In-Phase Variations of Spring and Summer Droughts over Northeast China and Their Relationship with the North Atlantic Oscillation

YUEPENG HU,a,b BOTAO ZHOU,a,b TINGTING HAN,a,b HUIXIN LI,a,b AND HUIJUN WANGa,b

a Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Ministry of Education, Joint International Research Laboratory of Climate and Environment Change, Nanjing University of Information Science and Technology, Nanjing, China

b School of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China

ABSTRACT: Analyses of the standardized precipitation evaporation index (SPEI), using the season-reliant empirical orthogonal function (S-EOF) method, indicate that the second leading mode of drought over Northeast China features an in-phase variation from spring to summer. Such an in-phase change is closely connected to the persistence of geopotential height anomalies around Lake Baikal. The positive height anomalies around Lake Baikal, with an equivalent barotropic structure in the troposphere, can decrease water vapor transport into Northeast China and induce anomalous descending motion over Northeast China during both seasons, favoring precipitation deficit and high temperature in situ and hence resulting in the synchronous variations of spring and summer droughts. Further investigation reveals that the spring North Atlantic Oscillation (NAO) plays a notable role in the in-phase change of spring–summer droughts over Northeast China. The positive phase of spring NAO could induce spring drought over Northeast China directly through its influence on the above atmospheric circulations via a zonal wave train emanating from the North Atlantic. Meanwhile, it can also increase the soil moisture in central Siberia by enhancing the local snow depth. The wetter soil moisture in the following summer, in turn, increases the meridional temperature gradient between the middle and high latitudes and then forces westerly anomalies around 60°N, consequently yielding positive height anomalies around Lake Baikal that favor the occurrence of summer drought over Northeast China. Therefore, the spring NAO is hypothesized to contribute to the in-phase variations of spring–summer droughts over Northeast China through the combined roles of zonal wave train and central Siberian soil moisture.

SIGNIFICANCE STATEMENT: Northeast China suffers from frequent droughts severely in recent decades. Thus, it is urgent to understand the physical mechanisms of drought in Northeast China. Using the season-reliant empirical orthogonal function (S-EOF) analysis, this study indicates that the second mode of S-EOF shows an in-phase change of drought from spring to summer over Northeast China, which is associated with the persistence of geopotential height anomalies around Lake Baikal. Our study further reveals that the spring NAO plays a pronounced role in the in-phase change of spring–summer droughts over Northeast China, through the combined roles of zonal wave train and the soil moisture in the central Siberian plateau. These findings are encouraging for better understanding of drought in Northeast China and are also important for disaster prevention and mitigation.

KEYWORDS: Atmosphere; Atmospheric circulation; Drought; North Atlantic Oscillation; Climate variability; Interannual variability

1. Introduction

Drought, which is characterized by water shortage for a period, is a major meteorological disaster throughout the world. Under the background of global warming, drought events have increased over most parts of the world and exerted major threats to natural ecosystems and human lives (Dai 2011, 2013; Romm 2011; IPCC 2021). Northeast China, known as the granary of China, also suffers from frequent droughts severely in recent decades (Liang et al. 2011; Liu et al. 2015). For example, the recent prolonged drought occurring in Northeast China from spring to summer in 2017 heavily damaged the crop production and caused an economic loss of CNY 7 billion (Wang et al. 2019). Thus, it is of great significance to improve the understanding of physical mechanisms associated with the variations of droughts in Northeast China for the purpose of disaster prevention and mitigation.

A number of studies have been devoted to understanding the variations of summer wet/dry events over Northeast China as well as their related physical mechanisms, and great progress has been achieved (e.g., Zhu 2011; Wang and He 2015; Fang et al. 2018; Han et al. 2018; H. Li et al. 2018; Zhang et al. 2019; Du et al. 2020, 2022). For instance, the East Asian summer monsoon (EASM) has been documented to significantly influence wet/dry spells in Northeast China on the interannual time scale. A strengthening of the EASM tends to increase the precipitation over Northeast China. Conversely, the weakening of the EASM corresponds to the occurrence of

Denotes content that is immediately available upon publication as open access.

