The North China/Northeastern Asia Severe Summer Drought in 2014

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ABSTRACT

In summer 2014, north China and large areas of northeastern Asia (NCNEA) suffered from the most severe drought of the past 60 years. This study indicates that the East Asian summer precipitation in 2014 exhibited a tripole anomaly, with severe negative anomalies in NCNEA, strong positive anomalies in south China, South Korea, and Japan, and intense negative anomalies in the western North Pacific. Along with the severe tripole precipitation anomalies, there were strong intensities of the Silk Road pattern, the Pacific–Japan pattern, and the Eurasian teleconnection pattern, which were responsible for the strong precipitation anomaly in 2014 through changes to the western Pacific subtropical high (WPSH) and the East Asian trough. Further analysis indicates that the sea surface temperature (SST) in the North Pacific was nearly the warmest in the past 60 years and, together with the strong SST warming in the warm pool region, thus caused the strong Pacific–Japan teleconnection pattern, southward positioning of the WPSH, and weakened East Asian summer monsoon. Additionally, the summertime sea ice cover in the Arctic Ocean was anomalous, resulting in high SST in the Laptev–Kara Sea and, hence, triggering a strong Eurasian teleconnection pattern and contributing to the severe drought of NCNEA. Furthermore, the intense warming over the European Continent and Caspian Sea favored the Silk Road pattern, also contributing to the southward positioning of the WPSH and the NCNEA drought. The NCNEA severe drought was therefore the joint result of Pacific SST anomalies, Arctic sea ice anomalies, and warming over the European Continent and Caspian Sea.

1. Introduction

Severe drought events are serious issues in north China, particularly since the end of the 1970s, when the East Asian monsoon became weakened and the monsoon rainfall decreased dramatically in north China (Wang 2001). As revealed by many previous studies, the weakening of the East Asian summer monsoon (EASM) in the late 1970s has contributed to the “southern flood–northern drought” pattern in China (Wang 2002; Yu et al. 2004; Ding et al. 2009). Drought events often cause serious problems for agriculture and human life in north China because of the shortage of water resources (Zhou and Chan 2007; Zhou et al. 2006, 2012). In response, China initiated an unprecedented south-to-north water diversion project beginning in the year 2010. Seven provinces in north China suffered from a severe drought in July–August (JA) of 2014, and some of these provinces experienced the most serious drought of the past 60 years. Meanwhile, large areas of northeastern Asia, including Mongolia and far eastern Russia, also received below-average summer rainfall. Our motivation for the present work was to investigate the atmospheric circulation anomalies, as well as the forcing from the sea surface temperature (SST) and Arctic Ocean sea ice in the context of global warming, and try to determine the physical mechanisms that were responsible for the severe drought in JA 2014.

Prior to the current study, there has already been various research conducted on north China drought events. Wei et al. (2004) analyzed the north China
drought in the summer of 1999 and 2000 and indicated that there was a quasi-stationary wave train over Eurasia (EU pattern; found by Wallace and Gutzler 1981), and there were positive and negative precipitation anomalies in northern Asia and southern China, respectively. In this case, the western Pacific subtropical high (WPSH) was weaker than normal, and thus the route of water vapor transport was more southward compared to normal years, leading to reduced water vapor transport to north China and decreased precipitation. Another study suggested that the winter North Atlantic Oscillation (NAO) has an in-phase correlation with eastern China summer precipitation, as determined by using two indices for the past 530 years, with the NAO leading the precipitation by 2–3 yr (Fu and Zeng 2005). On the impact of the decadal mode, Pei et al. (2015) indicated, based on a 400-yr historical dataset, that the positive (negative) phase of the Pacific decadal oscillation normally corresponds to a North China drought period (plentiful rainfall period). This relationship is, however, on the multidecadal time scale.

All the above studies focus on discussions of drought- associated atmospheric circulation features and atmosphere/ocean modes, but investigation into the physical mechanisms responsible for severe drought remains insufficient. We are interested in the drought of summer 2014, not only because it showed the largest drought intensity in the past half century, but also because this drought event occupied north China and large areas of northeastern Asia (NCNEA). Investigating such a wide-ranging severe drought in the context of global warming and studying its physical causes from the perspective of atmospheric circulation–SST–sea ice coupling will help to improve understanding of the predictability of drought and, hence, to project drought events in the future.

