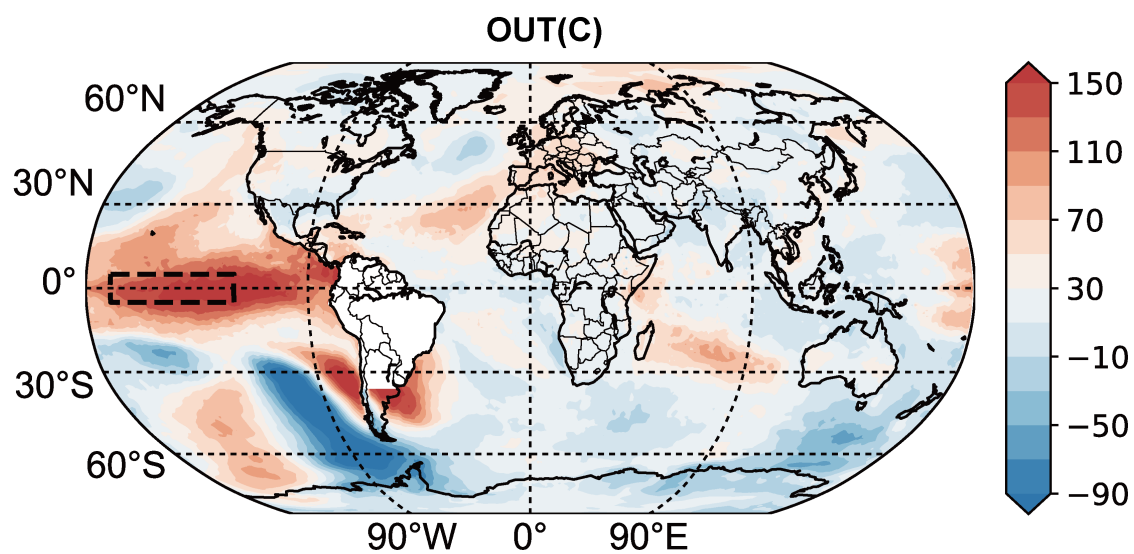


Fig. S1. The influence patterns between the ARA and the outside world for the past 40 years. The influence pattern of the ARA on inside the world (a) and outside world on ARA (b) for past 40 years (1979-2018). The area enclosed by the black dotted line is the Niño 3.4 region, which shows strong positive influence on the ARA;

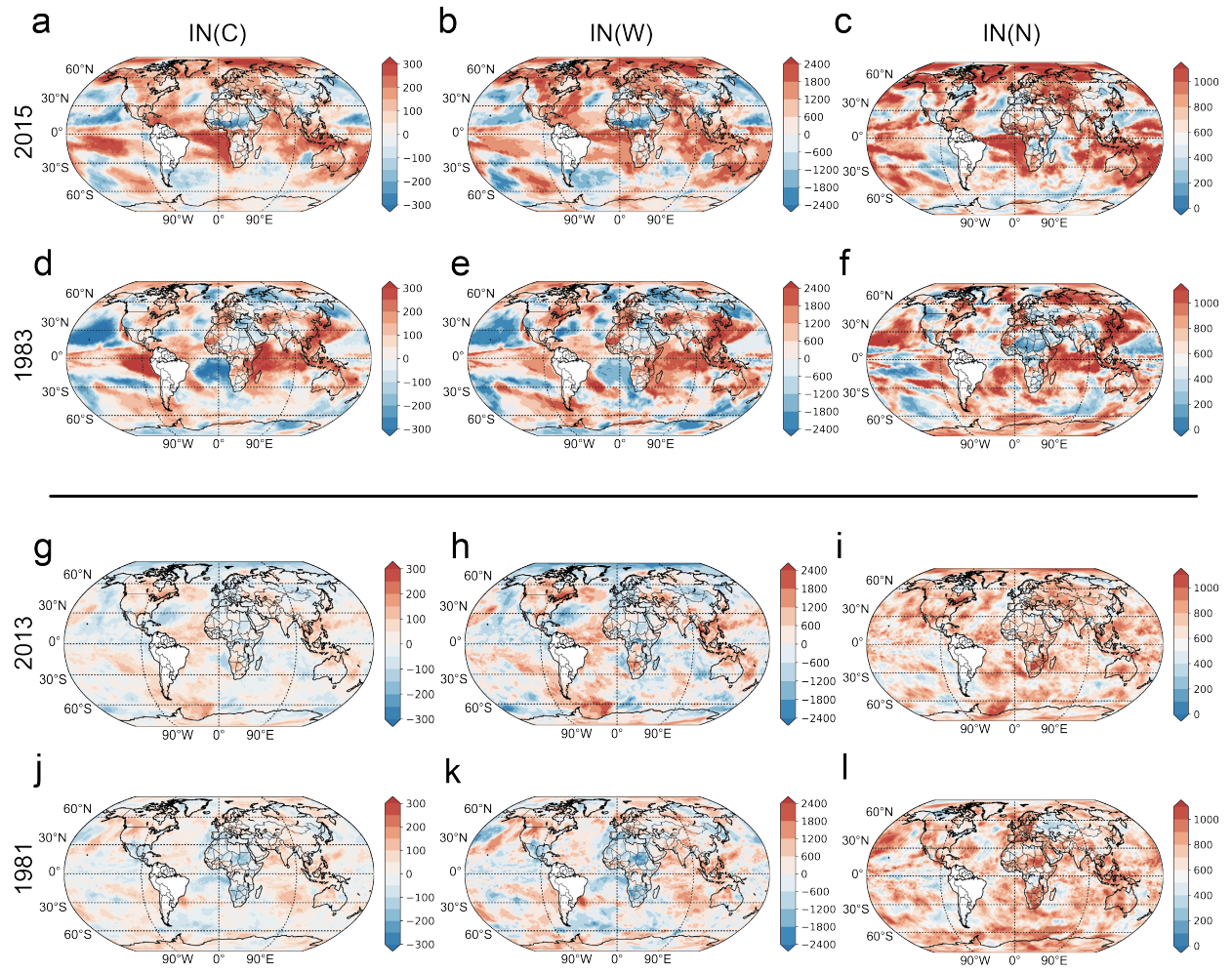


Fig. S2. The mode of ARA during ENSO years and normal years. $IN(C)$, $IN(W)$, and $IN(N)$ show a more localized and higher intensity pattern in ENSO years (2015 and 1983, **a-f**) than in normal years (2013 and 1981, **g-l**).