Corresponding author: Botao Zhou, zhoubt@nuist.edu.cn

DOI: 10.1175/JCLI-D-22-0052.1

© 2022 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
drought in Northeast China (Huang et al. 2007; Z. Wu et al. 2009; Shen et al. 2011; Zhang and Zhou 2015). The zonal Silk Road pattern and the meridional Pacific–Japan pattern have also been highlighted to play important roles in the spatial distribution of summer precipitation and thus affect the interannual variation of drought in Northeast China (Wang and He 2015). Du et al. (2020) proposed that the negative phase of the North Atlantic Oscillation (NAO) may be a driver of extreme drought in northern China. The interannual variation of summer drought/flooding over Northeast China is also closely associated with the anomalies in the tropical sea surface temperature (SST) (Han et al. 2018, 2020), and the reduction of spring sea ice in the Barents Sea is conducive to the occurrence of summer drought over Northeast China via the bridge of the polar–Eurasian teleconnection (H. Li et al. 2018; Chen et al. 2022; Du et al. 2022). On the decadal time scale, Han et al. (2015) indicated that the Pacific decadal oscillation shifting from a positive phase to a negative phase in the late 1990s contributes to the decrease of summer precipitation over Northeast China and hence results in an increase of drought in situ. The phase shift of the Atlantic multidecadal oscillation also accounts for the decadal variation of drought in Northeast China through the Eurasian wave train (Li et al. 2020).

As spring precipitation is vital to agricultural production, some attention has been gradually shown to the variations of spring precipitation or drought over Northeast China in recent years (e.g., Lu et al. 2020; Zhang and Sun 2020; Hu et al. 2021; Li et al. 2021; M. Zhang et al. 2022). M. Zhang et al. (2022) showed that the out-of-phase (in-phase) change of precipitation in Northeast China from April to May is related to the SST variability in the midlatitude North Atlantic (the northern tropical Atlantic). Lu et al. (2020) indicated that the positive SST anomalies in the northern tropical Atlantic benefit the increase of spring precipitation on the interannual time scale. The decadal warming of the tropical Atlantic SST contributes to the alleviation of drought over Northeast China in early spring (Hu et al. 2021) and the interdecadal decrease of sea ice in the Barents Sea could lead to an interdecadal increase of precipitation over Northeast China in late spring (Li et al. 2021).

In brief, previous studies regarding the characteristics and physical mechanisms of drought in Northeast China mostly focused on the spring or summer season independently. Recently, prolonged drought events have occurred frequently in northern China, especially between spring and summer (X. Li et al. 2018; Zhang et al. 2018; Yu and Zhai 2020). However, the candidate physical mechanisms behind the spring–summer droughts over Northeast China are not clear. Exploration of this issue could deepen our scientific understanding of the variations of drought over Northeast China and could also improve the prediction of summer drought when one drought event begins in spring. Thus, this study is motivated with the

![Image](https://example.com/image.png)

**Fig. 1.** The second mode of S-EOF of (a) spring and (b) summer SPEI over Northeast China and (c) the corresponding normalized PC2 time series during 1980–2018.
aim to address the following questions: 1) What is the characteristic of the spring–summer droughts over Northeast China? 2) What is the candidate physical mechanism underlying the variations of spring–summer droughts over Northeast China?

2. Data and methods

It is challenging to objectively measure the process of drought due to its complexity (Heim 2002). So far, many drought indices have been defined, including the Palmer drought severity index (Palmer 1965; Dai et al. 2004), the standardized precipitation index (SPI; McKee et al. 1995), and the standardized precipitation evaporation index (SPEI; Vicente-Serrano et al. 2010). In short, the Palmer index has a shortcoming in that the built-in fixed time scales and autoregressive characteristics have not been solved (Guttman 1998). The SPI index is easy to calculate and shows multiscalar characteristics. However, it only takes precipitation into account.
consideration. Compared with the Palmer and SPI indices, the SPEI index has the advantages of sensitivity to the change in evapotranspiration and simplicity in calculation (Chen and Sun 2015a,b; Wang et al. 2015). In the present study, the SPEI index at 1-month time scale, which represents the meteorological drought, is utilized for analysis. The SPEI data are downloaded from the global SPEI database (http://spei.csic.es/database.html).

