

Solar activity regulates geographical swings of droughts in the circum–North Pacific region with an 11-year cycle

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Abstract

Drought risk has increased in many regions under ongoing climate change, but changes in the geographical distribution of droughts and their underlying drivers remain poorly understood. Our analysis of summer droughts across the circum-North Pacific regions of Asia and North America (1950–2021) reveals a prominent ~11-year cycle of drought region swings with significant covariability between the two continents. We find that solar forcing is associated with the drought swings, with its effects likely amplified by ocean-atmosphere interactions over the Pacific. Tree-ring reconstructions support the existence of a long-term link between drought swings and solar activity spanning at least 700 years. Our findings highlight a pronounced trend of shifting drought patterns over the past century, portending heightened risk of severe drought in southwestern U.S., Mexico, and North China. Understanding these spatial shifts provides new insights for drought forecast and prevention strategies.

Key words: drought shift, sunspot, Interdecadal Pacific Oscillation, sea surface temperature, tree ring

1. Introduction

Global warming is expected to increase drought frequency and intensity, but it may also alter the spatial distribution of droughts, with profound implications for ecosystems, water resources, and human societies (IPCC, 2021). Shifts in drought-prone regions can disrupt population centers, amplify wildfire and desertification risks, and trigger cascading environmental impacts (Clark et al., 2016; Vicente-Serrano et al., 2020; Brottrager et al., 2023). The circum-North Pacific region, encompassing large parts of Asia and North America, hosts dense populations and climate-sensitive ecosystems, making them particularly vulnerable to changes in drought location rather than magnitude alone (Vicente-Serrano et al., 2020; IPCC, 2021).

Assessing drought remains challenging due to its spatial and temporal heterogeneity and the diversity of drought definitions (Mishra and Singh, 2010; Zargar et al., 2011). While global drying trends remain debated, regional analyses reveal pronounced and sometimes reversing trends (Dai, 2012; Sheffield et al., 2012; McCabe and Wolock,

2015; Vicente-Serrano et al., 2022). For example, the wetting trend in northwest China since the 1950s reversed around 1990 (Deng et al., 2022), while drylands in the Americas and the Africa experienced opposite shifts around the 1980s (Li et al., 2019). These reversals highlight that drought-prone regions are not stationary but can migrate over time, underscoring the need to examine long-term spatial trends in drought distribution.

Beyond long-term trends, drought patterns are also shaped by climate variability on interannual to decadal timescales. Ocean–atmosphere interactions, particularly over the Pacific, exert a strong influence on hydroclimate variability in Asia and North America, generating coherent teleconnection patterns (Ashok et al., 2007; Cook et al., 2007; Li and Zhu, 2016). Recent studies further suggest that solar activity, commonly represented by the ~11-year sunspot cycle, may contribute to quasi-decadal climate oscillations by interacting with Pacific ocean–atmosphere processes (Fang et al., 2014a; Fang et al., 2014b; Du et al., 2023). However, whether such cyclic forcing produces regular, spatially coherent shifts in drought locations across the North Pacific remains unclear.

Instrumental records are often too short to robustly distinguish long-term trends from cyclic variability in drought spatial patterns (Ault et al., 2014). Tree-ring–based drought reconstructions offer a unique opportunity to place both trends and cycles into a longer historical context (Cook et al., 2010). Here, we analyze drought centroid displacements in Asia and North America using instrumental and reconstructed datasets to address two key questions: (1) whether drought locations exhibit regular variability, and (2) how such variability and longer-term spatial shifts shape the evaluation of drought patterns. We find that drought centroids in both continents undergo coherent ~11-year oscillations that are associated with solar activity and appear to be modulated by Pacific ocean–atmosphere interactions, alongside a recent trend toward the Pacific, with important implications for drought risk in densely populated regions.

2. Materials and methods

2.1 Drought centroid and displacement analyses

The Palmer Drought Severity Index (PDSI) is a widely used drought indicator based on a water balance model (Palmer, 1965). This study employs the Self-Calibrated PDSI (scPDSI), which improves comparability across different climate regimes (van

der Schrier et al., 2013). To reduce uncertainties associated with snow accumulation and melt processes, our analysis focused on low- and middle-latitude land areas surrounding the North Pacific (up to 60°N), where snowmelt has less impact. The study area extends from the equator to 60°N, but begins at 15°N in North America to focus on drought displacement across contiguous landmasses. We use the scPDSI dataset (Barichivich et al., 2021) at 0.5° spatial resolution, covering the period 1950–2021, which is generally regarded as a more reliable period (Trenberth et al., 2013).

Drought areas are identified for each summer independently using an iterative clustering process (Andreadis et al., 2005). Grid cells with scPDSI values below -1 are classified as being under drought conditions (Palmer, 1965; Wells et al., 2004). The clustering procedure begins by identifying an individual drought grid, and then searching its 3×3 surrounding grids for adjacent drought-affected cells. Neighboring cells meeting the drought criteria are merged into a single drought cluster. The search-and-merge process continues iteratively around newly added cluster members until no further expansion is possible, yielding a spatially contiguous drought area. This procedure is repeated for all drought grid cells to identify all distinct drought clusters in a given summer.

To focus on large-scale drought events with greater societal and environmental relevance, only clusters exceeding 200,000 km² are retained for further analysis (Sheffield et al., 2009; Herrera-Estrada et al., 2017). This threshold corresponds to a minimum of about 65 grid cells at the equator to 128 grid cells at 60° N, providing adequate spatial sampling to ensure statistical robustness in centroid calculations. For each summer, drought centroids are calculated from the retained clusters using a weighted approach, in which grid cells with more severe drought conditions (lower scPDSI values) exert a stronger influence on the centroid position.

To quantify spatial shifts in drought occurrence, the centroid positions for each summer are assembled into time series for Asia and North America, respectively. Centroid displacements are then calculated as projected distances along longitude and latitude relative to fixed reference points. Latitudinal displacement is calculated relative to a reference point located at the minimum latitude and the midpoint of the longitude range for all annual centroids, while longitudinal displacement is calculated relative to a reference point located at the westernmost longitude and the midpoint of the latitude range. These displacement series represent meridional and zonal shifts of drought centroids expressed as projected distances (km).