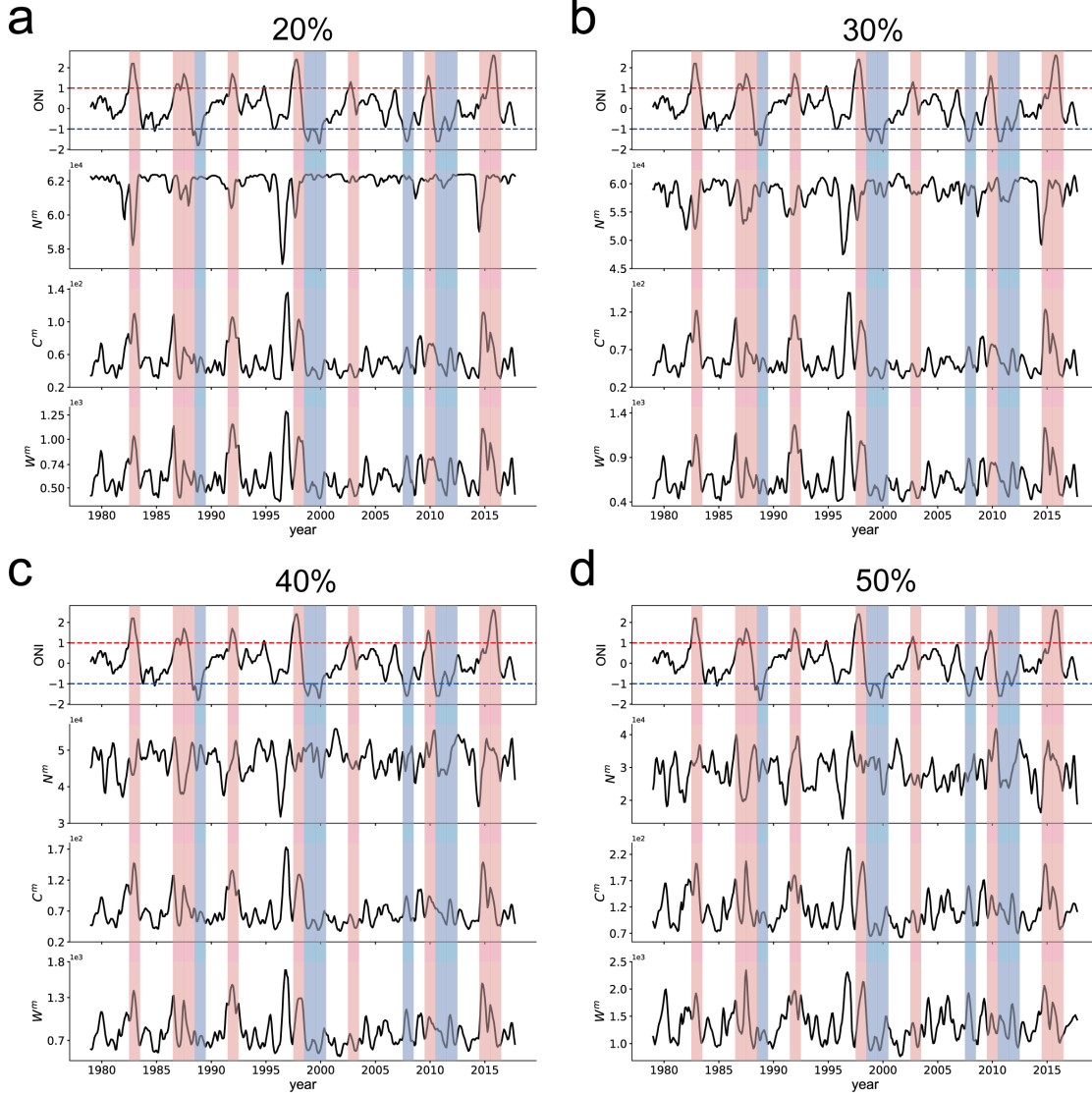


Fig. S3. Strongly localized planetary impact pattern of the ARA. El Niño index ONI, number of nodes influenced by the ARA, N^m , the average in-weights C^m and the average in-strengths W^m , are plotted as a function of time. **a-d**, The corresponding results under the thresholds of 20%, 30%, 40%, 50% percentiles. The red and blue shadings emphasize the El Niño and La Niña years (defined by the $|ONI| > 1$), respectively. We find that N^m drops dramatically during the ENSO years, indicating the total area influenced by the ARA is localized. However, the increment of C^m and W^m reveals a stronger influence from ARA.

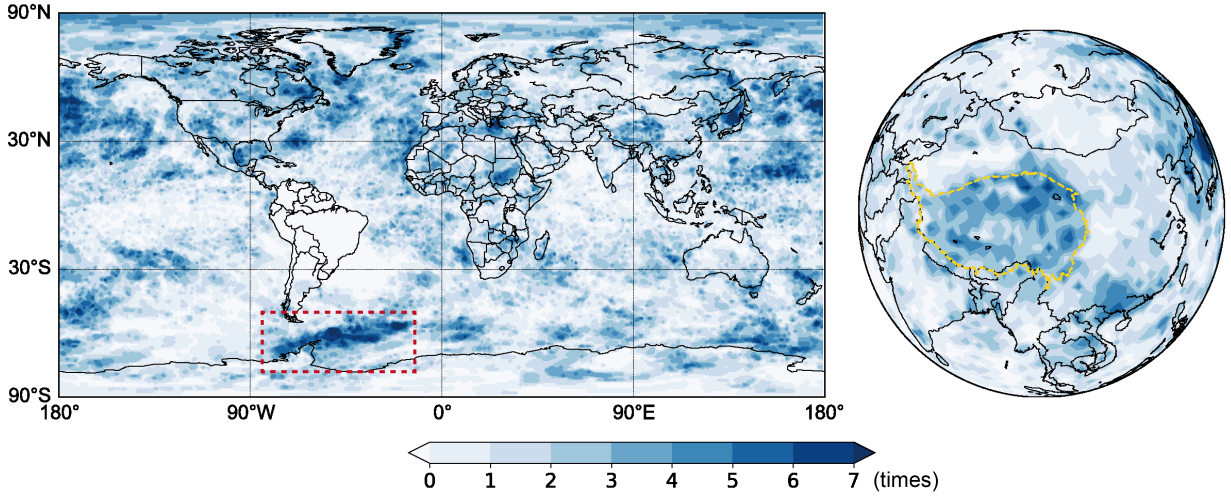


Fig. S4. The spatial distribution of $F(W)$ supports the negative teleconnection of ARA-TP and ARA-West Antarctic. $F(W)$ is defined as the frequency of the nodes with negative $IN(W)$ signal exceeds the threshold in the past 40 years. The annually changing threshold is defined as the smallest 10% negative $IN(W)$ intensity distribution. The result of $F(W)$ has a similar pattern to $F(C)$ (Fig. 3b). The nodes within the TP and the West Antarctic show high intensity, and the spatial pattern is perfectly characterised by the TP's cartographic boundary (the dashed orange line).

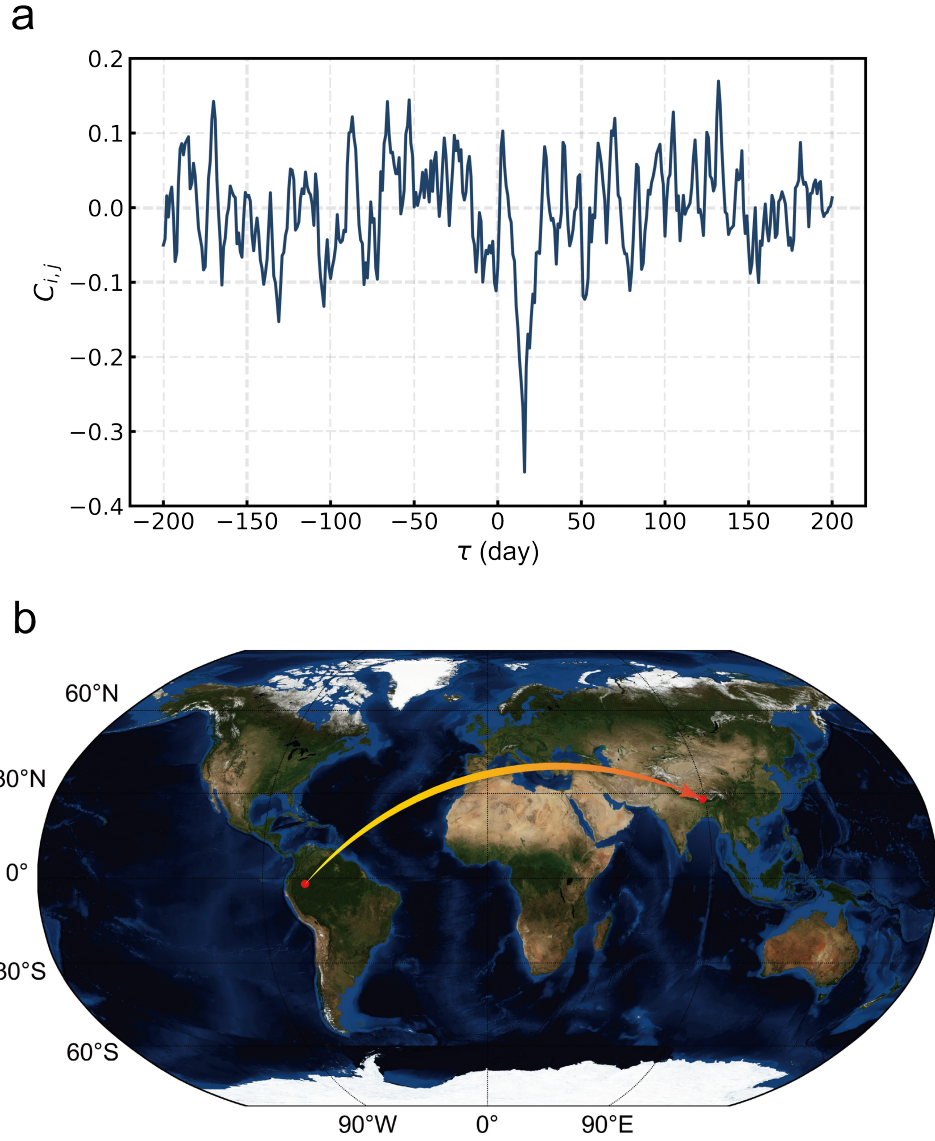


Fig. S5. **a**, A typical cross-correlation function versus the time delay for two nodes in ARA and TP. The location of the node in ARA is $(2^\circ \text{ S}, 73^\circ \text{ W})$, and the node in TP is $(28^\circ \text{ N}, 89^\circ \text{ E})$ (the red dots in **b**). The direction of the arrow shows the the interaction is from the ARA to the TP). The shown example is calculated from the temperature time series from 2002/01/01 to 2003/01/01 and shows obvious negative correlation.