We also use the monthly atmospheric reanalysis data with a horizontal resolution of $2.5^\circ \times 2.5^\circ$, which are obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kalnay et al. 1996). The monthly reanalysis data of snow depth and top-layer (0–7 cm) soil moisture with a horizontal resolution of $1^\circ \times 1^\circ$ are derived from the ECMWF reanalysis version 5 (ERA5) (Hersbach et al. 2019). The monthly precipitation and surface air temperature datasets (version 4.03) with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ are collected from the Climatic Research Unit (CRU) (Harris et al. 2014). Data for the NAO index, which is defined as the time series of the first leading empirical orthogonal function (EOF) mode of the sea level pressure (SLP) over the Atlantic sector (20°–80°N, 90°W–40°E), are downloaded from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based.

Wang and An (2005) developed a season-reliant empirical orthogonal function (S-EOF) method to capture season-dependent
modes of the climate evolution. This method is applied in this study for the SPEI over Northeast China (38°–54°N, 110°–135°E) during spring [March–May (MAM)] and summer [June–August (JJA)] to obtain the coupled patterns of spring-summer droughts. Specifically, the spring and summer SPEIs over Northeast China are treated as two variables to construct a combined covariance matrix. Then, the EOF is performed for the combined covariance matrix. Each S-EOF mode contains two sequential spatial patterns that represent the evolution of spring–summer droughts over Northeast China and share the same principal component (PC).

The horizontal wave activity flux $W$ is calculated based on the following equation (Takaya and Nakamura 2001):

$$W = \frac{p}{2|U|} \left[ U(\psi' \psi' - \psi' \psi'_{\psi'}) + V(\psi' \psi'_{\psi'} - \psi' \psi'_{\psi'}) \right]$$

where $\psi$ is the perturbation streamfunction, $U$ is the zonal component and $V$ is the meridional component of the basic flow, $|U|$ is the horizontal wind velocity, and $p$ is the pressure scaled by 1000 hPa.

The time period used for the current analysis is 1980–2018. The two-tailed Student’s $t$ test is used to determine the statistical significance of regression and correlation analyses, before which the linear trends of all data are eliminated.

3. In-phase variations of spring–summer droughts over Northeast China

We first conducted the S-EOF analysis on the spring and summer SPEIs over Northeast China for the period of 1980–2018 to identify the leading modes of the spring-summer droughts. The result indicates that the first leading mode (S-EOF1) and the second leading mode (S-EOF2) account for 28.5% and 19.4% of the total variance, respectively. Based on North et al. (1982), the first two leading modes are independent from each other and are statistically separated from the remaining modes. The spatial distribution of the S-EOF1 mode features an out-of-phase variation of spring–summer droughts over Northeast China, and the corresponding time series (PC1) presents a distinct decadal change around 2000 (figure not shown). Such an out-of-phase decadal change in drought over Northeast China has been previously addressed by Hu et al. (2021). The spatial distribution of the S-EOF2 mode is characterized by an in-phase change of SPEI.
from spring to summer over the target region (Figs. 1a,b), and the time series of the S-EOF2 (PC2) exhibits an apparent interannual variation (Fig. 1c). In the current study, we focus on the in-phase change of SPEI from spring to summer over Northeast China.

To further demonstrate the in-phase change of spring–summer droughts over Northeast China, we have examined the anomalies of spring and summer precipitation, surface air temperature, and SPEI as projected against the PC2 series, respectively. No matter whether in spring or in the following summer season, associated with the positive values of the PC2 are uniformly negative precipitation anomalies (Figs. 2a,d) and positive surface air temperature anomalies (Figs. 2b,e) across the Northeast China region. Under the condition of precipitation deficit and high temperature, Northeast China is dominated by the significant negative SPEI anomalies in spring and summer (Figs. 2c,f).