Wavelet analysis is employed to assess how drought displacements vary across frequencies. The wavelet power spectrum is used to identify dominant periodicities, while cross-wavelet transform and wavelet coherence analyses are applied to examine co-variability between drought displacements and solar activity (Torrence and Compo, 1998; Grinsted et al., 2004). In addition, the multi-taper method is employed as a complementary approach to confirm dominant frequencies (Mann and Lees, 1996; Patterson et al., 2014). Pearson correlation analysis is used to investigate relationships between drought displacements, global sea surface temperature (SST), climate indices, and sunspot numbers.

2.2 Drought displacement reconstruction

Drought displacements were reconstructed for Asia (to 1300 AD) and North America (to 1500 AD) using the Drought Atlas (Cook et al., 2009; Cook et al., 2010). To ensure consistency with instrumental data, reconstructed displacements were aligned with the same reference points. We examined the interannual relationship between reconstructed displacements and solar activity until 1750, assessing the linkages between sunspot extremes (maxima/minima) and drought centroid locations (east/west, north/south) using phi correlation and Chi-squared tests to assess significance (Kim, 2017).

2.3 Solar activity, sea surface temperature and climate indices

Sunspot number data, a proxy for solar activity, were obtained from the World Data Centre SILSO, Royal Observatory of Belgium. Monthly data (since January 1749) were aggregated into annual series (preceding September to August) for summer drought analysis. Reconstructed total solar irradiance (1500–1961) and low-passed filtered (Butterworth filter, cutoff 0.01 cycle/year) annual sunspot numbers (1700–present) were compared to assess centennial-scale solar activity (Butterworth, 1930). The Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset provides monthly global SST on a 1° latitude-longitude grid from 1870 to date (Rayner et al., 2003), and is used to examine the relationship between SST variability and drought displacements, as well as its potential role in mediating the influence of solar activity. Summer 500 hPa geopotential height and 850 hPa wind fields from the ECMWF ERA5 reanalysis were used to characterize the large-scale circulation associated with drought displacement.

3. Results

3.1 Spatiotemporal characteristics of drought centroid displacements

Each summer, vast regions in Asia and North America experience large-scale droughts (contiguous areas exceeding 200,000 km² with June–August scPDSI, a widely used drought index, below -1). These extensive droughts encompass nearly 90% of the total drought area (Fig. S1). Spatially, these large-scale droughts exhibit a distinct pattern. In Asia, they predominantly occur in Central Asia, northern South Asia, and northern China, while in North America, the droughts occur more frequently in western regions (Fig. S2). To track the geographical shifts in drought patterns, we calculate annual centroids of these droughts in Asia and North America respectively. The centroid provides a representative location that can effectively indicate how droughts vary in space and time. Both Asia's and North America's centroids fall within a 1200 km radius circle (Fig. 1A). Crucially, the drought centroid exhibits a significant displacement trend towards the east in Asia (7.8 km/year, $p < 0.01$) and towards the west in North America (5.5 km/year, $p < 0.05$), indicating an east–west displacement pattern oriented toward the Pacific Ocean (Fig. 1B). The latitudinal displacements (Fig. 1B) exhibit clear interdecadal variability, characterized by alternating northward and southward shifts on multi-decadal timescales.