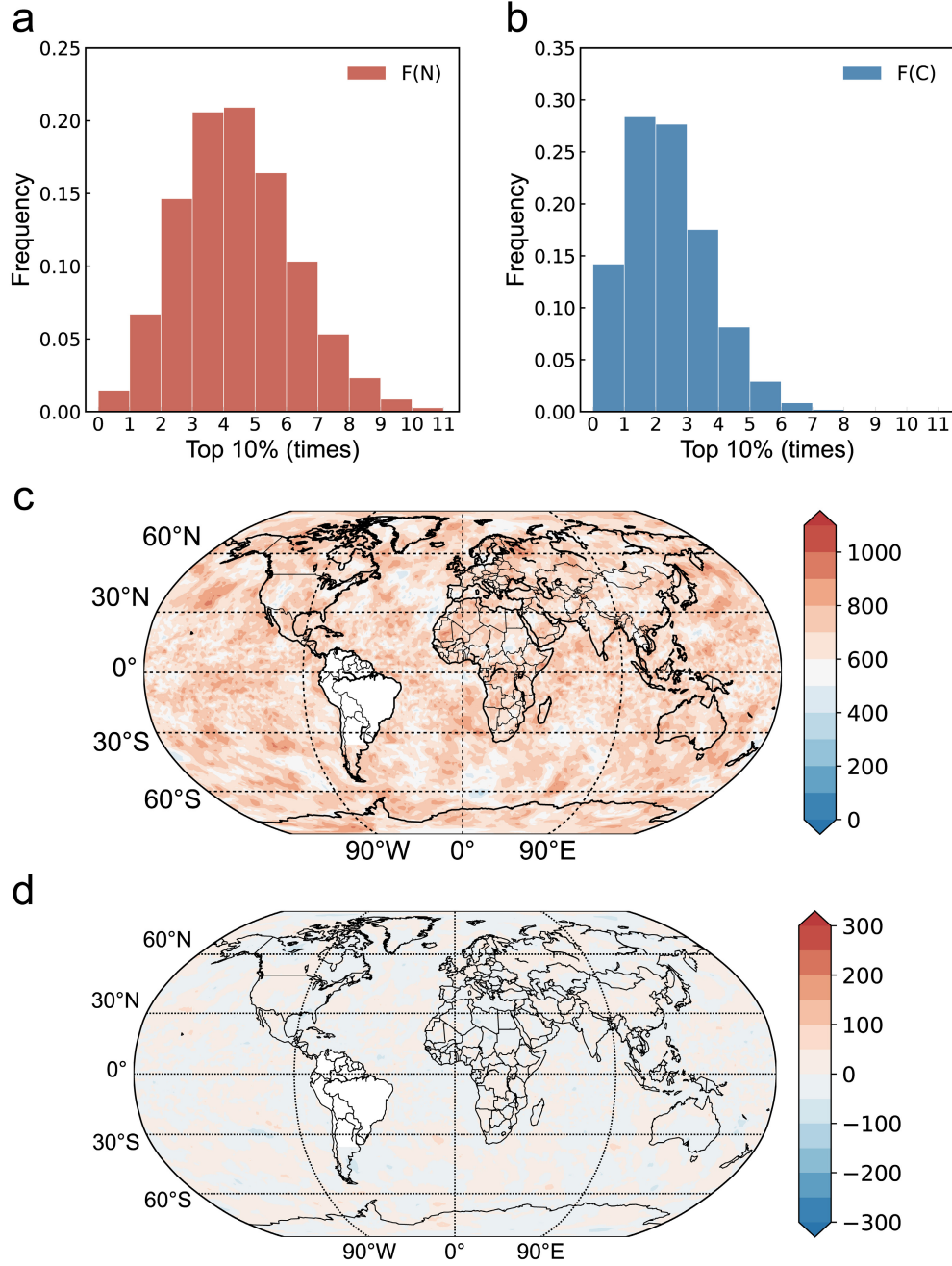


Fig. S6. Hypothesis testing results for $F(N)$ and $F(C)$. **a, b**, The histogram of frequency distribution of the $F(N)$ and $F(C)$, respectively. The results are calculated from the shuffled data, which was obtained by shuffling the real data 100 times. **c, d**, Typical examples of the $IN(N)$ and $IN(C)$ distribution of the shuffled data. The random patterns show that the intrinsic connection is broken by the shuffling process.

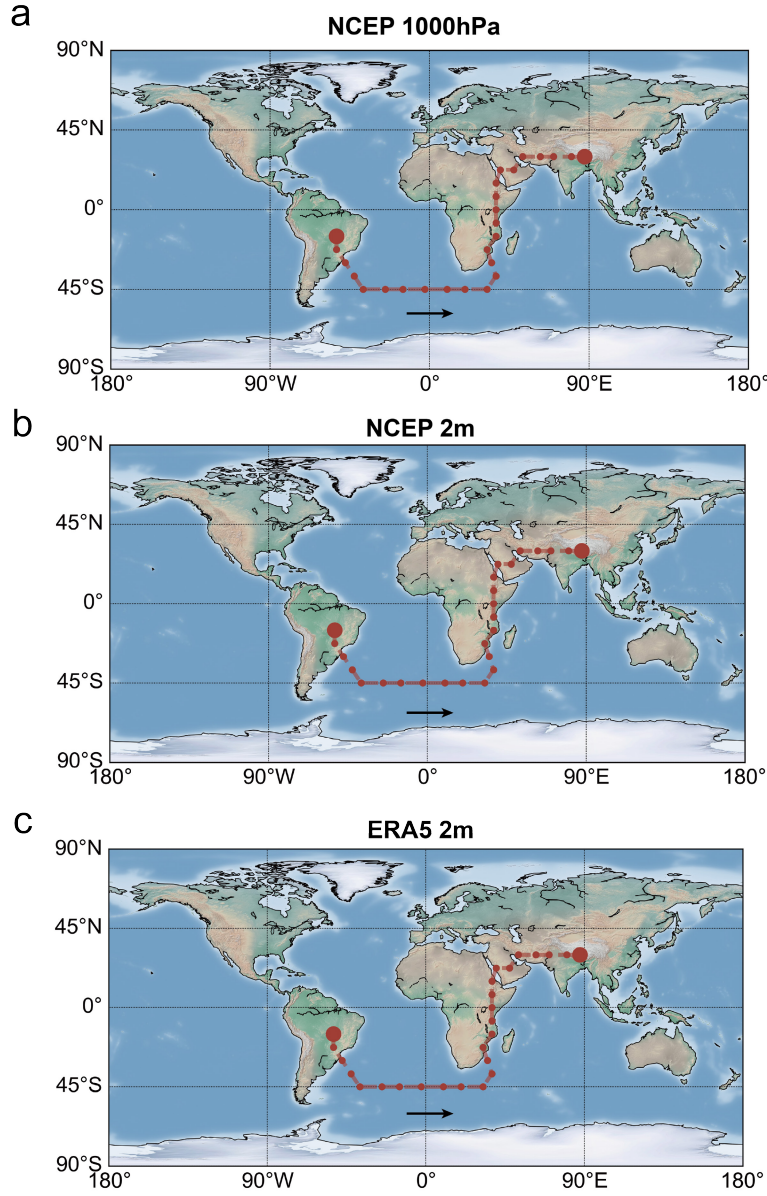


Fig. S7. The prorogation pathway of the ARA-TP teleconnection in different reanalysis datasets. The big red dots depict the starting and ending points, and the small red dots are the network nodes passed by the propagation pathway. The black arrow shows the direction of the pathway. **a-c**, The propagation paths calculated from the NCEP with 1000hPa, NCEP with 2m surface, and ERA5 with 2m surface temperature datasets, respectively.

To estimate the robustness of the optimal paths, we also calculate the second shortest paths for the ARA-TP teleconnection propagation path discussed in the main text, as shown in Fig. S8. We find that the second optimal paths are close to the first optimal paths. This suggests that the obtained first shortest paths are robust.