Figure 3 shows the PC2-regressed anomalies of spring and summer horizontal winds at 200 hPa, geopotential heights at 500 hPa, and horizontal winds at 850 hPa. Associated with the in-phase change of spring–summer droughts over Northeast China, the spring atmospheric circulations exhibit an equivalent barotropic structure with the significant anticyclonic circulation anomalies in the troposphere around the Lake Baikal region (Figs. 3a–c). Interestingly, the anomalies of summer atmospheric circulations (Figs. 3d–f) show a general resemblance to the counterparts in spring. Some previous studies revealed that such positive height anomalies in the middle to lower troposphere contribute to suppress activities of cold vortices and hence favor the occurrence of drought over Northeast China (Zhao and Sun 2007; Hu et al. 2010).

To further examine the connection between the equivalent barotropic circulation system and the in-phase change of spring–summer droughts over Northeast China, we defined area-averaged 500-hPa geopotential height over the Lake Baikal region (40°–55°N, 90°–120°E) as the Baikal high pressure index (BHI). The correlation coefficients of the PC2 with the spring and summer BHI are 0.40 and 0.35, respectively, both significant at the 95% level. We also calculated the correlation of BHI between the spring and summer seasons. Given that the S-EOF1 mode of spring–summer droughts over Northeast China features an out-of-phase variation, the PC1 signal in the spring and summer BHI was removed before the calculation in order to avoid its interference. After removing the PC1 signal, the spring BHI and the summer BHI are positively correlated with a coefficient of 0.30, which is significant at the 90% level.

The above atmospheric circulation anomalies may play a decisive role in the water vapor transport to Northeast China. In regard to climatology, the Northeast China region is mainly controlled by the westerly water vapor transport in spring, which originates from the low latitudes and the mid- to high latitudes (Fig. 4a). During the summer season (Fig. 4c), the southwesterly water vapor transport originating from the Pacific Ocean and the westerly water vapor transport from the mid- to high latitudes converge in Northeast China. Furthermore, the water vapor transport from the low latitudes is larger than that from the mid- to high latitudes in each season. Figures 4b and 4d present the anomalies of spring and summer water vapor transport flux regressed upon the PC2, respectively. It is clearly observed that the PC2-related anomalies in the water vapor transport flux coincide with the anomalous pattern of low-level horizontal winds as shown in Fig. 3. Corresponding to the anticyclonic circulation anomaly over Lake Baikal, there is a prevalence of anomalous northerly and easterly water vapor transport over Northeast China, which indicates an anomalous divergence of water vapor flux (Figs. 4b,d). As a consequence, the water vapor transport into Northeast China is generally reduced, thereby contributing to the occurrence of drought over Northeast China in both seasons.
The regression of the vertical motion along 110°–135°E against PC2 is displayed in Fig. 5. It is of interest to find that the Northeast China region is occupied by significant descending anomalies in both seasons, unfavorable for the occurrence of in situ precipitation. In addition to the impact on the precipitation, the anomalous descending motions also contribute to the decrease of total cloud cover over Northeast China (Figs. 6a,d), favoring more incoming shortwave solar radiation to warm the land (Figs. 6b,e). The warming of land then enhances the outgoing longwave radiation from the land surface to the atmosphere (Figs. 6c,f), leading to a higher temperature. The combination of precipitation deficit and high temperature during both seasons helps to aggravate the drought over Northeast China (Fig. 2).

In summary, the persistence of quasi-barotropic anticyclonic circulation anomalies over Lake Baikal from spring to summer is key to the in-phase change of spring and summer droughts over Northeast China. The anticyclonic circulation anomalies (positive geopotential height anomalies) not only weaken cold vortices but also decrease water vapor transport into Northeast China. Concurrently, anomalous descending prevails in Northeast China in both seasons, contributing to the precipitation deficit and high temperature. All these situations favor the simultaneous occurrence of drought over Northeast China in the spring and summer seasons.