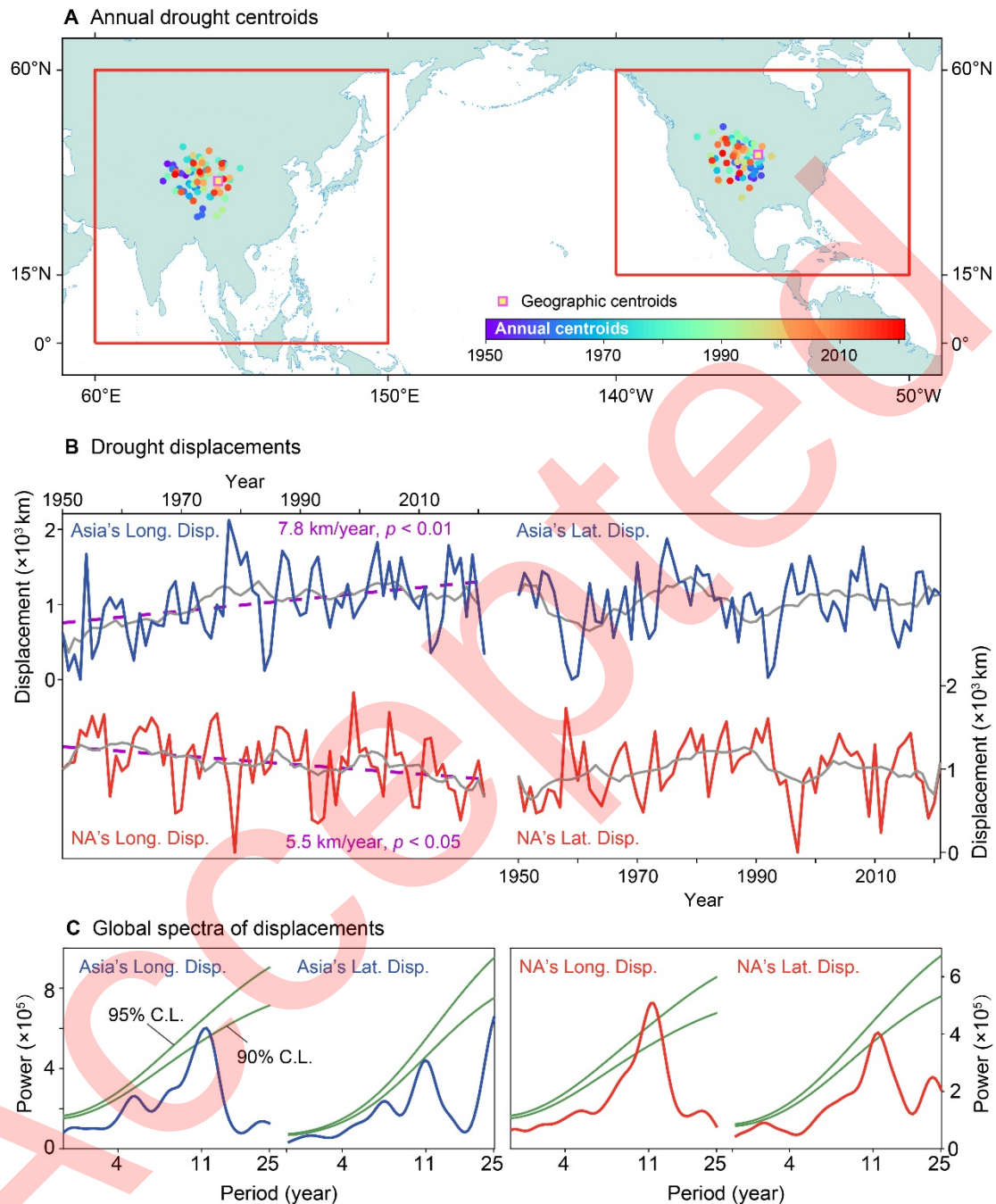


Fig. 1. Spatial distribution, displacement and spectral characteristics of annual drought centroids in Asia and North America. (A) Spatial distribution of the annual drought centroids. Red rectangles highlight the study areas in Asia (60°–160°E, 0°–60°N) and North America (NA, 140°–50°W, 15°–60°N). Squares represent the respective geographic centroids in the two study areas. (B) Annual longitudinal and latitudinal displacement of the drought centroids, with grey lines showing 11-year moving averages and dashed magenta lines indicating significant trends in longitudinal displacement. (C) Global wavelet spectra of the displacements, highlighting confidence levels with upper and lower green lines at 95% and 90%, respectively.

3.2 Covarying drought displacement related to 11-year solar cycle

Intriguingly, drought displacements in both the longitudinal and latitudinal directions exhibit a distinct ~11-year cycle. This periodicity is evident from the significant peaks within the relevant frequency band observed in the wavelet analysis results (Fig. 1C and Fig. S3), and is further confirmed by the multi-taper analyses (Fig. S4). The observed ~11-year cyclic displacements inspire us to consider the potential connection to the sunspot number due to their shared periodicity (Fig. S4 and S5). Consistent with this expectation, a strong relationship between drought displacements and sunspot numbers is observed at the ~11-year band by wavelet analyses (Fig. 2A–D and Fig. S6). Among these relationships, Asia's latitudinal displacement displays the most robust link to the solar activity, maintaining statistical significance ($p < 0.05$) throughout the 1950–2021 period. Notably, the strength of this linkage underwent a temporary decline during the 1980s, a phenomenon that was even more pronounced in other three displacement series (Fig. 2A, 2C and 2D). Furthermore, phase angle analysis indicates that the response of drought displacements to solar forcing is not instantaneous. Specifically, Asia's latitudinal displacement lags the sunspot cycle by ~1 year, while the other displacements exhibit lags ranging from near-zero to 2 years.

Given the shared solar influence on drought displacements across Asia and North America, we investigated potential teleconnections between their displacements. As expected, their teleconnections are confirmed at the ~11-year band in both longitudinal and latitudinal directions (Fig. 2E–F and Fig. S6E–F), suggesting coordinated behavior of drought displacements across the circum-North Pacific region. Interestingly, the drought centroids exhibit opposing movements, hinting at the formation of distinct east-west and south-north dipole patterns. The longitudinal teleconnection is stronger than the latitudinal one, and North America's longitudinal displacement lags behind Asia's by a consistent 1–2 years.

