Leading Pattern of Spring Drought Variability over East Asia and Associated Drivers

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Abstract: Drought events have become more frequent and intense over East Asia in recent decades, leading to huge socioeconomic impacts. Although the droughts have been studied extensively by cases or for individual regions, their leading variability and associated causes remain unclear. Based on the Standardized Precipitation Evapotranspiration Index (SPEI) and ERA5 reanalysis product from 1979 to 2020, this study evaluates the severity of spring droughts in East Asia and investigates their variations and associated drivers. The results indicate that North China and Mongolia have experienced remarkable trends toward dryness during spring in recent decades, while southwestern China has witnessed an opposite trend toward wetness. The first Empirical Orthogonal Function mode of SPEI variability reveals a similar seesawing pattern, with more severe dryness in northwestern China, Mongolia, North China, South Korea, and Japan but increased wetness in Southwestern China and southeast Asia. Further investigation reveals that the anomalously dry (wet) surface in North (Southwestern) China is significantly associated with anomalously high (low) temperature, less (more) precipitation, and reduced (increased) soil moisture during the previous winter and early spring, regulated by an anomalous anticyclone (cyclone) and thus reduced (increased) water vapor convergence. The spring dry-wet pattern in East Asia is also linked to cold sea surface temperature anomalies in the central-eastern Pacific. The findings of this study have important implications for improving the prediction of spring drought events in East Asia.

Key words: drought; leading pattern; East Asia; spring; drivers
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1 INTRODUCTION

Drought events, characterized by prolonged periods of abnormally low precipitation (Chen et al.1; Li et al.2), can exert significant impacts on the hydrological cycles, ecosystems, and human society (Huang et al.1; Chen et al.4; Kostopoulou and Giannakopoulos3). The occurrence of severe droughts not only affects crop growth and agricultural production in the spring (Han et al.8; Santini et al.7; Higgins et al.8), but also leads to an increased frequency of natural disasters such as heatwaves and wildfires in summer due to dry surface conditions (Purich et al.9; Wang et al.10; Heino et al.11). In recent decades, drought events have become more frequent across the world, resulting in substantial socioeconomic impacts (Suska and Piotr12; Li et al.13; Dong et al.14). Notably, East Asia is a region particularly susceptible to the drought disasters (Zhou and Wang15; Deng et al.16). For instance, Southwestern China experienced unprecedented droughts during the spring of 2010, resulting in water scarcity, crop failures, and significant economic losses (Zhang et al.17; Liu et al.18). Between July and August 2022, the Yangtze River basin of China faced its most severe drought on record, causing water levels in China’s largest freshwater lake, Poyang Lake, to plummet from 19 meters in June to 9 meters by the end of August (Mallapaty19). Moreover, the frequency and severity of extreme dry events are projected to increase in a warming climate (Qiao et al.20; Tang et al.21; Ullah et al.22). Hence, it is important to enhance our understanding of the changes and variations in drought events over East Asia, as well as their underlying physical causes.

The drought severity in East Asia is significantly influenced by the Asian monsoon system (Yu et al.23; Cen et al.24; Huang et al.25). Previous studies have indicated that the East Asian summer monsoon circulation has
weakened in recent decades (Wang [26]; Wang et al. [27]; Zhou and Yu [28]), causing reduced precipitation in North China and consequently exacerbating the dry conditions there (Li et al. [39]; Zhou et al. [30]; Zhang et al. [31]). In contrast, the changes in the South Asian summer monsoon can affect the transport of water vapor from the tropical Indian Ocean through the Bay of Bengal to Southwestern China, affecting the dryness in the region (Simmonds et al. [12], Zhou and Yu [24]). Moreover, the global SST anomalies can significantly regulate the interannual to interdecadal variations of the drought events in East Asia. Particularly, the El Niño-Southern Oscillation (ENSO) plays a crucial role in driving the interannual variations of extreme dry conditions in China (Cao et al. [32]; Wang and Li [40]). The El Niño-like SST can lead to the intensification and westward shift of the North Western Pacific subtropical high, resulting in reduced precipitation and increased temperatures in South and Southwestern China, which in turn favor the occurrence of drought events (Wang et al. [39]). In addition, Asian large-scale orography forcing, particularly the Tibetan Plateau (TP), significantly increases ascent, low-middle cloud formation, and resultant strong spring cloud radiative cooling over Southeastern China (SEC) and downstream ocean, thereby affecting climate change (Kiehl and Trenberth [30]; Li et al. [37]). Studies suggest that the western Pacific subtropical high anomaly was stronger, westward and southward in the spring of 2019, which directly led to significantly more precipitation in Northeastern China, eastern Northwestern China, and South China, while the Huang-Huai, Jiang-Huai and most Yunnan provinces had less precipitation (Liu and Chen [38]).