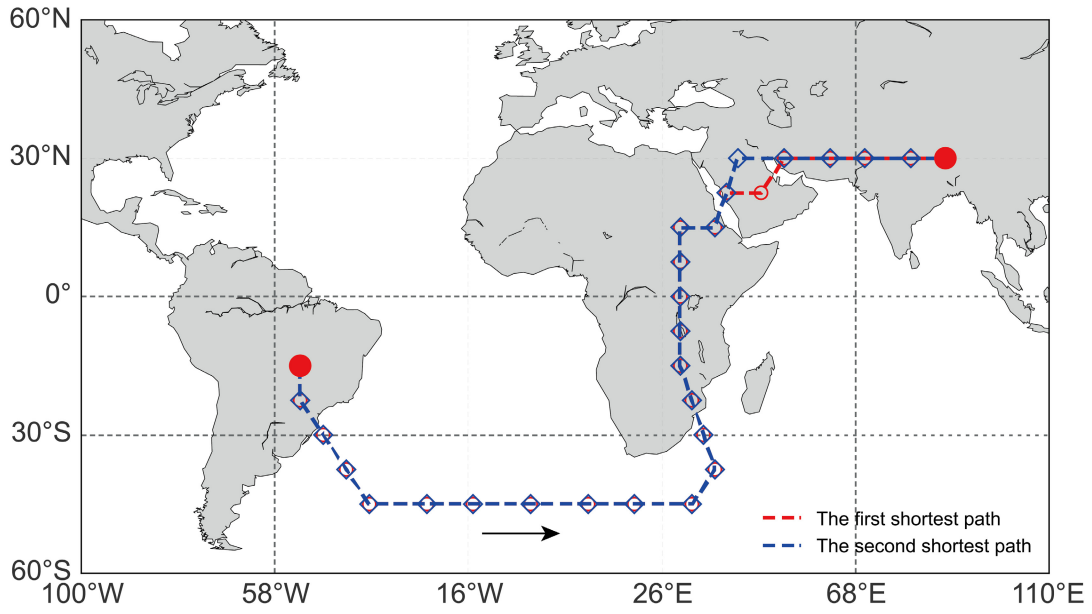


Fig. S8. (Color online) The first shortest paths (red lines with circles) and the second (blue lines with diamonds) shortest paths for the ARA-TP teleconnection.

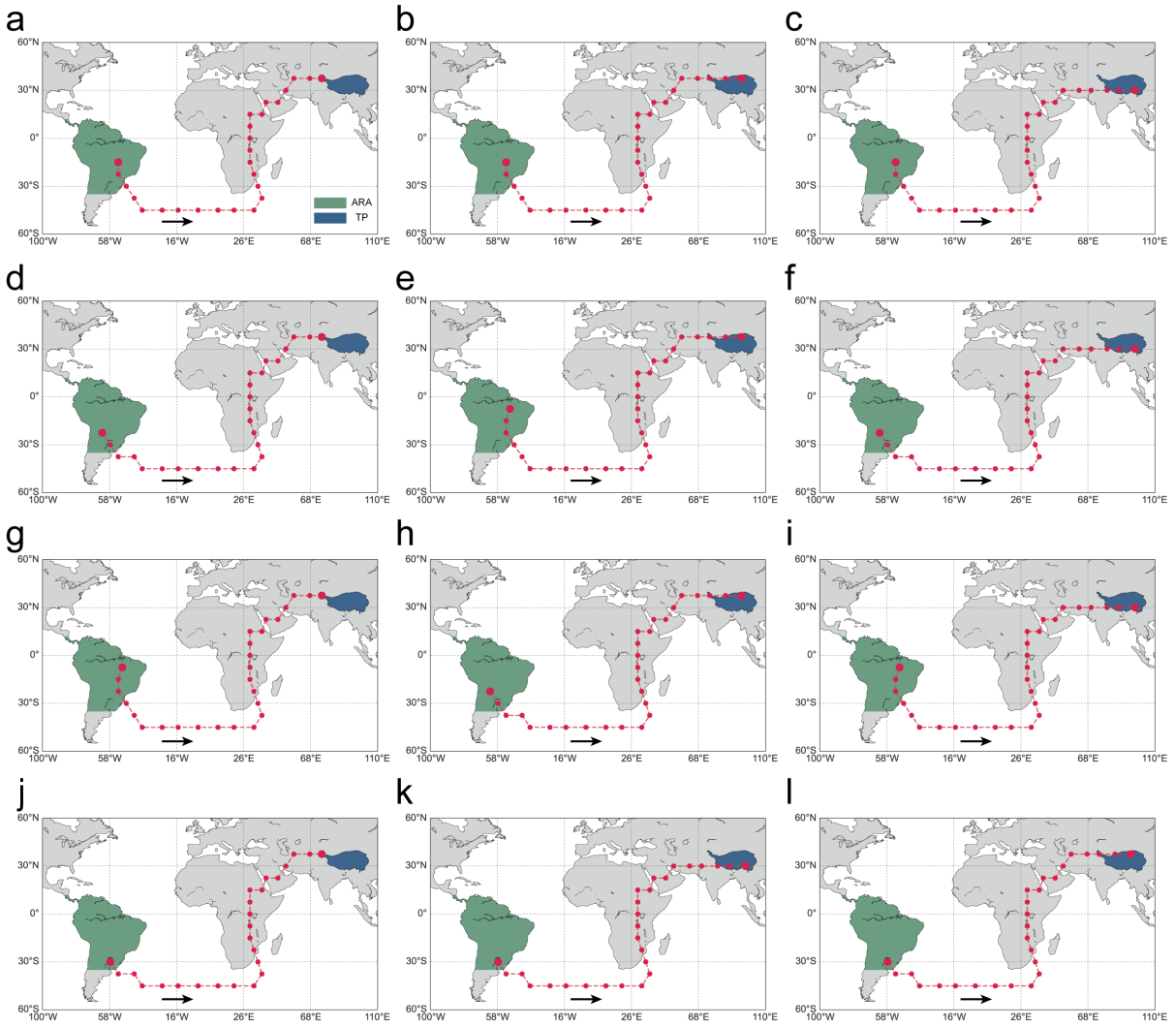


Fig. S9. The prorogation pathway of the ARA-TP teleconnection with different starting and ending nodes. The big red dots depict the staring and ending points, and the small red dots are the network nodes passed by the propagation pathway.

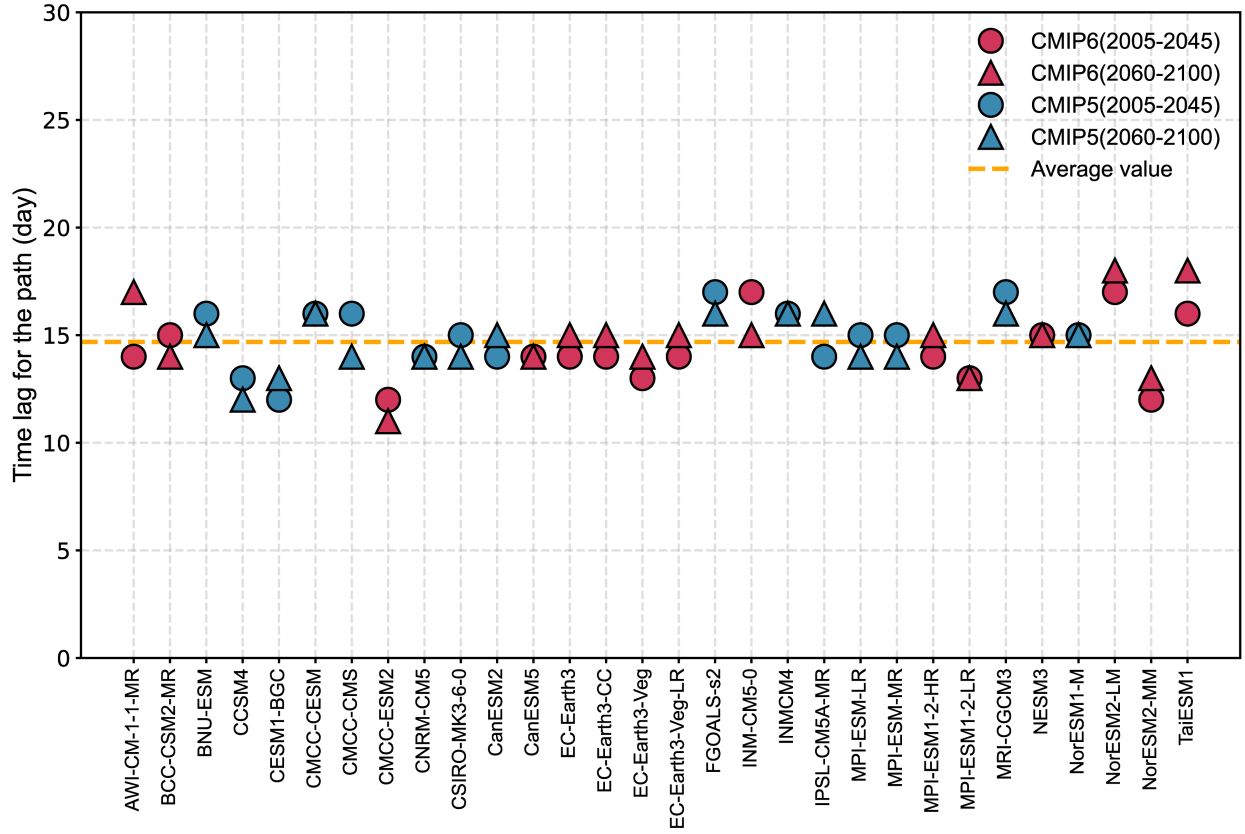


Fig. S10. The time lag of the prorogation pathway of the ARA-TP teleconnection in CMIP5 and CMIP6 models. The propagation time is calculated by summing the time lags for each individual step. The different colors show the results for CMIP5 and CMIP6, respectively. Circle and triangle labels are used to distinguish the results from the first 40 years and last 40 years of the same CMIP dataset. The orange dished line shows the average time delay with 14.7 days.