Fig. 6. Regressions of (a),(d) total cloud cover (%), (b),(e) net surface shortwave radiation flux (W m⁻²), and (c),(f) net surface longwave radiation flux (W m⁻²) in (a)–(c) spring and (d)–(f) summer with the PC2 during 1980–2018. Downward radiation flux is represented by positive values. Regions above the 90% significance level are dotted.
4. Role of the NAO in the in-phase variations of spring–summer droughts over Northeast China

As a large-scale dominant atmospheric mode in the North Atlantic sector, the NAO has been documented to exert great influence on the dry/wet climate in China (e.g., Sun and Wang 2012; Tian and Fan 2012; Zhou 2013; Du et al. 2020, 2022). A question arises naturally whether the NAO plays a role in the in-phase variations of spring–summer droughts over
Northeast China. In this section, we attempt to address this issue although other factors may also play roles.

Figure 7a shows the regression of spring SLP over the North Atlantic sector with the PC2. A seesaw pattern featuring positive and negative SLP anomalies respectively residing in the south and north flanks of the North Atlantic, which corresponds to a positive phase of NAO, can be obviously detected. We calculated the correlation between the PC2 and the spring NAO and found that their correlation reaches 0.42 (Fig. 7c), higher above the 99% significance level. However, the summer SLP anomalies regressed against the PC2 generally delineates no significant signal in the North Atlantic sector (Fig. 7b). Thus, we hypothesize that the spring NAO may play an important role in the in-phase change of spring–summer droughts over Northeast China.

Some studies indicated that the NAO exerts impacts on the climate variability in a downstream region with the aid of atmospheric Rossby wave (Sun et al. 2008; Sun and Wang 2012; Zhou 2013; Zhou and Cui 2014; Du et al. 2020). Therefore, to investigate the candidate physical process linking the spring NAO and the in-phase change of spring–summer droughts over Northeast China, we checked the 300-hPa horizontal wave activity flux and 500-hPa geopotential height anomalies in spring and summer in association with the spring NAO (Fig. 8). During the springtime (Fig. 8a), the NAO-related wave activity flux is strong over the North Atlantic sector, concomitant with a meridional dipole pattern in the geopotential height. Besides, the wave activity flux emanates from the Atlantic eastward to northeastern Asia and induces a zonal wave train characterized by alternative positive and negative anomalies in geopotential height. Consequently, a positive height anomaly (an anticyclonic circulation anomaly) is introduced over the Lake Baikal region. The simultaneous correlation of the NAO with the BHI in spring is 0.42, significant at the 99% level. It means that the atmospheric teleconnection process associated with the spring NAO may stimulate positive height anomaly (anticyclonic circulation anomaly) around Lake Baikal, which favors the occurrence of spring drought in Northeast China (Figs. 3a–c).
During the summer season (Fig. 8b), the wave activity flux related to the spring NAO becomes much weaker over the North Atlantic sector, which cannot propagate the NAO signal downstream to influence the height anomaly around Lake Baikal. This can also be confirmed directly by the index correlation. The correlation coefficient between the spring NAO and the summer BHI is only 0.06, almost linearly independent to each other. Similar features can be observed in the PC2-related 300-hPa horizontal wave activity flux and 500-hPa geopotential height anomalies in spring (Fig. 9a) and summer (Fig. 9b).

How does the spring NAO influence the variation of summer drought over Northeast China? Naturally, due to the short memory of atmosphere, the propagation of spring NAO to the following summer needs to be accomplished by the aid of slowly varying boundary conditions. Previous studies indicated that the Eurasian snow depth or soil moisture in spring could modulate the climate over China in the following summer (B. Wu et al. 2009; Dumka et al. 2014; Shen et al. 2020; Sang et al. 2022; Sun et al. 2021). On this basis, we turn to discuss the possible role of snow depth and soil moisture in linking the spring NAO to summer atmospheric circulations.