Although previous studies have extensively explored the dry and wet extremes in East Asia (Du et al. [39]; Huang et al. [41]; Qiao et al. [30]), most are focused on the trends, on individual cases, or for specific regions. The leading mode of drought variability across East Asia during the boreal spring and its underlying causes remain unclear. Since spring marks the period of crop development in East Asia, alterations in springtime drought conditions can significantly affect crop growth, posing a potential threat to regional food prices and security. Therefore, this study aims to assess the severity of drought in East Asia and investigate its variations and physical causes during the boreal spring. Section 2 presents the data and methods used in this research. Sections 3 and 4 present the research findings, followed by a summary and discussion in Section 5.

2 DATA AND METHODS

2.1 Standardized Precipitation-Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) is a multiscale drought index derived from climatic data. It serves as a tool for identifying the onset, duration, and severity of drought conditions in comparison to typical circumstances (Vicente-Serrano et al. [40]). Mathematically, SPEI is simply computed by total precipitation minus potential evapotranspiration. However, the estimation of potential evapotranspiration is difficult in regions without sufficient data, which follows the Penman-Monteith method (Allen et al. [41]),

\[
ET_0 = \frac{0.408\Delta (R_a - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} 
\] (1)

In Formula 1, ET_0 is the potential evapotranspiration (mm d\(^{-1}\)); and R_a is the net radiation (MJ m\(^{-2}\) d\(^{-1}\)). G is soil heat flux (MJ m\(^{-2}\) d\(^{-1}\)); T is the daily average temperature (°C); u_2 is the wind speed at 2 m (m s\(^{-1}\)), obtained by multiplying the wind speed at 10 m by 0.75. e_s is saturated vapor pressure (kPa); e_a is the actual water vapor pressure (kPa); \Delta is the slope of saturated water vapor pressure-temperature curve (kPa °C\(^{-1}\)); and \gamma is a hygroscopic constant (kPa °C\(^{-1}\)) (Valiantzas [42], McCell [43]). SPEI offers a comprehensive assessment of drought by taking into account both evapotranspiration and precipitation, enabling the detection of drought across various temporal scales (Vicente-Serrano et al. [40]; Homdee et al. [44]; Wang et al. [45]). In the context of studies in China, the Penman-Monteith method has been found to be particularly suitable (Chen et al. [46]).

2.2 ERA5 reanalysis data

ERA5 is the state-of-the-art reanalysis dataset, which is generated through the 4D-Var data assimilation of the ECMWF Integrated Forecast System (IFS) and the CY41R2 model (Hersbach et al. [47]). In this study, the variables that we analyze in this study include 2-m temperature, precipitation, soil moisture (at a depth of 1 m underground), three-dimensional winds, geopotential height, surface pressure, sea surface temperature, specific humidity, total cloud cover, and solar downward short-wave radiation. The horizontal resolution of these variables is 1°×1° (longitude × latitude) for the period from 1979 to 2020. The study area of this study, i.e., East Asia, spans from 15°N to 55°N and from 70°E to 150°E.

2.3 Statistical methods

In this study, various statistical methods have been employed to investigate the characteristics and the associated drivers of spring drought severity across East Asia. These methods include the Empirical Orthogonal Function (EOF) analysis, correlation/regression analysis, composite analysis, trend analysis, and lagged correlation/regression analysis. The correlation coefficient (r) is calculated as follows:

\[
r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} 
\] (2)

where \(x_1, x_2, ..., x_n\) and \(y_1, y_2, ..., y_n\) is a random variable for two groups of data (Ahlgren et al. [48]). The range of correlation coefficient \(r\) is between [-1, 1]. The greater the absolute value of \(r\), the greater the correlation between the two sets of data.
3 CHARACTERISTICS OF SPEI AND ITS LEADING VARIABILITY

Figure 1 shows the climatology, trend, and standardized deviation of SPEI in the spring for the period 1979–2020. The climatology of SPEI shows that Northwestern China, North China, and Mongolia typically featured an arid climate (Fig. 1a). The trend in SPEI reveals that Northwestern China, North China, and Mongolia experienced a drying trend over the past several decades, while Southwestern China displayed a wetting trend (Fig. 1b). The standardized deviation of SPEI is relatively large in Northwestern China, North China, and Southwestern China, implying that there exists a larger variability of drought in these regions (Fig. 1c).