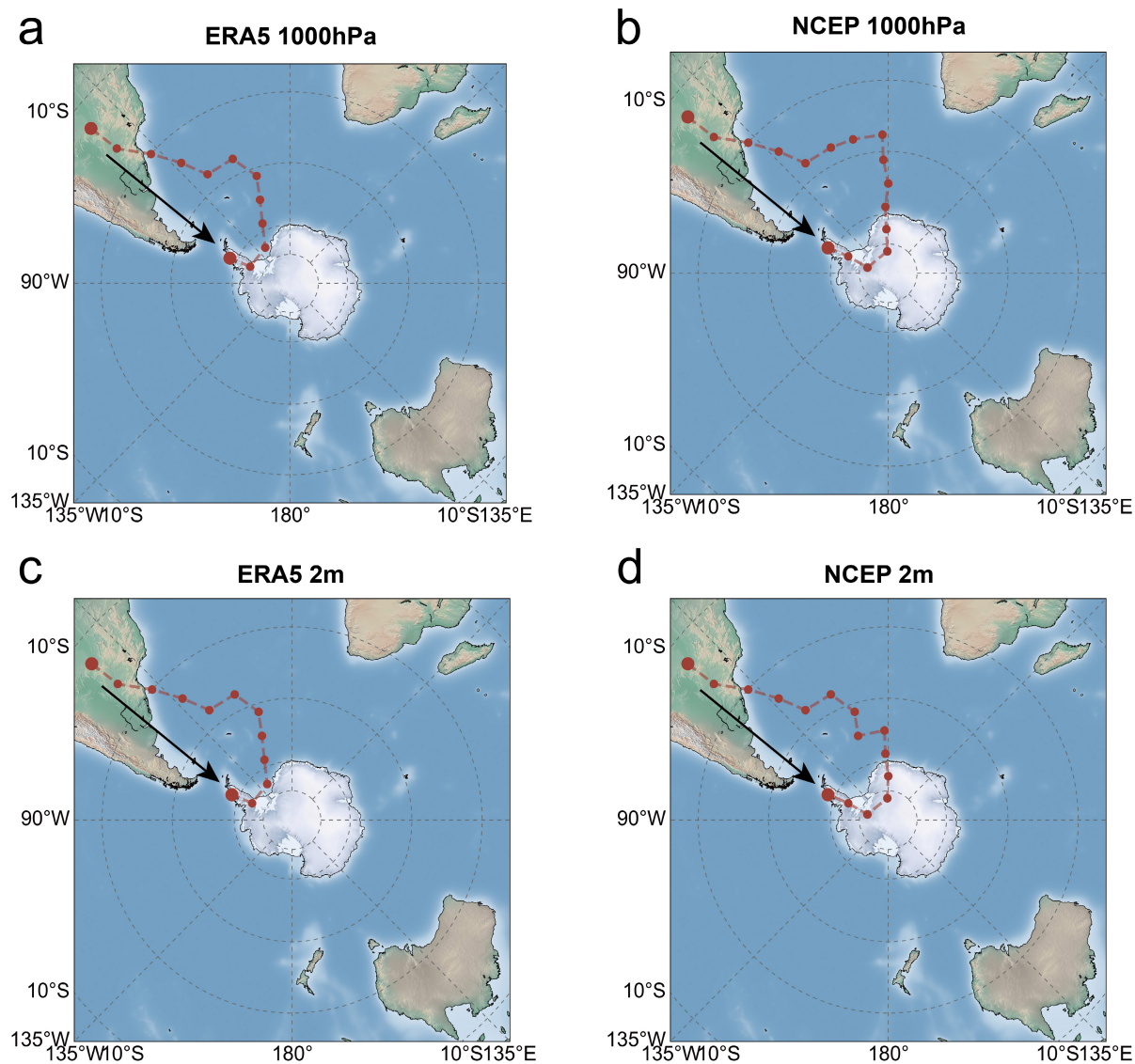


Fig. S11. The prorogation pathway of the ARA-WAIS teleconnection in different reanalysis datasets. The red dots are the network nodes passed by the propagation pathway, and the black arrows show the direction of the pathway. **a-d**, The propagation paths calculated from the ERA5 with 1000hPa, NCEP with 1000hPa, ERA5 with 2m surface and NCEP 2m surface temperature datasets, respectively.

Besides TP and WAIS, we find some other locations in the $F(N)$ distribution that exhibit high-intensity signals (Fig. S12a), implying potential teleconnections with ARA. We choose two hot spots, Central Africa and Australia (the areas marked by the yellow boxes in Fig. S12a), as examples and analyze the propagation pathways. For Central Africa, the pathway (Fig. S12b) is the same as the first half of the ARA-TP teleconnection pathway (Fig. 4a), and it is probably also caused by anticyclones at mid-latitude. For Australia (Fig. S12c), a similar pathway can be found in previous research [4], and it is probably related to Rossby waves activity in the southern hemisphere.

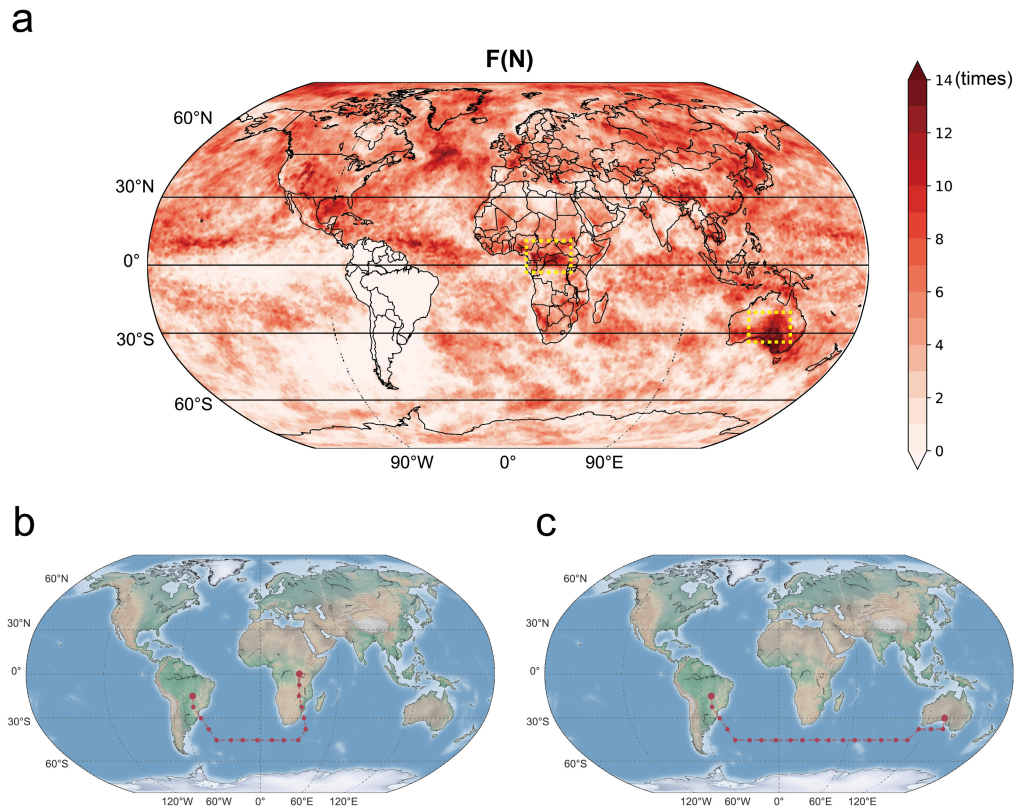


Fig. S12. Two examples of observed teleconnections and their direct link optimal pathways. **a**, The area marked by the yellow boxes show high intensity signal of $F(N)$, implying the potential connection between ARA and these area. **b**, **c**, The corresponding propagation pathways between ARA and these two area.

