Out-of-Phase Decadal Change in Drought Over Northeast China Between Early Spring and Late Summer Around 2000 and Its Linkage to the Atlantic Sea Surface Temperature

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Abstract Based on the standardized precipitation evaporation index (SPEI) and empirical orthogonal function (EOF) analysis, this article presents that the primary mode (i.e., a monosign pattern) of drought over Northeast China (NEC) in early spring (February-March-April, FMA) and late summer (July-August-September, JAS) shows an out-of-phase decadal change, which is characterized with a wetting polarity in FMA while a drying polarity in JAS approximately after 2000 as compared to the counterparts before that time. Such an out-of-phase decadal change is generally supported by the decadal changes in atmospheric circulations. Compared to the former period, during the latter period, the equivalent barotropic cyclonic (anticyclonic) anomalies dominate northeastern Asia and an anomalous ascending occupies NEC in FMA (JAS), which help to alleviate (aggravate) drought over NEC. In addition, decreases in water vapor transport toward the NEC region act in the aggravation of drought in JAS, while the variation of drought in FMA is not closely connected to the change in water vapor transport. Further analyses indicate that the shifts of the sea surface temperature (SST) in the tropical and mid-high latitude Atlantic Ocean from a cold phase to a warm phase also play a role in the decadal change of drought in FMA and JAS, respectively, through their influences on the above atmospheric circulations with the aid of downstream propagation of wave trains. Hence, the seasonal dependence of the Atlantic SST and atmospheric circulations contributes to the out-of-phase decadal change of drought in NEC.

1. Introduction

Drought, which features a shortage of water that results from uneven precipitation and evaporation, is a common meteorological disaster throughout the world (H. J. Wang et al., 2012). The prevalence of drought could exert substantial impacts on agricultural production, human life, social development, and economic prosperity. The Northeast China (NEC) region, which is located in the mid-to-high latitudes, is a vital agricultural base of China. Under the background of global warming, extreme drought events hit NEC frequently and caused serious economic losses (Dai, 2012; Liu et al., 2012; Yu et al., 2014; L. Zhang & Zhou, 2015). For example, the spring-summer drought in 2017, which lasted 5 months, resulted in an economic loss of about CNY seven billion (S. Wang et al., 2019). Thus, it is essential to study the characteristics and physical mechanisms of drought in NEC in order for disaster prevention and mitigation.

Previous studies have documented some physical factors that have significant effects on summer wet/dry conditions in NEC. For instance, Fu and Zeng (2005) indicated that the negative phase of the North Atlantic Oscillation (NAO) contributes to less precipitation in NEC. H. Wang and He (2015) showed that the meridional Pacific-Japan (PJ) pattern and zonal Silk Road pattern (SRP) may modulate the spatial distribution of summer rainfall over NEC and hence affect in situ drought. The Eurasian warming could also lead to extreme droughts via its influence on the SRP pattern (J. Zhang et al., 2019), and the reduction of spring sea ice in the Barents Sea favors the occurrence of summer drought in NEC through the bridge of the polar-Eurasia teleconnection pattern (Li et al., 2018).

In recent years, more and more attentions have been shown to the decadal variability of climate in East Asia. The well-known climate shift in the late 1970s was previously reported to play a role in the arid tendency...
over northern China including NEC (R. Huang et al., 2012; Y.Y. Huang & Li, 2015; H.J. Wang, 2002). As is known, a new decadal shift of climate system occurred approximately in the late 1990s (Cummins et al., 2005; Huangfu et al., 2015; Peterson & Schwing, 2003; Xu et al., 2015). Zhu et al. (2011, 2015) indicated that the shift of the Pacific Decadal Oscillation (PDO) from a positive phase to a negative phase in the late 1990s exerts a remarkable impact on the decadal change of summer precipitation in eastern China through weakening the East Asian westerly jet stream. Han et al. (2015) further revealed that the negative PDO phase may induce an anomalous anticyclonic circulation over NEC and consequently result in a decrease of local precipitation in summer. In addition, the relationship between the summer precipitation over NEC and the El Niño-Southern Oscillation (ENSO) has strengthened after the late 1990s (Han et al., 2017). The phase change of the Atlantic Multidecadal Oscillation (AMO) in the 1990s could also aggravate summer drought in NEC via two Eurasian wave patterns which resemble the SRP and the polar-Eurasian pattern, respectively (Li et al., 2020).