Figure 2 further presents the first EOF mode (EOF1) of SPEI variability in East Asia during the boreal spring. EOF analysis is also known as principal component analysis (PCA) (Pearson [49]). The first EOF mode (EOF1) has the most obvious evolution of spatial distribution characteristics and coefficients over time and has the largest interpretation variance. Only EOF1 is analyzed here. The EOF1 shows a north-south dipolar pattern, with opposite signs of SPEI anomalies between northeastern and southwestern parts of East Asia (Fig. 2a). Moreover, the primary component of EOF1 (PC1) shows an overall upward trend, generally changing from negative phases to positive phases (Fig. 2b). Combined with the spatial characteristics of EOF1, it indicates that Northwestern China, North China, central China, and Mongolia have experienced a drying trend, while Southwestern China has experienced a wetting trend.

Figure 3 shows the SPEI composite results of extremely dry and wet years based on a 1.5 standardized deviation of the de-trended PC1. The years with standard deviations higher than 1.5 are characterized by dry surface conditions in Northwestern China, North China, and Mongolia and wet surface conditions in Southwestern China (Fig. 3a). The opposite results were obtained for the years with standard deviations below 1.5 (Fig. 3b). The differences in SPEI between the positive and negative phases of PC1 further highlight the dry-wet pattern, where the absolute value of the SPEI differences can be higher than 4.5 in North China and Southwestern China (Fig. 3c).
4 POSSIBLE CAUSES OF THE LEADING SPEI VARIABILITY IN EAST ASIA

4.1 Local physical processes

Figure 4 displays the lagged correlations between PC1 and the SPEI. The signal of the East Asian dry-wet patterns appeared four months before spring. In periods with two- and zero-month advance, the correlation coefficients between PC1 and SPEI become more significant, with the main dry areas occurring in Northwestern China, North China, and Mongolia, while wet areas in Southwestern China.

The SPEI variations are closely related to the temperature and precipitation. As illustrated by Fig. 5, the anomalous dryness in Northwestern China, parts of...
North China, and Southern Mongolia corresponds to increased air temperature (left panels) and decreased precipitation and soil moisture (middle and right panels, respectively) four and two months preceding the spring drought (left panels). By comparison, the anomalous wetness in Southwestern China is correlated with abnormal temperature and precipitation patterns, opposite to those in the dry areas. These significant lagged correlation patterns also imply that the dry-wet variations of East Asian drought, as revealed by the EOF1, possess a potential for subseasonal and seasonal predictions.

Figure 6 shows the spatial distributions of regressions of geopotential height and horizontal winds onto the PC1 over East Asia. The results show that preceding the spring dry and wet variations, an abnormal high pressure accompanied by anticyclonic circulation occurred over Northwestern China and Mongolia, and an abnormal low pressure accompanied by cyclonic circulation existed over Japan. North China is located between the anomalous high and low pressure systems and is affected by northerly wind anomalies.

Figure 7 further presents the regression patterns of water vapor flux, total cloud cover, and solar shortwave radiation onto PC1. The results show that the water vapor flux anomalies are closely linked to the wind anomalies. The drying areas such as Northwestern China, North China, and Mongolia are primarily featured by divergent anomalies of water vapor fluxes. The variability of precipitation is directly controlled by local vertical velocity anomaly, and anomalous ascent (descent) leads to excessive (deficient) precipitation (Ni and Hsu [50]; He and Li [51]). According to isentropic gliding mechanism, the climatological isentropic surfaces tilt northward with altitude in the extratropics, and anomalous northerly...
A southerly (southerly) wind generates descent (ascent) anomaly by gliding along the sloping isentropic surfaces (Hoskins et al. [52]; Wu et al. [53]; He [54]), associated with anomalous divergence (convergence) in lower troposphere. Therefore, the dry areas are accompanied by water vapor divergence, reduced total cloud cover, and increased short-wave solar radiation due to the anomalous anticyclone and stronger descending motions. By comparison, the anomalous wetness in Southwestern China has obtained increased water vapor transport from the north Pacific, increased total cloud cover, and decreased solar radiation. As a result, the increased surface air temperature and reduced precipitation favor anomalous dry conditions in Northwestern China and North China and vice versa in Southwestern China.