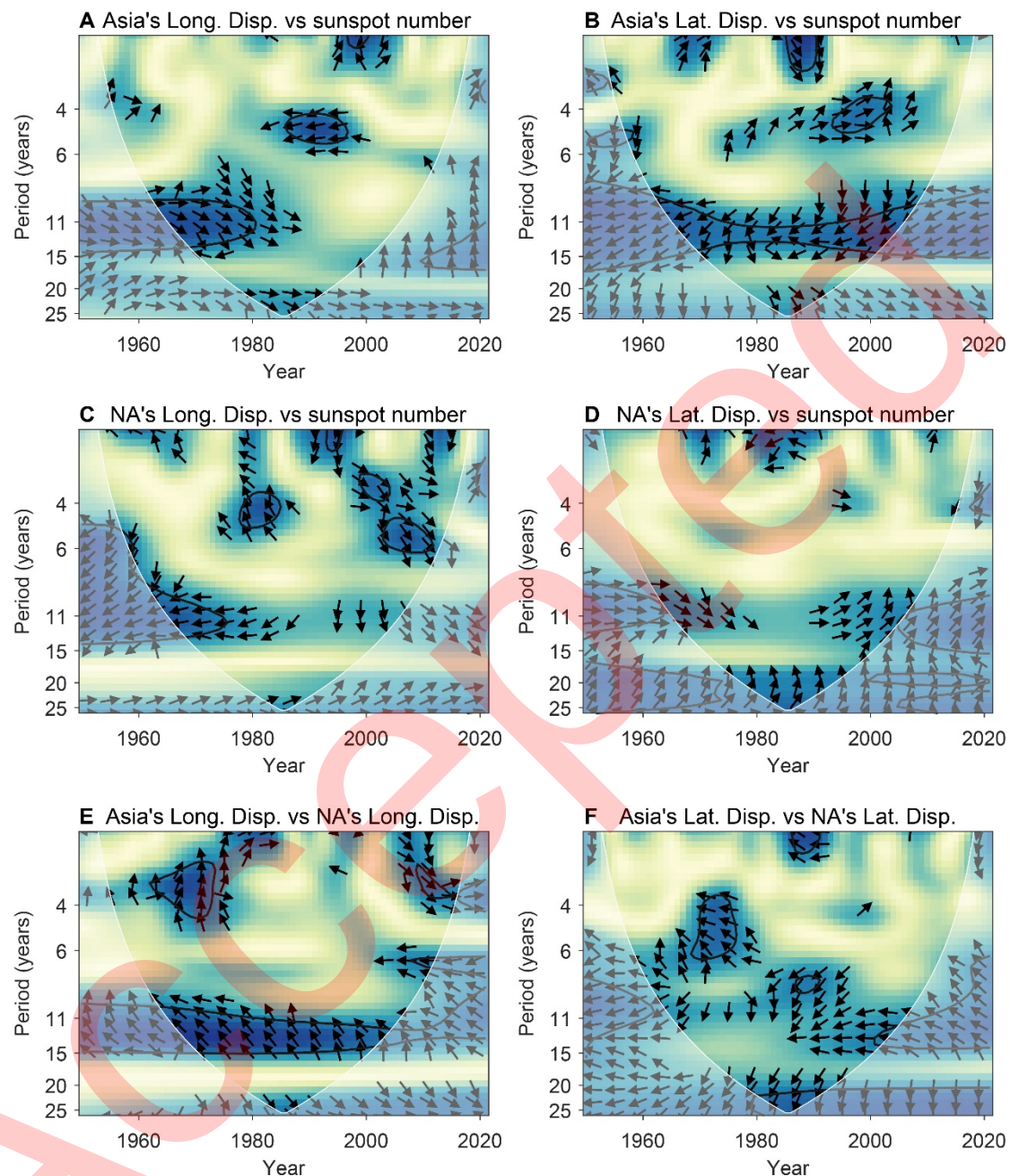


Fig. 2. Wavelet coherence analysis of drought displacements: Asia-North America linkages and sunspot number associations. The areas with arrows indicate a magnitude-squared coherence exceeding 0.5, with solid lines demarcating the 95% confidence level. The direction of the arrows signifies the phase relationship with in-phase pointing right, and anti-phase pointing left. Arrows pointing upward (downward) indicate that the sunspot number leads (lags) the drought displacement, with the angular deviation from the rightward direction corresponding to the relative time lag within a given periodic band. The cone of influence, where edge effects exist, is indicated using a semi-transparent overlay.

These findings extend beyond the drought defined by contiguous area exceeding 200,000 km² and scPDSI < -1. Sensitivity analyses, using different area thresholds (no constraint, > 100,000 km², and > 200,000 km²) and intensity levels (scPDSI < -1

and < -2), show that the results remain consistent regardless of the specific criteria (Figs. S7–S10). Notably, larger-scale and more severe droughts exhibit more dispersed centroid distribution, with longitudinal displacement trends being even stronger (Fig. S11).

3.3 SST as a mediator between solar and drought displacement

The solar cycle is widely recognized to have far-reaching effects on Earth's climate system (Haigh et al., 2010; Ineson et al., 2011). However, its small amplitude ($\sim 0.1\%$) is considered insufficient to account for the observed climate response, which is suggested to be amplified through the ocean-atmosphere interactions (Foukal et al., 2006; Meehl et al., 2009). To examine whether ocean variability is associated with drought displacement on the solar-cycle timescale, we applied an 8–13-year band-pass filter (Butterworth, 1930) to the SST fields, corresponding to the dominant frequency band of solar activity (Fig. S5), and then calculated their spatial correlations with drought displacements. The results show significant correlations ($p < 0.05$) across broad areas, particularly for preceding winter SST (Fig. 3, similar spatial correlations derived from the original SST fields are shown in Fig. S12 and S13). The dominant SST correlation patterns exhibit an Interdecadal Pacific Oscillation (IPO)-like pattern (Power et al., 1999), suggesting a Pacific-wide mode of variability associated with the drought displacement. During a positive IPO phase, droughts tend to occur in eastern and southern Asia and western and northern North America. This pattern reverses during the negative phase. These results suggest that Pacific SST variability is associated with drought displacement variability in a manner consistent with the ~ 11 -year solar cycle timescale. While the IPO itself is often regarded as an internally generated mode, its spatial coherence at the ~ 11 -year band is consistent with the view that ocean–atmosphere coupling may contribute to the amplification or organization of weak solar forcing (see Section 4.2).