However, previous studies regarding the characteristics and physical mechanisms of drought in NEC mostly focused on the summer season. Given that droughts also occur in the spring season, some questions arise naturally: (1) How is the decadal change of drought over NEC in the spring time? (2) Are there any differences in the decadal change of drought between the spring and summer time? (3) If so, what are the physical reasons underlying such differences? This study is motivated to address these questions.

The reminder of this paper is structured as follows. Section 2 introduces the data and methods used in this study. The decadal changes of drought in NEC during the spring and summer seasons are compared in Section 3. The possible physical mechanisms responsible for the differences of decadal changes in spring and summer droughts in NEC are examined in Section 4, in terms of atmospheric circulations and the role of the Atlantic sea surface temperature (SST). The main findings are concluded in Section 5.

2. Data and Methods

There is no uniform standard to measure the process of drought due to its complexity (Heim, 2002). Overall, a drought index is supposed to capture the intensity and extent of drought. So far, many indices have been defined such as the Palmer drought severity index (Dai et al., 2004; Palmer, 1965), the standardized precipitation index (SPI, McKee et al., 1995), and the standardized precipitation evaporation index (SPEI, Vicente-Serrano et al., 2010). In general, the Palmer index has large errors because of its dependence on the quality of soil moisture data. The SPI index is simple in calculation and owns the applicability of multi-time scales. The SPEI index is not only as easy as the SPI index for calculation, but also incorporates the characteristic of the Palmer index, which considers evapotranspiration at the same time. Hence, SPEI is a better index to describe the characteristics of drought, and has been widely used in recent studies (Chen & Sun, 2015). In this study, we employ the SPEI index for analysis. The SPEI data are obtained from the Global SPEI database (http://spei.csic.es/database.html). As a validation, the monthly precipitation and temperature data derived from the CN05.1 gridded data set are also used. This data set was constructed from observations at 2400 stations in China and has a resolution of 0.25° × 0.25° (Wu & Gao, 2013). To reflect detailed changes of drought, the SPEI index is calculated at one-month time scale from the precipitation and temperature data. The potential evapotranspiration (PET) is calculated following the method of Thornthwaite (1948).

The monthly atmospheric reanalysis data with a resolution of 2.5° × 2.5° are derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996). The extended reconstructed SST version 5 (ERSST v5) data with a resolution of 2° × 2° are provided by the National Oceanic and Atmospheric Administration (NOAA) (B. Huang et al., 2017). The time period for the current analysis of this study is from 1980 to 2018.

The empirical orthogonal function (EOF) analysis (Lorenz, 1956) is performed for the SPEI index over NEC (42°–54°N, 110°–135°E) during early spring (February-March-April, FMA) and late summer (July-August-September, JAS), respectively. Composite, regression, and correlation analyses are adopted to explore relationships of the drought over NEC with the large-scale atmospheric circulations or SST. The statistical significance is determined by the student’s t-test.
Figures 1a and 1b show the spatial distributions of the first EOF mode (EOF1) for the FMA and JAS SPEI over NEC, respectively. The EOF1 modes in FMA and JAS account for 59.3% and 57.5% of their respective total variances, and both behave monosign variations in the target region. Seen from the nine-years smooth curves (black lines) in Figures 1c and 1d, the principal components of EOF1 modes (PC1s) feature pronounced interdecadal changes. Of particular interest, the PC1s of FMA and JAS generally display an out-of-phase decadal variation approximately around 2000, after which the FMA condition tends to become wetter while the JAS condition becomes drier. This out-of-phase decadal change around 2000 between FMA and JAS over NEC is demonstrated to be significant at the 99% level as determined from the nine-years moving t-test (Figure 2). In the following, two subperiods, that is, 1980–1999 (P1) and 2000–2018 (P2), are selected as composites to represent this decadal change.

Figure 3 depicts the differences in SPEI between the P2 and P1 periods for FMA and JAS, respectively. A strong positive SPEI center in FMA and a sizable negative center in JAS are clearly observed. In other words, the NEC region is wetter in FMA in the latter period (P2) compared to the former period (P1), whereas the case is almost opposite in JAS.