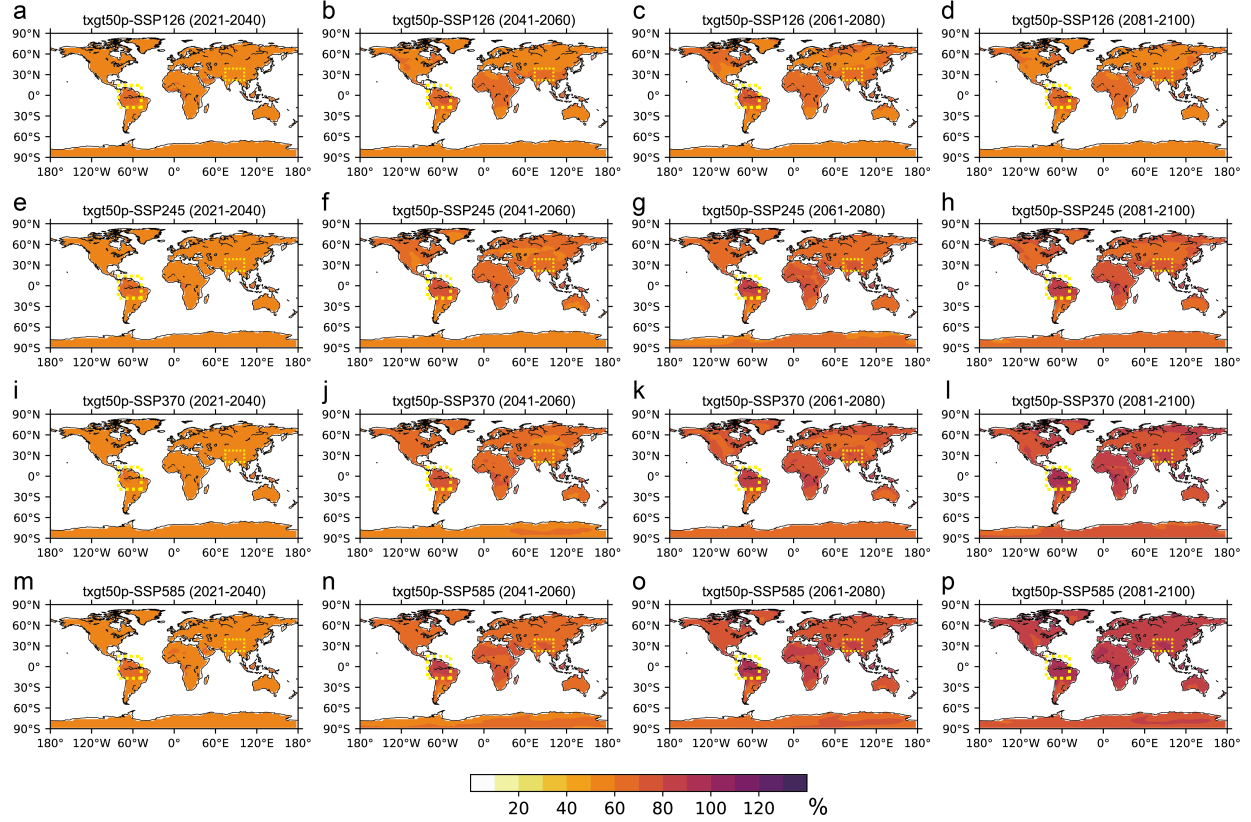


Fig. S13. The fraction of days with above-average temperature (TXgt50p) index shows a robust correlation between ARA and TP in all four scenarios (SSP126 (a)-(d), SSP245 (d)-(h), SSP 370 (i)-(l) and SSP585 (m)-(p)), especially towards the high end of the range of future pathways with a strong effective radiative forcing (SSP585). **a-d**, The results of the TXgt50p index calculated from datasets in different time periods (2021-2040, 2041-2060, 2061-2080, 2081-2100) under the scenario of SSP126; **e-h**, The corresponding results under the scenarios of SSP245; **i-l**, The corresponding results under the scenario of SSP370; **m-p**, The corresponding results under the scenario of SSP585.

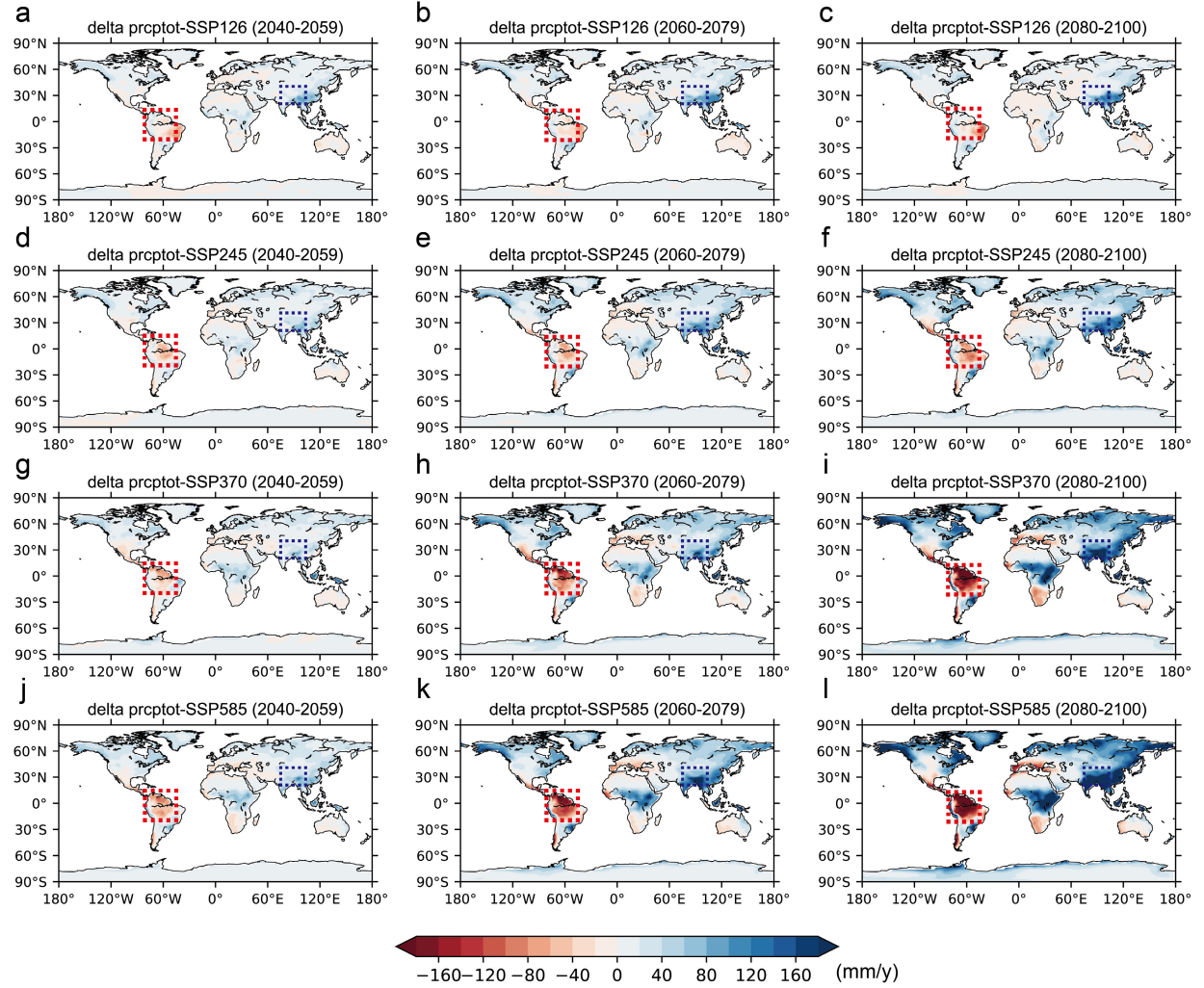


Fig. S14. The annual sum of the daily precipitation (≥ 1 mm) (PRCPTOT) index shows a robust negative correlation between ARA and TP in all four scenarios (SSP126 (a)-(c), SSP245 (d)-(f), SSP 370 (g)-(i) and SSP585 (j)-(l)). While ARA is significantly getting drier, the whole TP region is getting more precipitation in all scenarios. The increasing trend in the southern TP is particularly significant.