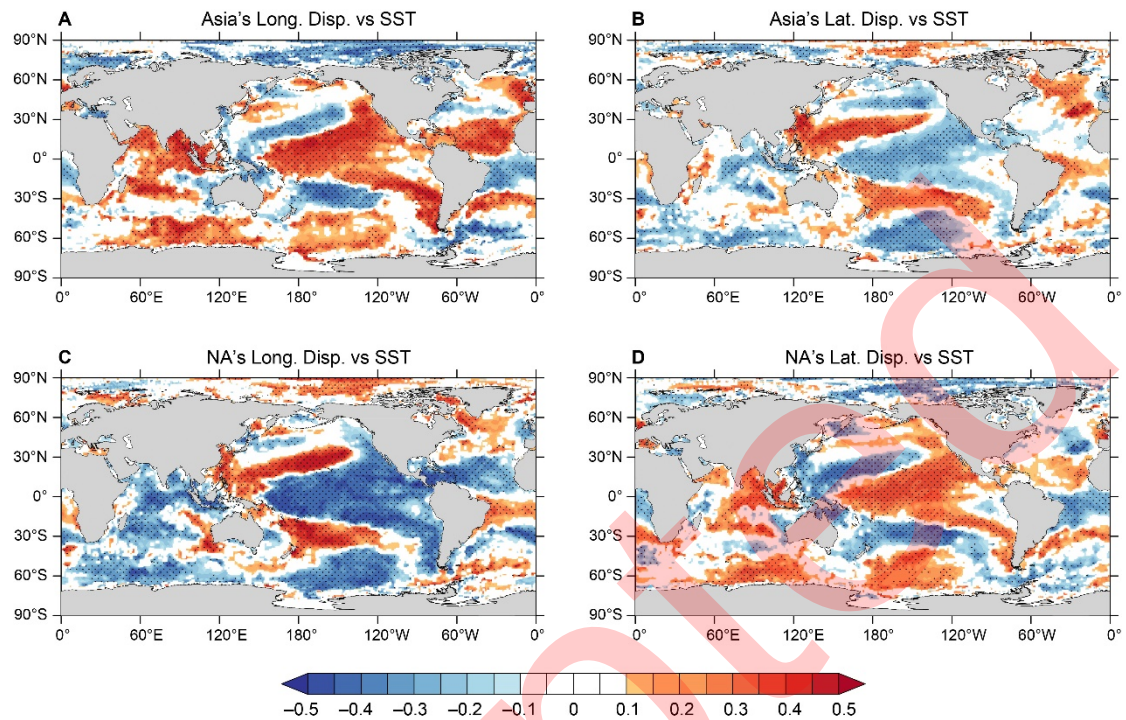


Fig. 3. Spatial correlation between the drought displacements and boreal winter (December–February) sea surface temperature (SST) after applying an 8–13-year band-pass filter, for the period 1950–2021. Areas with an absolute correlation coefficient greater than 0.1 are shaded in color, and statistically significant correlations ($p < 0.05$) are indicated by stippling. All datasets were detrended prior to the spatial correlation analysis.

We found that SST variability is significantly associated with solar radiation, with a crucial overlap with the dominant SST patterns (Fig. S14 and S15). This suggests that SST may serve as an intermediate pathway, modulating the relationship between solar activity and drought displacement. Intriguingly, SST exhibits a pronounced 1–2-year lag in response to the solar cycle, mirroring the delay observed in drought displacements. This consistency holds true across the sub-periods (1950–1979, 1980–1999, 2000–2021) (Fig. S16 and S17). Notably, during 1980–1999, the link between SST and solar radiation weakened, which may help explain the weakened drought displacement–solar relationship during this period.

Summer 500 hPa geopotential height anomalies were regressed onto the preceding winter–spring IPO index after applying an 8–13-year band-pass filter to both series (Fig. S18). The regression reveals a coherent wavetrain-like pattern extending from East Asia across the North Pacific to North America, with alternating positive and negative height anomalies over the North Pacific sector. These anomalies suggest a reorganization of the large-scale midlatitude circulation over the North Pacific, which may modulate downstream westerly flow and storm-track position, thereby providing

a plausible atmospheric background for the observed spatial shifts of drought centroids in Asia and North America.

Central Pacific El Niño events are associated with extreme drought patterns (Fig. 4A). Unlike traditional El Niño events, they are associated with droughts on the west coast of North America (Ashok et al., 2007; Weng et al., 2007). In Asia, these events exacerbate droughts in eastern regions (northern China and northeastern Asia) due to weakened monsoon associated with large-scale North Pacific circulation anomalies. This eastward shift in Asian droughts is often accompanied by droughts in the Indian Peninsula. Notably, extreme eastern North America droughts are accompanied by drought in the west as well, with an anticyclonic circulation anomaly in the east (Fig. 4B).

An extreme north-south drought pattern in North America is associated with the meridional wind anomalies (Fig. 4C–D). Intensified southerlies transport moisture northward causing northern wet conditions, while northerly anomaly reverses the pattern. Extreme northern droughts are likely accompanied by warm east-central tropical Pacific SSTs. Concurrently, El Niño events disrupt Asian monsoon patterns, resulting in droughts in South and Southeast Asia, forming covarying Asia-North America drought distribution patterns.