To further illustrate the FMA-JAS opposite decadal change, Figure 4a plots the time-latitude cross section of the composite difference in SPEI that is averaged over 110°−135°E between the P2 and P1 periods. The result indicates that there is a transition in sign during May-June. Before this time, the SPEI anomalies lie in the positive phase. After that time, however, the SPEI anomalies switch to the negative phase. Impressively, the centers of positive and negative anomalies right appear in FMA and JAS, respectively. We also performed the same analysis using the CN05.1 data (Figure 4b). The missing data in the grids outside China are replaced with values derived from the solving Poisson’s equation via relaxation. It is found that Figure 4b shows an overall similarity to Figure 4a. This similarity validates the out-of-phase decadal change of FMA and JAS droughts over NEC.
4. Possible Reasons for the Out-of-Phase Decadal Changes in FMA and JAS Droughts Over NEC

4.1. Associated Atmospheric Circulation Anomalies

To figure out the crucial atmospheric circulation regimes that are related to the drought over NEC, we analyzed the simultaneous regressions of 200 hPa horizontal winds, 500 hPa geopotential heights, and 850 hPa horizontal winds, respectively, with the PC1 in FMA and in JAS over the course of 1980–2018 (Figure 5). No matter whether in FMA or in JAS, associated with the drought over NEC are anticyclonic circulation anomalies at the upper and lower layers and positive height anomalies at the middle troposphere over northeastern Asia, which presents an equivalent barotropic structure.

Figure 6 shows the composite differences of above atmospheric circulations between the P2 and P1 periods. It is of interest to find that the result from the composite differences is generally consistent with that shown in Figure 5. Compared to the former period (P1), during the latter period (P2), cyclonic anomalies dominate northeastern Asia in the upper and lower troposphere, concurrent with negative height anomalies in the middle troposphere during FMA (Figures 6a–6c). According to Figure 5, such circulation anomalies are helpful for the alleviation of drought in NEC. Some studies also demonstrated that negative height anomalies prevailing in the mid-low troposphere contribute to the enhancement of activities of cold vortices and favor the wetting over NEC (Hu et al., 2010; Zhao & Sun, 2007). To the contrary, during JAS, the NEC region is controlled by anticyclonic anomalies from the upper troposphere to the lower troposphere (Figures 6d–6f), which helps to aggravate the drought over NEC through weakening cold vortices in this region.

Anomalies in the above atmospheric circulations are also related to anomalous convergence and divergence over NEC. As shown in Figure 7a, during FMA, the convergence anomalies in the lower level and divergence anomalies in the upper level are observed, which is accompanied by an anomalous ascending in NEC.

**Figure 2.** Nine-years moving t-test for PC1 in (a) FMA and (b) JAS during 1980–2018. Red dashed lines represent the 99% significance level.

**Figure 3.** Composite differences of SPEI in (a) FMA and (b) JAS between 2000–2018 and 1980–1999. Regions above the 90% significance level are dotted.
The anomalous ascending is beneficial for the wetting through enhancing convective activities and adiabatic cooling (Huaman & Schumacher, 2018; Manganello et al., 2012). In contrast, during JAS, the NEC region is occupied by the divergence anomalies in the lower level and convergence anomalies in the upper level, which consequently excite anomalous descending in NEC (Figure 7b). Given that the anomalous descending is unfavorable for the moisture accumulation and adiabatic cooling, the drought tends to be aggravated in NEC. Hence, the seasonal differences in vertical motion show a contribution to the out-of-phase decadal change of FMA and JAS droughts over NEC.