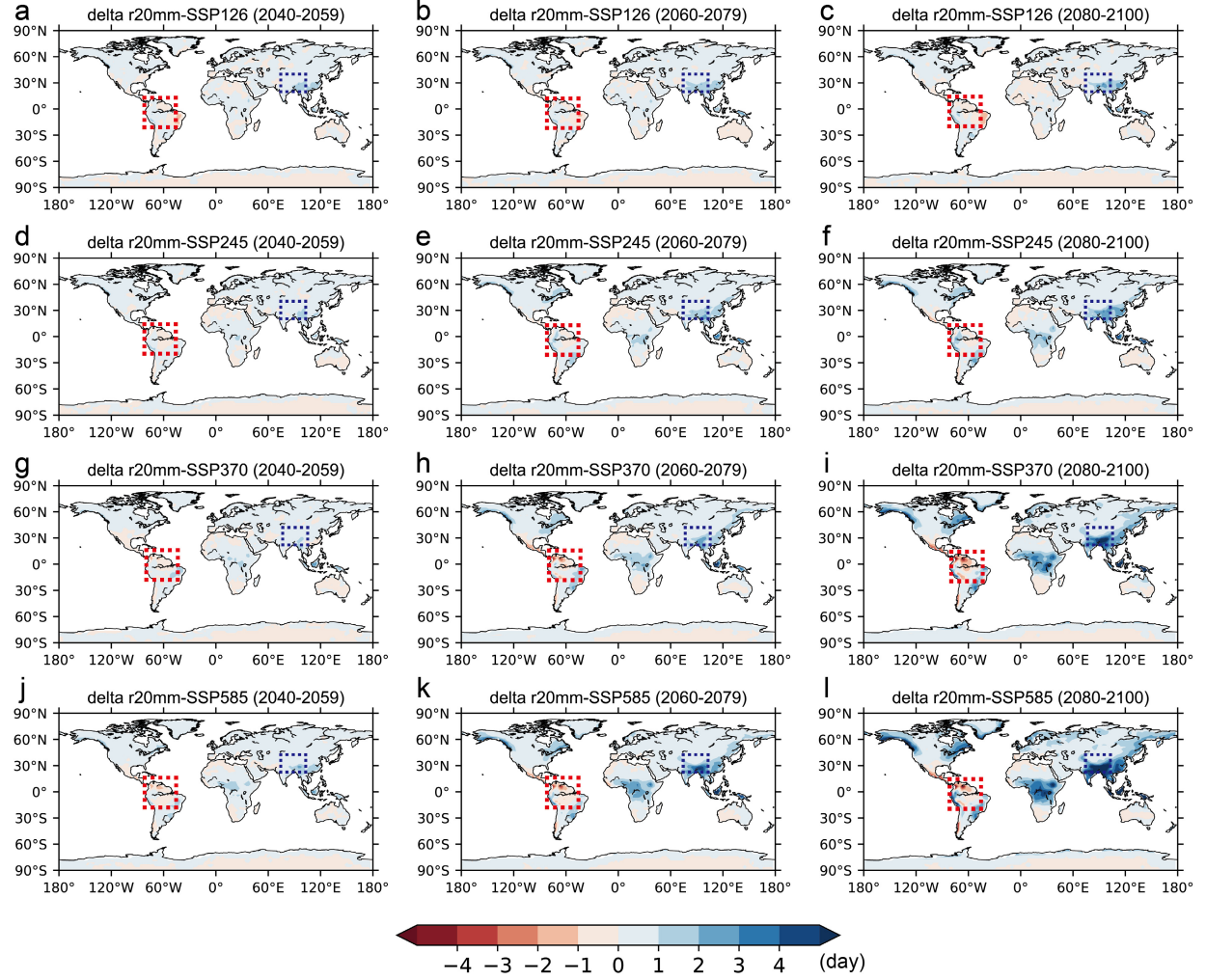


Fig. S15. The number of days with precipitation ≥ 20 mm shows a robust negative correlation between ARA and TP in all four scenarios (SSP126 (a)-(c), SSP245 (d)-(f), SSP 370 (g)-(i) and SSP585 (j)-(l)). While extreme rainfall is decreasing in ARA, TP is getting more extreme precipitation in all scenarios, especially in the southern TP.

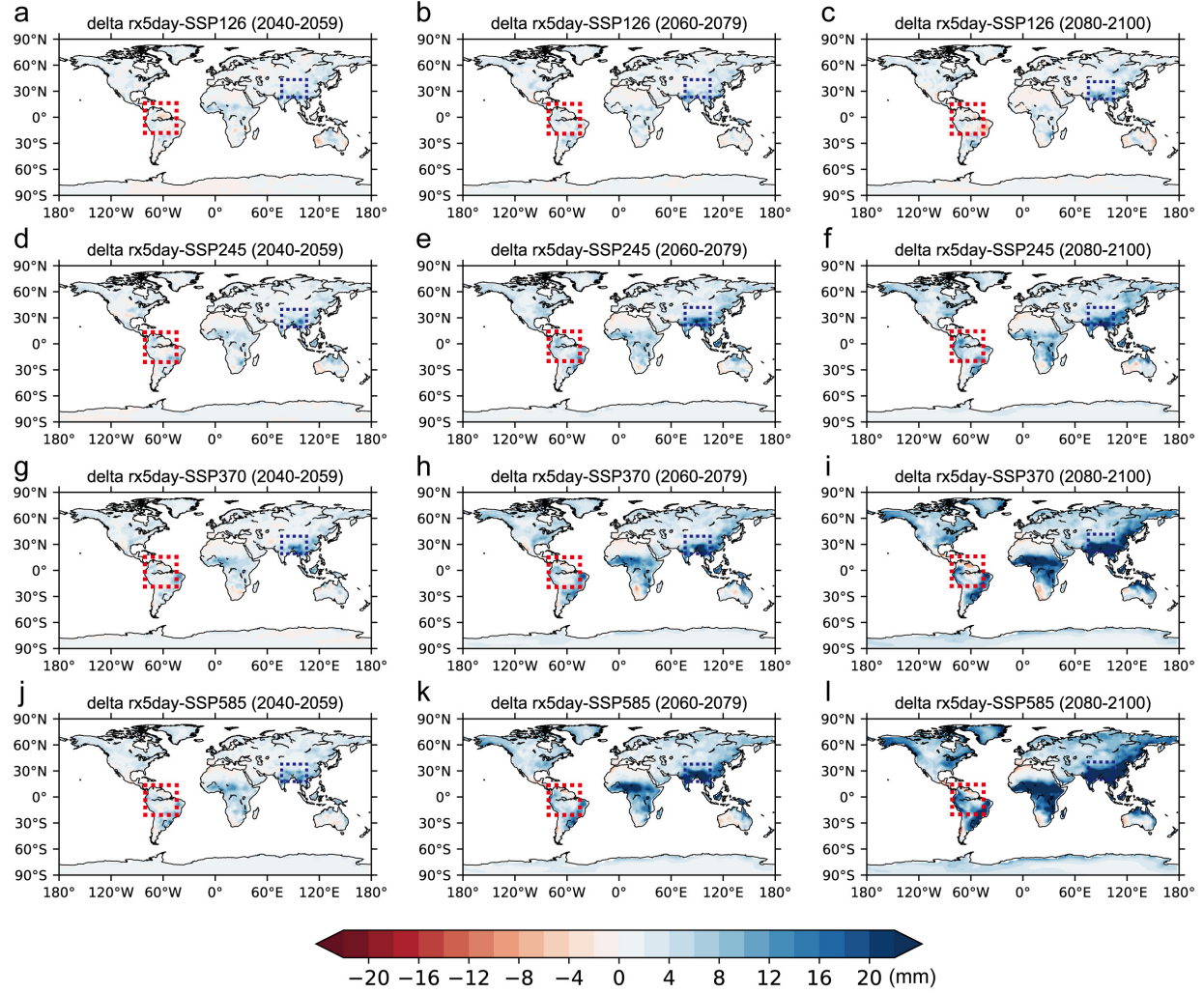


Fig. S16. The yearly maximum consecutive five-day precipitation shows a robust negative correlation between ARA and TP in all four scenarios (SSP126 (a)-(c), SSP245 (d)-(f), SSP 370 (g)-(i) and SSP585 (j)-(l)). While this extreme rainfall index is slightly decreasing in ARA, TP is getting more severe extreme precipitation in all scenarios, especially in the southern TP.