2. Materials and methods

Arctic sea ice extent was calculated from the Arctic sea ice concentration data, derived from the Hadley Centre’s HadISST1 with 1° × 1° resolution for 1870–2014 (Rayner et al. 2003). Monthly mean SST data were obtained from NOAA with 2° × 2° resolution for 1854–2014 (Smith et al. 2008). Monthly mean atmospheric data were derived from the NCEP/NCAR (Kalnay et al. 1996). The precipitation anomaly at a horizontal resolution of 2.5° × 2.5° (Chen et al. 2002) was obtained from the NOAA (http://www.esrl.noaa.gov/psd/). All the linear regression analyses were based on data with the linear trend having been removed. Since the north China precipitation anomaly was the largest in JA, our analysis focuses on the JA mean precipitation. In this paper, all observed anomalies in 2014 were computed relative to the climatology of 1979–2014, and the linear trend is not excluded. Therefore, the magnitude of observed anomalies in 2014 is larger than those of linear regression.

Several climate indices were used to facilitate the analysis, including the EU pattern index, defined as

\[
\begin{align*}
-1.0H500_{(70^\circ-80^\circN,60^\circ-90^\circE)} + 2.0H500_{(45^\circ-55^\circN,90^\circ-110^\circE)} \\
- H500_{(15^\circ-45^\circN,120^\circ-140^\circE)} / 4,
\end{align*}
\]

and the Pacific–Japan teleconnection pattern (PJ pattern) index, defined as

\[
\begin{align*}
-1.0Vort_{(10^\circ-15^\circN,125^\circ-145^\circE)} + 2.0Vort_{(20^\circ-30^\circN,132.5^\circ-142.5^\circE)} \\
- Vort_{(30^\circ-40^\circN,120^\circ-135^\circE)} / 4,
\end{align*}
\]

where H500 represents the geopotential height at 500 hPa, Vort denotes the vorticity at 850 hPa, and the overbars denote the area average. The EU pattern and PJ pattern are based on the definitions of Wallace and Gutzler (1981) and Nitta (1987), respectively; however, appropriate modification is adopted. That is, we chose the regions that are most significantly correlated with the tripole precipitation anomaly pattern (please refer to Figs. 6a and 14e).

The Silk Road pattern (SR pattern) index is identified as the first leading principal component of the empirical orthogonal function for the 200-hPa meridional wind velocity anomalies in JA over the region of (30°–60°N, 30°–130°E) (Lu et al. 2002; Chen et al. 2013). To better exhibit the horizontal structure of the SR pattern, the regressions of 200-hPa meridional wind velocity and the Takaya–Nakamura (T–N) flux (Takaya and Nakamura 2001), anomalies are calculated (results shown in Fig. 9c). To identify the covariability relationship between the atmosphere (i.e., precipitation and geopotential height) and SST/sea ice coupling, singular value decomposition (SVD) analysis was employed. The WPSH index was defined as the area-averaged 850-hPa eddy geopotential height in the domain of (15°–30°N, 120°–150°E) (Huang et al. 2015). The EASM index was defined as the area-weighted mean of 850-hPa velocity in the domain of (30°–40°N, 115°–125°E), which is modified from Wang (2002) to describe the intensity of EASM in the north parts of East Asia.

3. The strong precipitation anomalies and the associated atmospheric circulation

We first plot the JA mean precipitation anomalies in 2014 over East Asia (Fig. 1), which clearly shows the
large-scale features of the precipitation anomalies, with intensive positive anomalies in south China, South Korea, and south Japan. Meanwhile, Mongolia, north Asia, and the eastern part of north China experienced considerably lower rainfall than normal, with the largest negative anomalies in central parts of north China, exceeding the record from 1979 (Fig. 2a) and even from 1958 (figure not shown). In addition, there are a large number of negative precipitation anomalies over the western North Pacific (Fig. 1). The spatial distribution of this summer precipitation anomaly resembles well the typical tripole rainfall pattern revealed by Nitta and Hu (1996) and Hsu and Lin (2007). We then defined a precipitation index (PI) to describe the strength of this tripole pattern as