Figure 8a shows the composite differences of the FMA water vapor flux that is vertically integrated from the surface to 300 hPa between the P2 and P1 periods. It clearly indicates an insignificant change in water vapor transport toward the target region from the P1 period to the P2 period. The correlation of the net moisture flux in NEC with the FMA PC1 is −0.11, which is lower than the 90% significance level (Figure 8c). This result suggests that the variation of drought over NEC in FMA is not closely connected to the change in water vapor transport. That is to say, the dynamical condition plays a dominant role in the decadal change of FMA drought over NEC. During JAS, the decadal change of the water vapor flux (Figure 8b) coincides with the anomalous pattern of the low-level horizontal winds. In the P2 period, with respect to the P1 period, anomalous northerly airflows across the eastern boundary of NEC prevent the moistures over the Pacific Ocean from being transported to the target region. Seen from Figure 8d, we can notice that the variation of net moisture flux over NEC is in pace with the JAS PC1. The correlation coefficient between them reaches 0.76 and is significant at the 99% level. This implies that the drought variation over NEC in JAS is closely linked to the change of moisture budget. In other words, both the dynamical condition and the water vapor transport contribute to the decadal change of JAS drought in NEC. The seasonal difference of the role of water vapor transport in the drought variation over NEC may be attributed to the different climate backgrounds in FMA and JAS, which deserves further investigation.

To sum up, the decadal change in atmospheric circulations is in general in good agreement with the out-of-phase decadal changes of FMA and JAS droughts over NEC. During the latter period (P2), compared to the former period (P1), anomalous barotropic cyclonic circulations are dominated over northeastern Asia in FMA, which can strengthen activities of cold vortices. Meanwhile, anomalous ascending prevails over NEC. As a result, the NEC region tends to become wetter in the P2 period than in the P1 period, and thus
the drought is alleviated. To the contrary, in JAS, anomalous barotropic anticyclonic circulations are predominated, which can not only weaken cold vortices but also lead to anomalous divergence of water vapor flux. Furthermore, the NEC region is under the control of the anomalous descending. These situations are favorable for the occurrence of drought and thus the drought in NEC is aggravated.

4.2. Impact of the Atlantic SST

Figures 9a and 9b depict the correlations of the PC1s in FMA and JAS with the synchronous SST in the Atlantic Ocean, respectively. It can be detected that the FMA PC1 is highly correlated to the SST in the tropical Atlantic Ocean (10°–25°N, 70°–30°W). In comparison, the large extent of significant correlations for the JAS PC1 and SST are located in the mid-high latitudes of the Atlantic Ocean (48°–65°N, 50°–10°W). Following, we defined the area-averaged SST over the above two key regions as indices (TAO-SST and
MHAO-SST) to estimate the SST variation in the tropical and mid-high latitude Atlantic Ocean, respectively. Their respective temporal variations are illustrated in Figures 9c and 9d. During FMA, the TAO-SST exhibits a decadal change approximately around 2000, which conforms to the decadal change in FMA PC1. The correlation coefficient between them is 0.43, significant at the 99% level. During JAS, the MHAO-SST also shows a decadal shift from a negative phase to a positive phase. The correlation coefficient between the MHAO-SST and PC1 in JAS is −0.47 (significant at the 99% level). To examine the spatial pattern of SPEI related to the FMA TAO-SST and JAS MHAO-SST, we plotted the regressions of the SPEI with the FMA TAO-SST and JAS MHAO-SST. During FMA (Figure 10a), associated with the warm TAO-SST is positive SPEI anomalies across NEC. In contrast, during JAS (Figure 10b), associated with the warm MHAO-SST is negative SPEI anomalies throughout NEC. Thus, we hypothesize that the shifts of the TAO-SST and MHAO-SST from a cold phase to a warm phase may play important roles in the decadal changes of FMA and JAS droughts over NEC, respectively.

Figure 6. Composite differences of (a and d) 200 hPa winds (m s$^{-1}$), (b and e) 500 hPa geopotential height (gpm), and (c and f) 850 hPa winds (m s$^{-1}$) between 2000–2018 and 1980–1999 in (a–c) FMA and (d–f) JAS. Shadings from the light to dark indicate regions significant at the 90%, 95%, and 99% level, respectively. Northeast China is outlined by the rectangle.
Figure 7. Latitude-height cross section of the composite differences of meridional wind (vector, m s\(^{-1}\)), vertical velocity (vector, 10\(^{-2}\) Pa/s), wind divergence (shading, 10\(^{-7}\) s\(^{-1}\), regions above the 90% significance level are dotted), and geopotential height (contour, gpm) averaged along 110°–135°E between 2000–2018 and 1980–1999 in (a) FMA and (b) JAS.