As illustrated in Fig. 10, the positive phase of spring NAO corresponds to an anomalous ascending (Fig. 10a) and an increase of westerly water vapor transport (Fig. 10b) over central Siberia (65°–75°N, 105°–130°E). These atmospheric anomalies benefit the formation of snowfall (Xu et al. 2019) and hence enhance the spring snow depth in central Siberia (Fig. 10c). The simultaneous correlation between the NAO and the snow depth averaged in central Siberia [snow depth index (SDI)] in spring is 0.33, significant at the 95% level. The enhanced spring snow depth in central Siberia can cause a wetter soil condition, which may persist into the following summer. From Fig. 11a we do notice that an increase of spring snow depth is followed by higher summer soil moisture in central Siberia. The correlation between the spring SDI and the summer soil moisture averaged in central Siberia [soil moisture index (SMI)] is 0.38, higher above the 95% significance level. Therefore, the positive spring NAO can result in wet soil moisture in central Siberia through the influence on snow depth. The effect of spring NAO on the summer soil moisture can be further verified by Fig. 11b, which indicates that the positive phase of spring NAO is associated with a positive anomaly of summer soil moisture in central Siberia.

Considering that the positive phase of spring NAO is also related to a significant decrease of spring snow depth in mid-latitude Asia (Fig. 10c), we checked the correlation of spring snow depth averaged in the region (50°–58°N, 90°–100°E) with PC2. It is found that their correlation coefficient is −0.16, below the 90% significance level. Hence, we focused on the role of snow depth in central Siberia.

Figure 12a shows the time series of the summer SMI and the PC2, which indicates that they are significantly correlated with a coefficient of 0.45 (above the 99% significance level). It suggests that the SMI may closely link to the variation of summer drought over Northeast China. A key issue is how the SMI affects the summer drought over Northeast China. Previous studies highlighted that anomalous variation of soil moisture may give rise to large-scale atmospheric circulation anomalies via land–atmosphere coupling (Halder and Dirmeyer 2017; Zhang et al. 2017; Sang et al. 2022). As shown in Fig. 12b, the wetter soil moisture in central Siberia is associated with negative anomalies of local sensible heat flux, while its connection with the latent heat flux in situ is less significant (figure not shown). The negative sensible heat flux anomalies could directly decrease the overlying air temperature, which eventually increases the meridional temperature gradient between the middle and high latitudes (Fig. 12c). According to the results of previous studies, this process reflects the dominant influence of soil moisture on the temperature (Seneviratne et al. 2010; Koster et al. 2016; Gao et al. 2018; Sang et al. 2022). In line with the thermal wind relationship, the increased meridional temperature gradient tends to strengthen the westerly anomalies around 60°N (Fig. 12d). Such a distribution of zonal wind anomalies acts to generate the meridional dipole pattern in the geopotential height field, with positive height anomalies (anticyclonic circulation anomalies) and negative height anomalies (cycloclonic circulation anomalies) to the south and north flanks, respectively (Fig. 12e). As a result, the Lake Baikal region is dominated by the positive height anomalies, beneficial for the occurrence of summer drought over Northeast China (Fig. 3e). The correlation between the SMI and the BHI during the summer season is 0.37, significant at the 95% level. The wetter soil moisture in central Siberia also corresponds to an anomalous descending over Northeast China (Fig. 13a) and a decrease of
water vapor transport into Northeast China (Fig. 13b). According to Figs. 4d and 5b, these atmospheric situations benefit the occurrence and development of summer drought over Northeast China. Note that Fig. 12d also shows easterly anomalies around 40°–50°N and westerly anomalies to its south. Since the climatological location of the East Asian jet core is located around 40°N, this anomalous pattern suggests a southward anomaly of the East Asian jet, which may exert impacts on summer precipitation over southern China (Lu 2004; Zhou and Wang 2006; Shen et al. 2020). However, this issue is beyond the scope of the present discussion.