$$\text{PI} = 0.25 \text{PI}_1 + 0.50 \text{PI}_2 - 0.25 \text{PI}_3$$

(positive and negative anomalies are given the same weighting factors), where PI1, PI2, PI3 are the area mean JA precipitation amounts in the three subregions marked in Fig. 1 from north to south. In the present study, the tripole precipitation anomaly pattern in Fig. 1 denotes the positive phase (i.e., PI1 < 0, PI2 > 0, and PI3 < 0). Therefore, positive phase years (1980, 1982, 1983, 1991, 1993, 1997, 1999, 2002, 2003, 2005, 2007, and 2014) and negative phase years (1979, 1981, 1985, 1986, 1988, 1990, 1994, 2004, 2011, and 2013) are defined, which are marked in Fig. 2c. Reasonably symmetric patterns are shown between the positive and negative precipitation anomaly years (Fig. 3), which is a well-known tripole precipitation anomaly pattern characterized by a zonally elongated and meridionally banded structure with signs changing alternatively from 20° to 50°N (Hsu and Lin 2007).

To better document the reason for the 2014 summer precipitation anomaly over East Asia, especially in northeast China, in the following analysis, we compared the atmospheric circulation anomaly in 2014 with that associated with the typical tripole rainfall anomalies, based on the data from 1979–2014. Subsequently, we show our analysis of the physical mechanisms relating to the precipitation anomaly.

The regressed velocity at 850 hPa against the PI is depicted in Fig. 4a. There is a well-organized meridional
pattern in East Asia and the northwestern Pacific, with alternate appearances of cyclonic and anticyclonic circulation systems from the tropical western Pacific to the East China Sea and Japan: namely, the PJ pattern (Nitta 1987), which is also called the East Asia/Pacific pattern teleconnection (Huang 1992). Specifically, during the positive phase, an anomalous anticyclone is evident in the western North Pacific between 15° and 30°N, indicating a stronger-than-normal southwesterly flow in southern China and a westerly flow in the region south of Japan. Thus, more moisture is transported to central-eastern China and Japan, leading to abundant precipitation. Meanwhile, there is an anomalous cyclone located over the Yellow Sea and the Sea of Japan, suggesting an anomalous northeasterly in northeast China, which is opposite to the climatological southwesterly. Therefore, less moisture is transported to north China, resulting in drought. This means that the positive phase of the PJ pattern corresponds to the weaker meridional winds over northeastern Asia or a weaker EASM. In addition, the weaker EASM leads to decreased summer rainfall in northeastern China and increased rainfall in south China. The PJ pattern is closely connected to the summer precipitation in East Asia and the WPSH. The correlation coefficients of the PJ pattern index with the PI, PI1, PI2, PI3, and the WPSH indices are 0.73, −0.36, 0.68, −0.81, and 0.40, respectively (Table 1), which are highly significant at the 95% confidence level. Meanwhile, a wave train originating from the Arctic Ocean (i.e., the


Fig. 4. (a) Regression maps of summer 850-hPa wind (units: m s⁻¹) anomalies with regard to simultaneous PI during 1979–2014. Light (dark) shaded regions indicate the values are significant at the 90% (95%) confidence level, based on the Student’s t test. (b) The 850-hPa wind anomaly (vectors) of JA 2014. The color shading indicates the anomalous magnitude of wind. The letters AC and C indicate the anomalous anticyclone and cyclone, respectively.
EU pattern is apparent (Wallace and Gutzler 1981; Nakamura et al. 1987), showing an anomalous cyclone, anticyclone, and cyclone in the Kara Sea, Lake Baikal, and Yellow Sea, respectively (Fig. 4a). There are also significant correlations between the EU pattern and the EASM-related indices, showing correlation coefficients of 0.61, −0.39, 0.63, −0.45, and −0.39 with the PI, PI1, PI2, PI3, and EASM indices (Table 1). The time series of PI, PI1, PI2, and EU are plotted in Fig. 5, indicating the close connections of PI with the PJ and EU indices and the synchronous stronger-than-normal intensity in JA 2014.