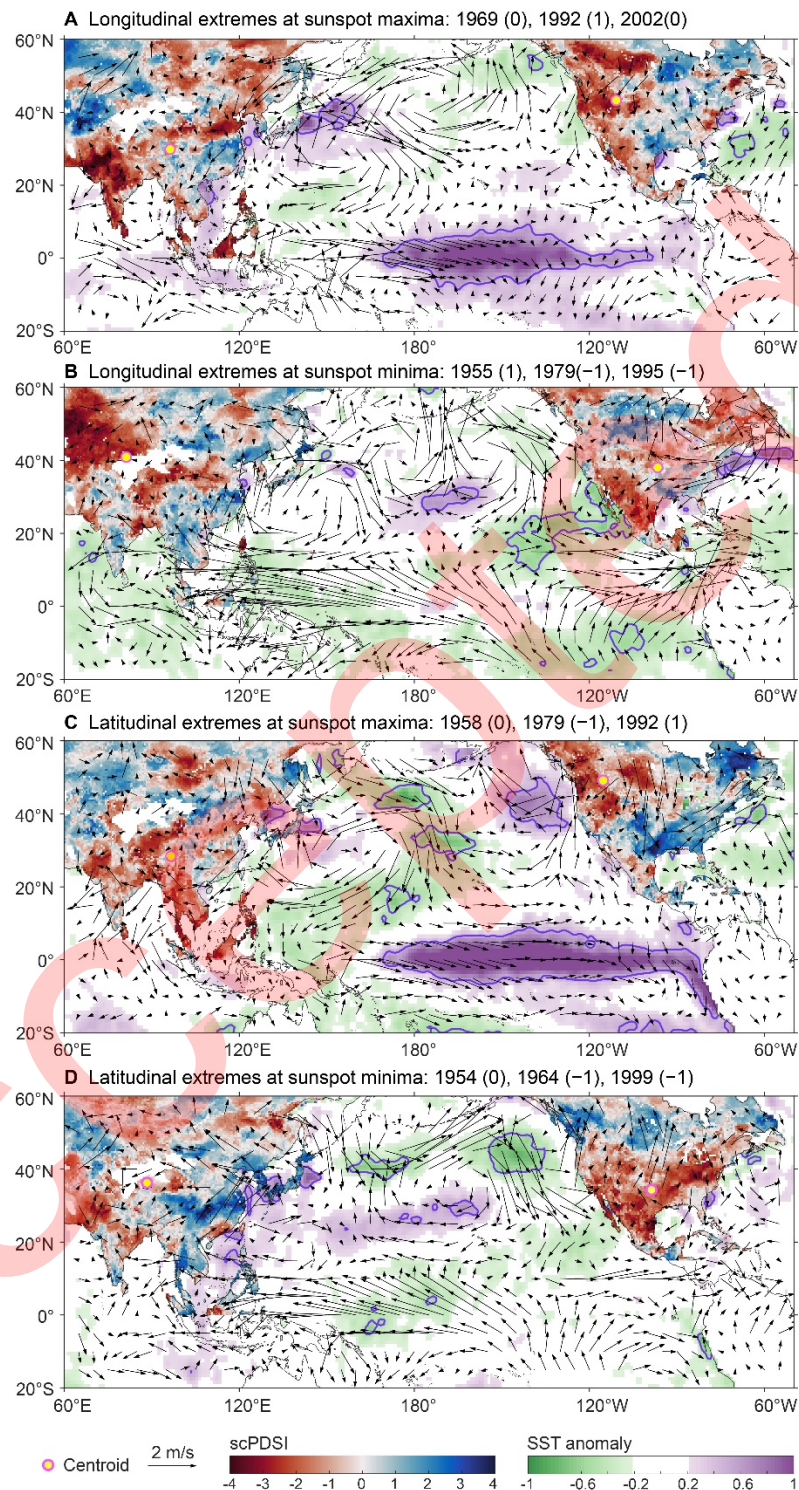


Fig. 4. Average scPDSI, summer wind anomalies (850 hPa), and preceding winter SST anomalies during typical years. For each panel, typical years are defined as the three years exhibiting the most pronounced drought displacement in the corresponding direction. The numbers 0, 1, and -1 in parentheses following the year denote the current, preceding, and subsequent years corresponding to a sunspot extreme year, respectively. Yellow points mark centroid locations, and colored shading indicates SST anomalies exceeding 0.2 °C, with anomalies surpassing 0.5 °C represented by purple solid lines.

3.4 Long-term persistence of the solar–drought linkage in reconstructions

We employed tree-ring based drought reconstructions to examine the association between solar activity and drought displacements beyond the modern observations (Cook et al., 2009; Cook et al., 2010). The reconstructed drought displacements over 1750–2005 (Fig. 5, Fig. S19) indicate a recurrent association between sunspot extremes and drought displacements. Despite a weakened relationship during 1821–1874, significant correlations ($p < 0.05$) persist over most of the past three centuries, particularly for Asia (Fig. 5A and 5C) and for the latitudinal displacement in North America (Fig. 5B). Sensitivity tests varying the criteria for identifying drought-affected areas (Fig. S20 and S21) show comparable, and in some cases stronger, correlations between sunspot extremes and drought displacements. These results suggest that the solar–drought linkage has been persistent over the past three centuries. Notably, this association strengthens during 1875–1915, but weakens in 1916–1949, aligning with the SST response to solar activity (Fig. S22). This agreement suggests that SST may modulate the solar-related drought displacement variability on long timescales.

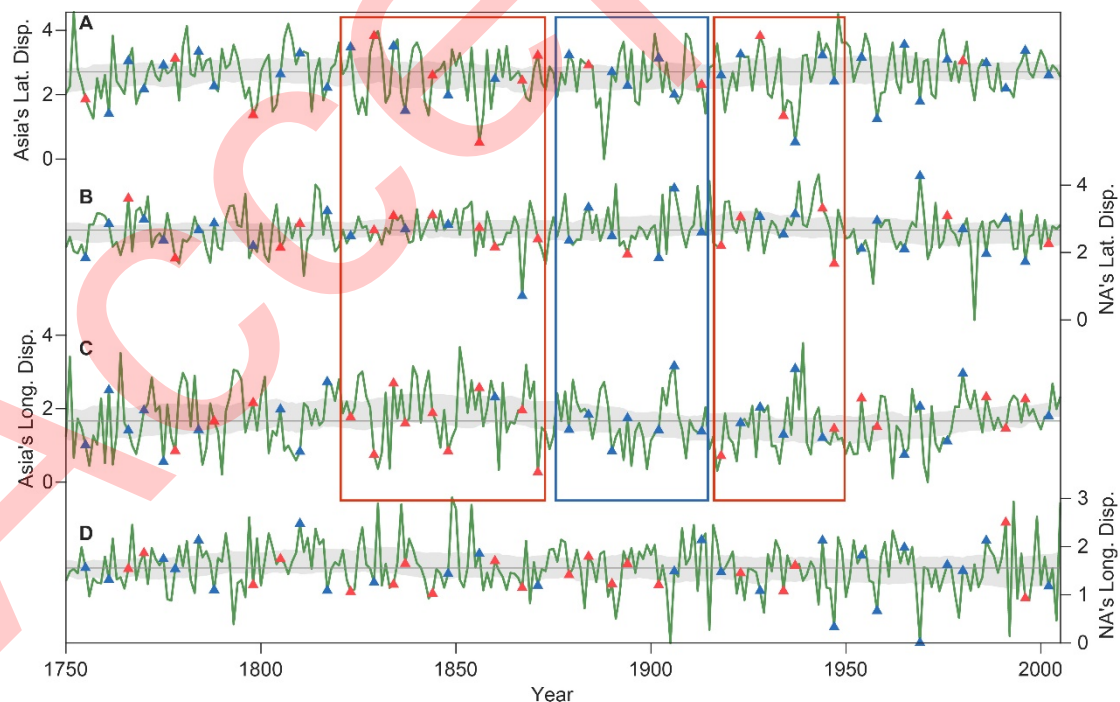


Fig. 5. Temporal variations of reconstructed drought displacements (1750–2005). Droughts are identified using scPDSI < -1 , with contiguous area exceeding 200,000 km². The Y-axis represents displacement distance in a unit of $\times 10^3$ km. Triangles denote centroid displacements during sunspot extremes, with blue indicating expected location, and red indicating unexpected location. The blue rectangle marks a strong link between sunspot extremes and centroid locations. The red rectangle highlights weaker linkages for the 1821–1874 and 1875–1915. Excluding the major chaotic period (1821–1874), their correlation

coefficients are -0.56 ($p < 0.01$), 0.39 ($p < 0.05$), 0.50 ($p < 0.01$) and -0.17 ($p = 0.31$).