4.2 Possible remote forcing
The tropical SST anomalies can exert significant impacts on weather and climate extremes in East Asia. Fig. 8a displays the correlation coefficients between PC1 and the SST, which shows that the spatial patterns of dry North China and wet Southwestern China are correlated with the La Niña-like SST anomalies, coinciding with warm SST anomalies in the western Pacific and cold SST anomalies in the central and eastern Pacific and the Indian Ocean. Consequently, the SST gradients between the western Pacific and the central and eastern Pacific increase. Fig. 8b shows the regression patterns of PC1 with geopotential height and horizontal winds, which show anomalous high and low pressures over East Asia, which resemble a Rossby wave-train linked to the SST anomalies. When the western Pacific Sea temperature rises, convective activities are motivated, abnormal high pressure will be generated over the northwest of Mongolia, Alaska, and the western coastal areas of the United States.
while obvious abnormal low pressure will appear over Japan, forming a “+–+” teleconnection wave train propagating from west to east.

Previous studies have indicated that SST changes in the Northern Indian Ocean and the tropical Northern Atlantic affect circulation systems in the Northwestern Pacific region through air-sea interactions, which has a significant impact on the weather and climate in East Asia (Kim and Hong [55]; Chen et al. [56]). The western Pacific (10°N–20°N, 120°E–180°), the middle Eastern Pacific (−5°S–15°N, 120°W–160°W), and the Northern Indian Ocean (−10°S–10°N, 70°E–120°E) are thus selected as three key ocean areas to define a new SST index:

$$S = 2 \times SST_1 - SST_2 - SST_3$$  \hspace{1cm} (3)

The correlation coefficient $r$ between $S$ and PC1 is about 0.514, which has passed the significance test (Fig. 9a), indicating that the tropical zonal SST gradient in the Indo-Pacific region is significantly correlated with the spring dry and wet variations in East Asia. When the Indo-Pacific SST gradient increases, dry (wet) surface conditions tend to occur in Northwestern China, North China, and Mongolia (Southwestern China). In addition, the results of Figs. 9c and 9d are consistent with those of Fig. 7a and Fig. 4e, indicating that the tropical Pacific SST anomalies could significantly influence the spring dry and wet variations over East Asia by triggering atmospheric circulations.

**5 SUMMARY AND DISCUSSION**

Based on the global SPEI data calculated by the Penman-Monteith method and the ERA5 reanalysis product from 1979 to 2020, this study investigates the characteristics and possible drivers of the spring dry and wet variations in East Asia. The main conclusions are as follows: (1) Over the past several decades, the leading variability in spring SPEI over East Asia has been characterized by a dipole pattern, with increased dryness (wetness) in Northwestern China, North China, and Mongolia (Southwestern China). (2) The leading mode of SPEI variability in East Asia during boreal spring by triggering atmospheric circulation.

It should be noted that our research shows that the
variability of spring dryness in East Asia signals 2–4 months in advance, which provides some help in predicting sub-seasonal and seasonal changes in the regional spring drought. Although our study suggests that the anomalous SSTs in the tropical Pacific may influence the spring drought in East Asia, these findings are primarily based on statistical analyses. Therefore, validation through numerical modeling experiments is critical for further substantiating the possible drivers. Furthermore, in addition to the tropical Pacific Ocean, the Northern Atlantic SST, and atmospheric variability, such as the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation, could also influence the spring drought in East Asia. However, how these factors interact synergistically with the Pacific SSTs remains unclear and requires further in-depth analyses in the future.

REFERENCES


Figure 9. (a) SST index averaged over the area in the box shown in Fig. 8a (bars) and the detrend PC1 (curve). (b), (c), and (d) respectively represent the regressions of 300-hPa geopotential height and horizontal winds, the water vapor flux and divergence, and the SPEI onto the SST index.


[38] LIU Y Y, CHEN L J. Features and possible causes for the