The observed velocity anomaly pattern for 850 hPa in summer 2014 is shown in Fig. 4b, which is reasonably similar to the regression pattern given in Fig. 4a. Both the PJ pattern and the EU pattern are apparent, along with the cyclonic circulation over the Yellow Sea and Korea and the weaker EASM. The presence of the EU pattern associated with the tripole precipitation anomaly is clearly proven by the regressed geopotential height fields at 500 and 200 hPa against the PI (Figs. 6a,b). The EU pattern originates from the high-latitude region of Europe, along with negative height anomalies in southern China and the midlatitudes of East Asia, implying that the WPSH is located more southward and is, thus, favorable to a weaker EASM. Furthermore, the observed geopotential height fields at 500 and 200 hPa (Figs. 6c,d) in summer 2014 have similar patterns as shown in Figs. 6a and 6b. As a result, the WPSH shifts southward, which would contribute to the increased precipitation in south China and Japan (Gong et al. 2011; He 2015). At the same time, the East Asian summer monsoon became weaker than normal, especially in the north parts of East Asia. The intensity of the 850-hPa wind in the domain of (30°–40°N, 115°–125°E) in the summer of 2014 is the weakest during 1979–2014 (figure not shown), thus leading to reduced summer precipitation in north China.

In addition to moisture, vertical motion also plays an essential role in inducing precipitation anomalies. Therefore, the change of summer vertical motion associated with the tripole rainfall anomaly was further examined. From the perspective of the vertical–meridional cross section of the wind, we show that the tripole precipitation pattern is closely associated with a quasi-barotropic and well-organized meridional overturning pattern (Fig. 7a), implying the potential impact of the PJ pattern (Hsu and Lin 2007). The results regressed against PI exhibit an anomalous ascending motion in south China (around 30°N) and an anomalous descending motion in northeastern China (around 40°N) and the South China Sea (centered at 20°N), which corresponds well to the location of the positive and negative summer precipitation anomalies (Fig. 3a). Interestingly, the observed distribution of JA 2014 (Fig. 7b) is quite close to the above pattern, with a quasi-barotropic meridional pattern. The northerly meridional wind anomalies in the lower troposphere between 30° and 40°N over East Asia further indicate a weaker summer monsoon circulation.

To summarize this section, we have found that the NCNEA severe drought was concurrent with the increased precipitation in south China, South Korea, and south Japan and the decreased rainfall over the South China Sea and tropical western Pacific. This tripole precipitation pattern was closely associated with the PI meridional pattern and the Europe–East Asia zonal pattern of atmospheric circulations. The apparent anomalies of the atmospheric circulation characterized by the PJ and EU patterns were favorable to the NCNEA drought in the summer of 2014 and the tripole precipitation pattern. Therefore, the next step is to try to determine why there were intense anomalies in the PJ and EU patterns from the perspective of the SST/sea ice forcing to the atmospheric circulation, both simultaneous
FIG. 6. Regression maps of summer (a) 500-hPa and (b) 200-hPa geopotential height anomalies (units: gpm) with regard to simultaneous PI during 1979–2014. Light (dark) shaded regions indicate the values are significant at the 90% (95%) confidence level, based on the Student’s $t$ test. (c) The 500-hPa and (d) 200-hPa geopotential height anomaly in JA 2014.
with and preceding the drought event, in order to detect some possible factors for use in the prior detection of severe drought events in China and East Asia.

4. Investigation of the physical mechanisms

In the above discussion, we address the linear relationship between the NCNEA severe drought and the anomalous atmospheric circulation characterized by the EU and PJ patterns. The question arises as to what caused these atmospheric circulation anomalies, which is important not just for the case of 2014, but also for the prediction of drought climate in future.