To sum up, the spring NAO plays a pronounced role in the in-phase variations of spring–summer droughts over Northeast China. The positive phase of spring NAO directly leads to spring drought through the zonal wave train originating from the North Atlantic, and the soil moisture in central Siberia acts as a bridge linking the spring NAO to the summer drought over Northeast China. For a solid foundation, we also used other datasets, including the atmospheric reanalysis from the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015), the snow water equivalent from the Finnish Meteorological Institute (FMI; Takala et al. 2011), and the top-layer (0–10 cm) soil moisture from the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004), to replot the above figures and get similar results.
5. Conclusions

In this study, we have examined the spatiotemporal characteristics of spring–summer droughts over Northeast China by use of the S-EOF analysis on the spring and summer SPEI. The result shows clear evidence that the S-EOF2 mode, accounting for 19.4% of the total variance of the variability in the spring–summer SPEI, features an in-phase variation between spring drought and summer drought over Northeast China. The persistence of equivalent barotropic anticyclonic circulation anomalies (positive height anomalies) over Lake Baikal is key to the in-phase change of spring–summer droughts over Northeast China. The anticyclonic circulation anomalies (positive height anomalies) could reduce the water vapor transport into Northeast China. Meanwhile, anomalous descending prevails over Northeast China. These conditions are unfavorable for the occurrence of precipitation and thus result in a deficit of precipitation over Northeast China. In addition, the anomalous descending over Northeast China tends to decrease the total cloud cover, causing higher temperature through affecting shortwave and longwave radiation flux. The consequence of precipitation deficit and high temperature in both seasons favors the synchronous drought over Northeast China from spring to summer.

Further analyses suggest that the spring NAO plays a remarkable role in the in-phase variations of spring–summer droughts over Northeast China, through its impacts on the geopotential height around Lake Baikal. On one hand, during the spring season, the spring NAO directly affects the downstream atmospheric circulations through a zonal teleconnection wave train that extends eastward from the North Atlantic to Asia, and consequently causes the geopotential height anomalies over the Baikal region. On the other hand, the positive phase of spring NAO could increase soil moisture in central Siberia by enhancing the in situ snow depth. The wetter soil moisture in spring persists to the following summer and then increases the meridional temperature gradient between the middle and high latitudes, thereby resulting in westerly anomalies around 60°N and inducing positive geopotential height anomalies over Lake Baikal. Therefore, the effect of spring NAO on the in-phase change of spring–summer droughts over Northeast China is presumed to be accomplished with the help of the zonal wave train and the central Siberian soil moisture.

Overall, the findings obtained in this study provide a clue for better understanding of the variability of drought over Northeast China. Certainly, the current study just presents a preliminary explanation from the observational analysis and focuses on the impact of spring NAO. Due to the complexity of climate system, other factors, such as El Niño–Southern Oscillation (Zhang et al. 2018) and the sea ice in the Barents Sea (H. Li et al. 2018; Du et al. 2022; S. Zhang et al. 2022), may also act in the in-phase variations of spring–summer droughts over Northeast China, which deserves further in-depth investigation in the future studies in order to get a full picture for the understanding of the variability of drought.

Acknowledgments. The authors thank the editor and the three anonymous reviewers for their insightful comments and suggestions to improve the manuscript. Thanks are also due to Professors Haishan Chen and Jiangfeng Wei for helpful discussion during the revision. This research was supported by the National Natural Science Foundation of China (42025502) and the Postgraduate Research and Practice Innovation Program of Jiangsu Province (KYCX22_1145).

Data availability statement. The SPEI data are obtained from the Global SPEI database at http://spei.csic.es/database.html. The CRU precipitation and surface air temperature data are acquired from https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/. The NAO data are downloaded from https://

REFERENCES


Li, X., M. Zhang, Y. Zhang, and J. Ma, 2021: Possible connection between declining Barents Sea ice and interdecadal


Zhang, M., and J. Sun, 2020: Increased role of late winter sea surface temperature variability over northern tropical Atlantic in spring precipitation prediction over Northeast China.