4. Discussions

4.1 Solar-driven teleconnections across annual to centennial timescales

The SST–drought relationships identified here are broadly consistent with previous regional studies, which highlighting the influence of Pacific decadal variability on drought in western North America, North China, and Northeast Asia (Saji et al., 1999; McCabe et al. 2004; Schoennagel et al. 2005; Yeh and Yoon 2010; Baek et al. 2017; Zhang et al. 2018). However, by expanding our spatial focus to the circum–North Pacific scale, we reveal a synchronized ~ 11 -year drought cycle that transcends these individual regions. Furthermore, while prior studies documented an dipole-like south–north drought teleconnection between the two continents, characterized by opposing anomalies (Fang et al., 2014a; Fang et al., 2014b), our approach offers a more dynamic perspective by tracking the continuous trajectories of drought centroids. Crucially, by extending the analysis back to 1500 through tree-ring based reconstructions, we find this east–west pattern teleconnection to be particularly strong (see coherence analysis in Fig. S23A) during periods of heightened solar activity (early 17th, 18th, and late 19th to present centuries; see reconstructed total solar irradiance in Fig. S23B) (Bard et al., 2000). This, coupled with the established south–north teleconnection, suggests a potentially important role of solar activity on drought patterns across the circum–North Pacific region at both annual and centennial timescales.

4.2 Solar activity amplification and atmospheric impacts

Our analyses suggest that solar activity may be linked to drought swings, with the Pacific ocean–atmosphere interactions potentially modulating this relationship. The “bottom up” process, proposed to explain the amplification of solar activity on climate system (Meehl et al., 2009; Shindell et al., 2020; Lin et al., 2021), provides a plausible framework for understanding the observed drought displacements. During peak solar activity, more energy is transported into subtropical ocean surface, leading to increased moisture transport to convergence zones. This enhances the Hadley and Walker circulations, resulting in fewer clouds in the equatorial eastern Pacific, and more solar radiation reaching the ocean surface. This creates positive feedback that amplifies the solar impact and intensifies the drought displacements.

The influence of solar activity on drought displacements is further evidenced by their

weakened relationship observed during the late 1980s to 1990s (Fig. 6). This period aligns with the broader phenomenon of global dimming, a widespread decline in surface solar radiation from the 1950s to the 1980s, followed by subsequent brightening (Pinker et al., 2005; Wild, 2009; Wild et al., 2026). In particular, intense volcanic eruptions between 1979 and 1982 and the eruption of Mount Pinatubo in 1991 injected large amounts of aerosols into the stratosphere, and thereby substantially reduced surface solar radiation (Ohvri et al., 2009; Schmidt et al., 2018; Dhomse et al., 2020). These results suggest that drought swings are highly sensitive to variations in surface-available solar radiation. Consequently, increasing clouds and aerosols could weaken the regularity of drought swings.

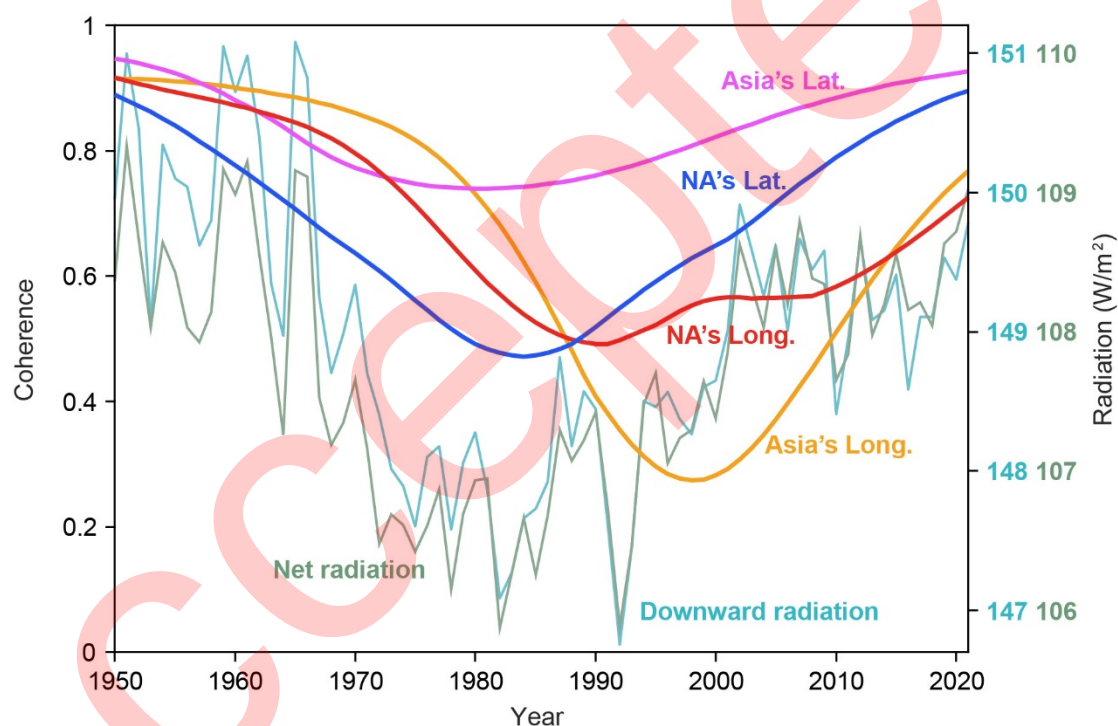


Fig. 6. Surface solar radiation variation and drought displacements coherence with sunspot numbers. The coherence curve represents the maximum magnitude-squared coherence within the 8–13-year band. The globally averaged surface solar radiation for land is presented, including both downward radiation and net radiation.