Given that the moisture transport is very important for the summer precipitation anomaly over East Asia, vertically integrated (from the surface to 300 hPa) water vapor transport flux (WVTF) anomalies in summer for the period 1979–2014 associated with the EU pattern and PJ pattern were further examined and then compared with those in 2014 summer. The EU-related WVTF pattern results in anomalous cyclonic water vapor transport in northeast Asia (including northeastern China and Korea), indicating decreased (increased) water vapor transport to north China and northeast Asia (Japan), corresponding to the positive EU phase (Fig. 8b). In addition, there are anomalous cyclonic and anticyclonic WVTF in the western and eastern north Eurasian continent, respectively, corresponding to the EU pattern (Fig. 8b). The PJ pattern also results in anomalous cyclonic WVTF in eastern China (Fig. 8a) and reduced water vapor transport to north China and northeast Asia. Evidently, the PJ-related WVTF is more significant over East Asia and the western Pacific than over other regions. It should be noted that the spatial distribution of the WVTF anomaly in the summer of 2014 is clearly consistent with that of the EU and PJ pattern (Fig. 8a, b). In general, the anomalous EU and PJ pattern atmospheric circulations contributed to the reduced water vapor transport to north China (Fig. 8c) and, therefore, caused the severe drought in 2014.

It should be noted that there is an obvious anomalous cyclone located over northeast China, Korea, and the Yellow Sea in both the EU and PJ patterns (Figs. 8a, b). In addition to the contribution of the EU and PJ patterns, the SR pattern, which originates at the entrance region of the Asian jet over the Mediterranean and Caspian Seas and propagates zonally along the core region of the Asian jet stream (Fig. 9c), also plays an important role in the formation of this anomalous cyclone (Enomoto et al. 2003; Enomoto 2004). When we plot the JA surface air temperature anomalies in the Eurasian area for 2014, we find that there are large positive anomalies in the Caspian Sea and the surrounding European Continent (Fig. 9a). Thus, the strong warming and associated low-level convergence and high-level divergence in this region can trigger the quasi-stationary Rossby wave pattern along the westerly jet (i.e., the SR pattern). The plotted meridional wind and wave activity flux anomalies at 200 hPa clearly exhibit the SR pattern (Lu et al. 2002; Enomoto et al. 2003; Enomoto 2004) and the wave sources in the Mediterranean Sea and Caspian Sea (Fig. 9b). This results in positive geopotential height anomalies in high-latitude Asia and negative anomalies in midlatitude East Asia, which would have been favorable for the NCNEA drought in 2014. Sun et al. (2008) also found...
that the convergence and divergence in the entrance area of the high-level jet stream, which is associated with the summer NAO, can trigger the quasi-stationary barotropic Rossby wave propagation along the jet stream and influence the East Asian summer climate.

Next, we attempt to determine what was responsible for the anomalous PJ pattern. Prior to our study, there were suggestions, based on both observational analysis and numerical experiments, that the tropical western Pacific (the warm pool region) SST anomaly (SSTA) can

FIG. 9. (a) Surface air temperature anomalies (shading) and the climatology (contours: 1979–2014); (b) meridional wind (shading; units: m s^{-1}) and wave activity flux (vectors; units: m^2 s^{-2}) anomalies at 200 hPa in JA 2014. (c) Regression maps of 200-hPa meridional wind anomalies (contour; units: m s^{-1}) and wave activity flux (vector; units: m^2 s^{-2}) associated with the simultaneous Silk Road pattern index during JA 1979–2014. Light (dark) shaded regions denote the anomalies are significant at the 90% (95%) confidence level from a two-tailed Student’s t test.

FIG. 8. Regression maps of vertically (from the surface to 300 hPa) integrated water vapor transport (vectors; units: kg m^{-1} s^{-1}; only those significant at the 90% confidence level are displayed) and corresponding magnitude (shading) anomalies during JA 1979–2014 with regard to the simultaneous (a) PJ pattern index and (b) EU pattern index. Dotted regions in (a),(b) indicate the magnitudes of anomalies are significant at the 90% confidence level, based on the Student’s t test. (c) Vertically integrated water vapor transport (vectors; units: kg m^{-1} s^{-1}) and corresponding magnitude anomalies during JA 2014.
trigger the planetary wave propagation northeastward, resulting in the PJ pattern (e.g., Nitta 1987). Kurihara and Tsuyuki (1987) proposed that the atmospheric convection activities over the Philippines could trigger a two-dimensional northward-propagating Rossby wave, which is similar to the observed PJ pattern. In the current investigation, we find that the SSTAs in the warm pool region (including the areas around the Philippines; Fig. 10d) were positive in 2014 relative to the 1979–2014 average, with considerable magnitudes. Thus, the PJ pattern could have been excited by the tropical Pacific SSTAs, according to the above theories. Meanwhile, because of the surface warming, summer 2014 saw an anomalous upward motion over the warm pool region (around 150°–180°E) and an anomalous downward motion in the western tropical region (around 100°–130°E; figure not shown), indicating a zonally oriented overturning circulation. The anomalous downward motion could further induce the meridional overturning circulation and the north–south wavelike pattern in the western North Pacific (Fig. 7b), which emanates poleward along the East Asian coast (i.e., the PJ pattern) (Hsu and Lin 2007).