Figure 8. Composite differences of (a and b) water vapor flux (kg m\(^{-1}\) s\(^{-1}\)) vertically integrated from the surface to 300 hPa between 2000–2018 and 1980–1999 and (c and d) normalized time series of moisture budget (red line) and PC1 (blue line) over NEC in (a and c) FMA and (b and d) JAS. Regions above the 95% significance level are shaded and Northeast China is outlined by the rectangle in (a and b).
With the aid of atmospheric Rossby waves, the climate variability in a downstream region is generally tele-connected with upstream disturbances. Thus, to explore the candidate physical mechanisms underlying the linkage of the Atlantic SST to the drought over NEC in FMA and JAS, we have examined the regressions of 500 hPa eddy geopotential height (defined as the deviation of geopotential height from its zonal mean) with the TAO-SST and MHAO-SST to check their influences on the downstream atmospheric circulations.

Figure 9. Correlations of the PC1 with the SST in the Atlantic Ocean in (a) FMA and (b) JAS, and the normalized time series of the SST averaged over (c) the tropical Atlantic Ocean (10°–25°N, 70°–30°W) in FMA and (d) the mid-high latitude Atlantic Ocean (48°–65°N, 50°–10°W) in JAS during 1980–2018. Regions above the 95% significance level in (a and b) are dotted. Red lines in (c and d) indicate the 9-years moving mean of the time series.

Figure 10. Regressions of SPEI with (a) TAO-SST in FMA and (b) MHAO-SST in JAS during 1980–2018. Regions above the 90% significance level are dotted.
As shown in Figures 11a, during FMA, the positive TAO-SST anomalies are associated with a meridional tripole pattern over the Atlantic sector, accompanied by a zonal wave train with the positive and negative anomalies alternating from the Atlantic Ocean toward northeastern Asia via northern Europe and central Asia. Similar distribution can also be noticed in the upper-tropospheric horizontal winds, which exhibits a quasi-barotropic structure. Accordingly, the westerly anomalies are dominant at the mid-latitudes of 40°–60°N and the easterly anomalies are predominant to its north side in the upper troposphere of Eurasia (Figure 12a). This anomalous pattern suggests a southward displacement of the East Asian polar front jet stream (EAPJ), since the active region of the EAPJ is climatologically located around 50°–60°N. The EAPJ is known to play a dynamical role in the vertical motion by evoking a secondary circulation. As the secondary circulation aroused by the EAPJ, ascending anomalies are introduced to the left-hand side of the exit of jet stream (Ding, 2005), where the NEC region is right located (Figure 12c). The anomalous ascending over NEC provides a favorable dynamic condition to alleviate local drought.

During JAS, associated with the positive MHAO-SST anomalies, a well-organized wave train with the alternative positive and negative anomalies extends from the high latitude Atlantic Ocean eastward to northeastern Asia (Figure 11b). As a consequence, the NEC region is dominated by the positive height anomalies (anticyclonic anomalies). Accordingly, anomalous westerlies and easterlies reside on the north and south sides of NEC in the upper troposphere, respectively (Figure 12b). The westerly anomalies on the north side of NEC hint at a southward shift of the EAPJ, as the climatological location of the EAPJ in JAS is located north of 60°N. Similarly, the EAPJ can evoke a secondary circulation with the descending anomaly on the right-hand side of the exit of jet stream (Ding, 2005), which is just situated in NEC (Figure 12d) and favors the aggravation of drought in situ. The easterly anomalies to the south side of NEC (Figure 12b) indicate a weakening of the East Asian subtropical jet stream (EASJ). The weakening of the EASJ is unfavorable for the occurrence of precipitation (Lan & Zhang, 2011), and hence helps to aggravate the drought in NEC. In addition, the anticyclonic circulation anomalies associated with the warm WHAO-SST can decrease the water vapor transport from the Pacific Ocean to NEC (Figure not shown), which is favorable for the occurrence of drought.

Therefore, the atmospheric teleconnection processes from the North Atlantic Ocean to northeastern Asia can play important roles in bridging the SST signal and the large-scale atmospheric circulations downstream. The season-dependent effects of the Atlantic SST on anomalous wave trains over Eurasia make for the out-of-phase decadal changes between FMA and JAS droughts over NEC.