4.3 The shift of droughts toward western North America and eastern China

A moving average was applied to the reconstructed drought displacements to reduce high-frequency variability and reconstruction noise, thereby facilitating the identification of long-term displacement trends (Fig. 7). Results show that in North America, interdecadal droughts (herein 10–50 years) experienced relatively stable longitudinal swings from the 16th to the 19th centuries, but a dramatic and irreversible westward shift occurred since the early 20th century (Fig. 7A). In contrast, Asian interdecadal droughts have generally shifted eastward over the past 700 years,

although punctuated by occasional westward excursions. The current western location of the drought centroid relative to its historical mean, coupled with the ongoing eastward trend since 1950s, suggests a continued eastward shift. The convergence of the recent interannual and long-term interdecadal longitudinal trends strongly suggests a shift of droughts towards western North America and eastern Asia. Despite relatively stable latitudinal swings (Fig. 7B), a clear southward trend in North America and a northward trend in Asia have emerged over the past century, particularly within the 50-year timescale. These combined trends indicate an increasing risk of heightened drought severity in the southwestern U.S., Mexico, and North China—regions particularly vulnerable to drought.

Our analysis identifies that the central Pacific SSTs may play a critical role in affecting longitudinal displacements, as significant correlations observed in both Asia and North America (Fig. 3A and 3C). Central Pacific El Niño events are found to enhance extreme longitudinal displacements, as illustrated by the typical-year composite (Fig. 4A). In addition, correlation analyses involving 24 major climate indices confirm central Pacific SSTs as the most influential factor (Fig. S24). Although the exact mechanisms behind its teleconnection patterns remain to be fully elucidated, studies have shown that the central Pacific El Niño is associated with summer dryness along the western US coast, unlike the eastern Pacific El Niño which brings wetness (Ashok et al., 2007; Weng et al., 2007). Similar distinct effects are observed in eastern China, where central Pacific El Niño events are associated with drier summer conditions, including less precipitation and heat extremes (Gao et al., 2020; Wen et al., 2020). Collectively, these findings support that central Pacific El Niño potentially promotes westward drought displacements in North America and eastward displacements in Asia.

Notably, recent studies report a strengthening and higher occurrence frequency of central Pacific El Niño events since the late 20th century (Yeh et al., 2009; Lee and McPhaden, 2010; Yeh et al., 2015; Gan et al., 2023). This evolution closely aligns with the intensified Pacific-ward displacement of drought centroids identified in our analysis, providing a plausible interpretation of the recent trend. Climate model projections suggest that central Pacific El Niño-like events may occur more frequently (Xu et al., 2017; Shin et al., 2022), implying elevating drought risk in western North America and eastern Asia. These changes underscore the need to reassess and strengthen drought management strategies in these regions to protect ecosystems and water resources against escalating threats.

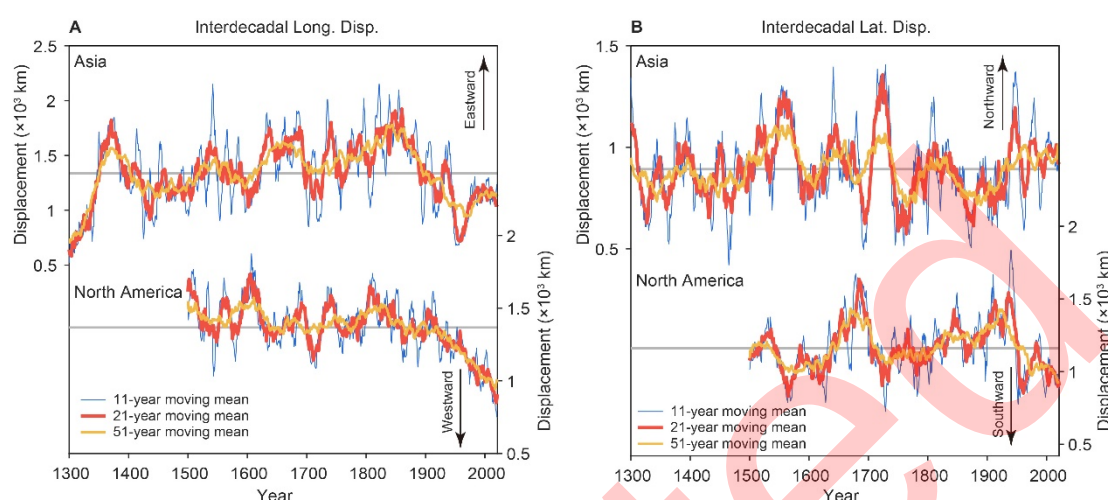


Fig. 7. Reconstruction-based interdecadal drought displacements in Asia and North America over the past ~700 years, shown as (A) longitudinal and (B) latitudinal displacements. The grey horizontal lines indicate the long-term means. Note that the reconstructions have been replaced by instrumental displacements after 1950.

5. Conclusions

From the perspective of geographical drought shift, we identify a swing of summer drought regions in an ~11-year cycle across the circum-North Pacific region, which is correlated to the solar activity cycle. The effects of solar activity may be amplified by the Pacific SSTs. Notably, we identify a recent trend of drought migration toward Pacific coastal regions, potentially increasing drought risk in vulnerable areas like the southwestern U.S., Mexico, and northern China. By highlighting the spatial dynamics of drought displacement, this study provides new insights relevant for drought risk management, and offers a transferable framework for investigating spatial pattern variability in other regions. Future targeted modeling experiments will help further examine the pathways through which external solar radiative forcing may influence large-scale drought displacement.

Data Availability Statement

Sunspot number can be obtained from <https://www.sidc.be/SILSO/datafiles>. HadISST1 dataset are available at <https://www.metoffice.gov.uk/hadobs/hadisst/>. Instrumental scPDSI is from <https://crudata.uea.ac.uk/cru/data/drought/>. Reconstructed scPDSI are available at

<https://www.ncei.noaa.gov/access/paleo-search/study/10435> (Monsoon Asia Drought Atlas), and <https://www.ncei.noaa.gov/access/paleo-search/study/19119> (North American Drought Atlas). ECMWF ERA5 reanalysis data provides wind fields and geopotential height data at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=overview> and surface solar radiation data at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview>. Reconstructed solar irradiance are available at <https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/noaa-forcing-5782/html>. The code used to calculate drought centroids and perform the analysis is provided at <https://github.com/HWuLab/DroughtCentroid>. All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

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Supporting Information

The supporting information is available online at <http://earth.scichina.com> and <http://link.springer.com>. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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