The SSTAs in the North Pacific in summer 2014, with strong warming at low and high latitudes and relative cooling at midlatitudes (Fig. 10d), might also have contributed to the NCNEA drought. To illustrate this, we performed an SVD analysis between the detrended and standardized summer SSTAs and geopotential height anomaly at 500 hPa. The results, shown in Fig. 10, demonstrate that the first component of the SVD analysis (SVD1) of SST is similar to the SSTAs pattern in JA 2014, with intense North Pacific and east Pacific warming, central cooling, and tropical western Pacific warming. The time series of the SVD1 for SST and geopotential height at 500 hPa are correlated at 0.76 during 1979–2014. In the SVD1 of geopotential height, there are negative anomalies in midlatitude East Asia and positive anomalies in the north and south of the region, which is similar to the PJ pattern. This indicates an intense East Asian trough and southward positioning of the WPSH, which is favorable to the southward positioning of the mean JA East Asian rain belt and NCNEA drought. Meanwhile, the intensive warming in the northwest Pacific could also weaken the thermal contrast between northeast Asia and the northwest Pacific, thus reducing the summer East Asian monsoon intensity and decreasing the precipitation in NCNEA.

Meanwhile, the EU pattern in the geopotential height at 500 hPa also contributed to the severe drought and should be further addressed. In this regard, we speculate that the observed sea ice anomalies in the Arctic Ocean may have been involved in the Eurasian atmospheric circulation anomalies in 2014, based on previous studies on the relationship between sea ice and Northern Hemisphere climate (e.g., Liu et al. 2012; Wu et al. 2009; Wang et al. 2015). We then performed the SVD analysis on the detrended and standardized Arctic Ocean March–June sea ice extent (SIE) and JA geopotential
height at 500 hPa during 1979–2014. The spatial pattern of the first mode for 500-hPa geopotential height is similar to the observed pattern over the Eurasian area for 2014, with a well-organized EU-like pattern and negative anomalies in midlatitude East Asia, indicating a strong East Asian trough (Fig. 11a). The strong East Asian trough is associated with a southward shift of the WPSH, more frequent cold air activities, and a southward position of the summer rain belt, thus leading to the NCNEA drought and flooding in south China. For the March–June sea ice first mode, there are positive anomalies in the Greenland Sea–Barents Sea region and negative anomalies in the Laptev Sea of the Arctic Ocean, which is also similar to the observed sea ice extent anomalies in 2014 (Figs. 11b, c). This results in the highest SST being located in the Barents–Kara Sea–North Atlantic region and the subsequent triggering of the EU teleconnection pattern. Figure 11d indicates that these time series are closely related during the 36-yr period, with a correlation coefficient of 0.68, which is significant at the 99% confidence level based on the Student’s t test.
Because of the persistence of the sea ice anomalies from spring to summer, the SVD analysis on JA Arctic sea ice and JA 500-hPa geopotential height shown in Fig. 12 is quite similar to the above result in Fig. 11, with a correlation coefficient of 0.70 between the time series of the first modes during 1979–2014. The spatial pattern for the SVD1 of 500-hPa geopotential height (which can explain 34.2% of the total variance) is also close to the observation of JA 2014, with a clear EU-like pattern. In addition, the SVD1 for the JA sea ice is also spatially similar to the observed sea ice anomalies in JA 2014.