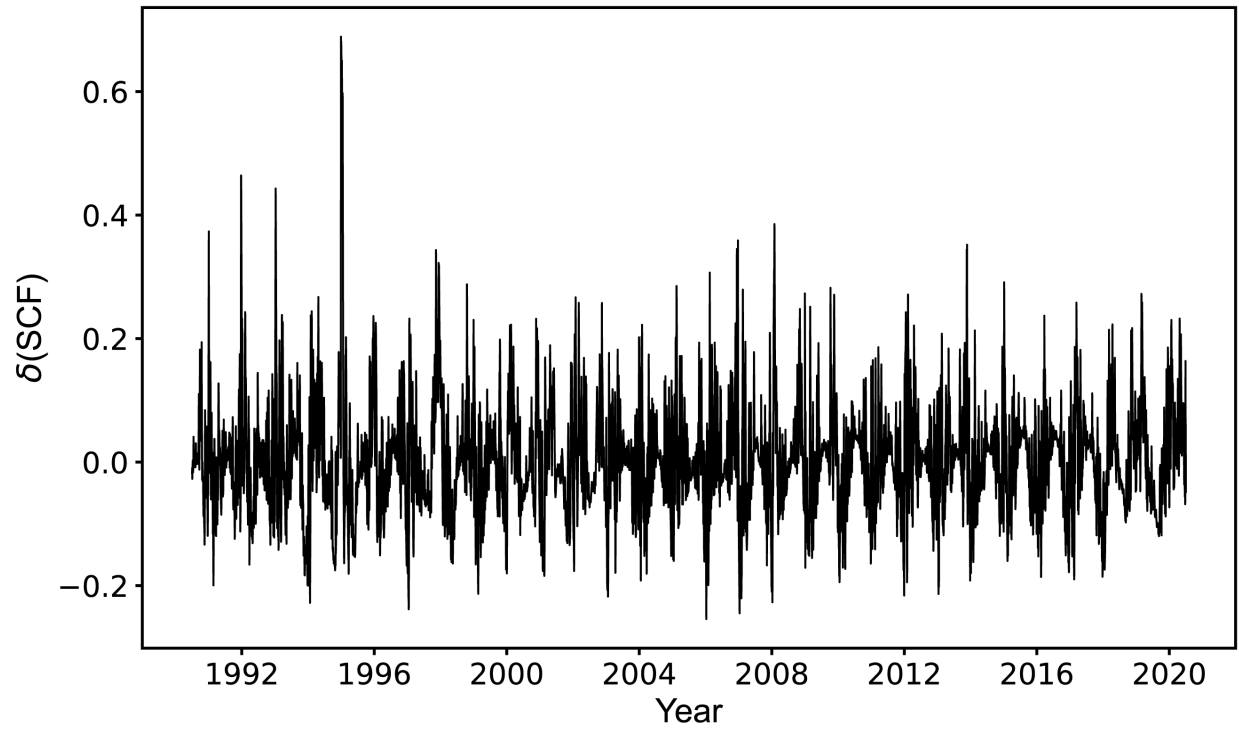


Fig. S17. The daily fluctuation of the snow cover fraction in TP from 1990 to 2020. $\delta(\text{SCF})$ is obtained by subtracting an overall trend and a repeating annual cycle from the original data.

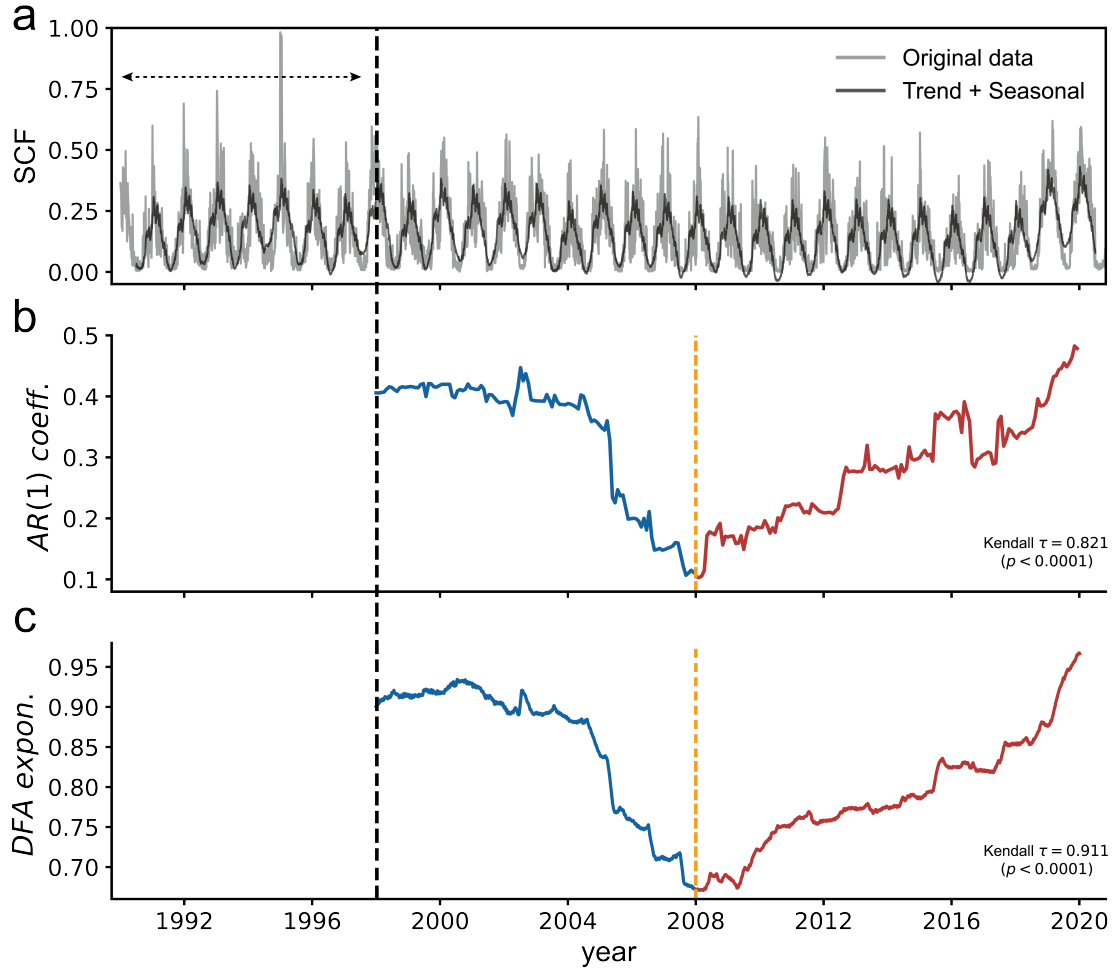


Fig. S18. The early warning indicators in Tibetan Plateau snow cover data show critical slowing down since 2008. **a**, The time series of the snow cover fraction (SCF) over the whole TP. Grey line shows the original data, black line shows the trend component and seasonal cycle component from the STL decomposed. **b**, The time series of lag-1 autocorrelation (AR(1)) coefficient. **c**, The time series of the detrended fluctuation analysis (DFA) exponent. AR(1) coefficient and DFA exponent are calculated using a sliding window with length 8 years. The black horizontal arrow represents the length of the moving window, and the vertical black dashed line indicates the time stamp from which the early warning measures are calculated. The line color depicts the different tendency of the time series. The Kendall τ values of the AR(1) coefficient and DFA exponent since 2008 are 0.821 ($p < 0.0001$) and 0.911 ($p < 0.0001$), respectively. The p value is obtained by two-sided hypothesis test.

Table S1.

List of CMIP5 climate simulation models used in this study. Resolutions are given as the number of latitude $\times$ longitude grid points. These simulations are available in the official archive of the Earth System Grid Federation.

Model	Experiment	Variable	Resolution
BNU-ESM	RCP85	TA(1000hPa)	96×192
CanESM2	RCP85	TA(1000hPa)	64×128
CMCC-CESM	RCP85	TA(1000hPa)	48×96
CMCC-CMS	RCP85	TA(1000hPa)	96×192
CNRM-CM5	RCP85	TA(1000hPa)	128×256
INMCM4	RCP85	TA(1000hPa)	120×180
MPI-ESM-LR	RCP85	TA(1000hPa)	96×192
MPI-ESM-MR	RCP85	TA(1000hPa)	96×192
NorESM1-M	RCP85	TA(1000hPa)	96×144
CCSM4	RCP85	TAS	192×288
CESM1-BGC	RCP85	TAS	192×288
MRI-CGCM3	RCP85	TAS	160×320
CSIRO-MK3-6-0	RCP85	TAS	96×192
FGOALS-s2	RCP85	TAS	108×128
IPSL-CM5A-MR	RCP85	TAS	143×144

Table S2.

List of CMIP6 climate simulation models used in this study. Resolutions are given as the number of latitude $\times$ longitude grid points. These simulations are available in the official archive of the Earth System Grid Federation.

Model	Experiment	Variable	Resolution
AWI-CM-1-1-MR	SSP 5-8.5	TA(1000hPa)	192×384
BCC-CSM2-MR	SSP 5-8.5	TA(1000hPa)	160×320
CanESM5	SSP 5-8.5	TA(1000hPa)	64×128
CMCC-ESM2	SSP 5-8.5	TA(1000hPa)	192×288
EC-Earth3	SSP 5-8.5	TA(1000hPa)	256×512
EC-Earth3-Veg	SSP 5-8.5	TA(1000hPa)	256×512
EC-Earth3-Veg-LR	SSP 5-8.5	TA(1000hPa)	160×320
EC-Earth3-CC	SSP 5-8.5	TA(1000hPa)	256×512
INM-CM5-0	SSP 5-8.5	TA(1000hPa)	120×180
MPI-ESM1-2-HR	SSP 5-8.5	TA(1000hPa)	192×384
MPI-ESM1-2-LR	SSP 5-8.5	TA(1000hPa)	96×192
NESM3	SSP 5-8.5	TA(1000hPa)	96×192
NorESM2-LM	SSP 5-8.5	TA(1000hPa)	96×144
NorESM2-MM	SSP 5-8.5	TA(1000hPa)	192×288
TaiESM1	SSP 5-8.5	TA(1000hPa)	192×288

-
- [4] Zhou, D., Gozolchiani, A., Ashkenazy, Y. & Havlin, S. Teleconnection Paths via Climate Network Direct Link Detection. *Physical Review Letters* **115**, 268501 (2015).