In addition, Figure 9 also shows significant SST signals over the high-latitude North Atlantic in FMA and over the western tropical North Atlantic in JAS. Thus, we further checked the role of these two SST signals. Similarly, we defined HAO-SST as the area-averaged SST over the high-latitude North Atlantic (55°–70°N, 60°–10°W) and defined WTAO-SST as the area-averaged SST over the western tropical North Atlantic (10°–25°N, 80°–50°W). In FMA, the correlation of PC1 with the HAO-SST is 0.34 (significant at the 95% level), lower than that with the TAO-SST. In JAS, the correlation of PC1 with the WTAO-SST is −0.37, also lower than that with the MHAO-SST. The wave train pattern related to the HAO-SST (WTAO-SST) in FMA (JAS) generally approximates that associated with the TAO-SST (MHAO-SST). However, the anomalous negative center over northeastern Asia moves northward in FMA and the positive center around NEC is somewhat insignificant in JAS (Figure not shown). This result suggests a less remarkable influence of the high-latitude North Atlantic (the western tropical North Atlantic) than the tropical Atlantic Ocean (the mid-high latitude Atlantic Ocean) during FMA (JAS).
5. Conclusion

In this study, based on the SPEI index, we have examined the spatial and temporal characteristics of drought over NEC in FMA and JAS. The result shows clear evidence that the EOF1 mode of FMA and JAS SPEI in NEC behaves a monosign variation. Moreover, their PC1 series both exhibit an interdecadal change approximately around 2000, but with an out-of-phase variation in tendency. From the former period to the latter period, the drought over NEC tends to alleviate in FMA while aggravate in JAS.

The candidate physical mechanisms underlying the out-of-phase decadal changes of FMA and JAS droughts over NEC are preliminarily explored from the perspective of anomalies in atmospheric circulations and the Atlantic SST. The results indicate that the large-scale atmospheric circulations associated with the drought over NEC in FMA and JAS are both featured by the equivalent barotropic anticyclonic anomalies over northeastern Asia. In addition, the decrease in water vapor transport toward the target region also contributes to the drought of NEC in JAS. Decadal changes in the above atmospheric circulations generally support the out-of-phase changes of FMA and JAS droughts over NEC. Compared to the former period, during the latter period, anomalous equivalent barotropic cyclonic circulations dominate northeastern Asia and anomalous ascending motion prevails over NEC in FMA. These situations are favorable for the alleviation
of drought in NEC. In contrast, in JAS, the NEC region is dominated by anomalous anticyclonic circulations and descending motion. Meanwhile, the water vapor transport to the target region also decreases. These conditions favor the aggravation of drought over NEC.

Further analyses reveal that the Atlantic SST anomalies also play important roles through their influences on the downstream atmospheric circulations via the teleconnection wave trains. During FMA, the shift of the tropical Atlantic SST from a cold phase to a warm phase links to the configuration that consists of a meridional tripole pattern in the Atlantic sector and a zonal wave train pattern extending from the Atlantic Ocean toward northeastern Asia. Consequently, anomalous cyclonic circulation is introduced over northeastern Asia and anomalous ascending motion appears over NEC, which helps to alleviate local drought. During JAS, a wave train pattern extending eastward from the high latitude Atlantic Ocean to northeastern Asia, the warming of the SST in the mid-high latitudes of the Atlantic Ocean can induce anomalous anticyclonic circulation and descending motion over NEC, which is favorable for the aggravation of in situ drought.

These findings are encouraging for better understanding of the variation of drought in NEC. Certainly, the analyses are just based on the observational and reanalysis data and focus on the influence of the Atlantic SST. Numerical simulations are necessary to verify the findings of this study in future researches. In addition, the mechanisms for the variation of drought over NEC are very complicated. Other processes and other external factors may also act, which needs further investigations in the future.

Data Availability Statement

The SPEI data are obtained from the Global SPEI database at http://spei.csic.es/database.html. The NCEP/NCAR reanalysis data and the NOAA ERSST v5 data are accessible at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html and https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html, respectively. The CN05.1 gridded temperature and precipitation data used for the calculation of this study are derived from Wu and Gao (2013) and can be downloaded online at http://doi.org/10.5281/zenodo.4451758.

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