We also performed an SVD analysis on the summer precipitation and summer Arctic sea ice (Fig. 13). The spatial patterns of the JA precipitation and sea ice for the first mode are quite similar to the observed pattern of the 2014 precipitation and to the sea ice anomalies, respectively. The SVD1 for the JA precipitation can explain 33.9% of total precipitation variance, and the time series of the first precipitation mode is highly correlated with the PI index (0.93) during 1979-2014. Therefore, the Arctic sea ice extent anomalies were at least partly responsible for the observed EU teleconnection and NCNEA drought in 2014.
Another typical drought case for north China took place in 1980 (Fig. 14a), when the JA precipitation anomalies possessed a similar spatial pattern to that of 2014 (i.e., the tripole rainfall anomaly). North China experienced the second droughtiest climate in summer 1980, which was only weaker than that in summer 2014 (Fig. 2a). At the same time, the most severe drought occurred in the western North Pacific (Fig. 2c) while the most abundant precipitation was observed over south China, Korea, and Japan (Fig. 2b). Similarly, there was an obvious anomalous cyclone centered in Korea and an anomalous cyclone located in the subtropical western North Pacific in the WVTF field, leading to the decreasing of moisture in north China and increasing of moisture in south China, Korea, and Japan (Fig. 14b). The major regions of anomalous downward and upward motion coincided well with the major negative and positive precipitation anomaly (Fig. 14c). At a brief glance, one might have an impression that the intensity of the PI, EU pattern, and PJ pattern peaked synchronously in summer 1980 (Fig. 5). It further supports the speculation revealed by the present study that the anomalous EU and PJ patterns would contribute to a significant tripole precipitation anomaly over East Asia. To demonstrate this issue, we examined the 500-hPa geopotential height and 850-hPa vorticity anomalies in summer 1980. As expected, the geopotential height anomalies at 500 hPa (Fig. 14d) and the vorticity anomalies at 850 hPa (Fig. 14e) clearly show anomalous EU and PJ patterns, which resemble those in 2014. It should be pointed out that the anomaly of the SR pattern in summer 1980 was not as significant as that in summer 2014 (figure not shown). As revealed by Enomoto et al. (2003), the SR pattern could affect the atmospheric circulation near Japan. This implies that the impact of the SR pattern on the East Asian climate might be located more northward. As illustrated by Table 1, the linear correlations between the SR pattern and the precipitation anomaly over East Asia are not statistically significant. However, there is a close correlation between the SR pattern and the north part of the EASM, with a correlation coefficient of $-0.27$ (barely significant at the 90% confidence level). Therefore, the SR pattern could reinforce the impact of the EU and PJ patterns on the summer precipitation anomaly over NCNEA, especially in north China, as happened in summer 2014. Another important feature associated with the precipitation anomaly in summer 1980 is that the spatial distribution of Arctic sea ice anomaly in summer 1980 (Fig. 14f) resembled that related to the tripole precipitation anomaly (as shown in Figs. 12b, 13b) and that in summer 2014 (as shown in Fig. 12c). Thus, the effect of Arctic sea ice on the East Asian summer precipitation anomaly should be taken into account, which has not been paid enough attention.

5. Summary

In this study, we analyzed the severe drought in north China and northeast Asia in JA 2014, which was the
strongest case in approximately the past 60 years. Our investigation focused on the associated atmospheric circulation anomalies and the physical mechanisms that were responsible for these anomalies.

The results show that the severe drought in north China and northeast Asia was accompanied by successive rainfall in south China, South Korea, and south Japan. This precipitation anomaly pattern has been the principal mode in the East Asia–west Pacific region in recent decades. The atmospheric circulation anomalies during JA 2014 were characterized by the PJ pattern, the SR pattern, and the EU teleconnection pattern. The teleconnection patterns resulted in a stronger-than-normal East Asian trough and a southward shift of the WPSH. Further investigation indicated that the strong SSTA in the North Pacific, along with the positive–negative–positive SSTA from the North Pacific to the tropical Pacific, was highly correlated with the precipitation

FIG. 14. Anomalies of (a) precipitation (units: mm day$^{-1}$); (b) vertically integrated (from the surface to 300 hPa) water vapor transport (vectors; units: kg m$^{-1}$ s$^{-1}$); (c) vertical wind (vectors) and omega (shading) averaged along 120°–130°E; (d) 500-hPa geopotential height; (e) 850-hPa vorticity (× 10$^{-6}$ s$^{-1}$); and (f) sea ice extent (units: 10$^3$ km$^2$) in JA 1980, relative to the climatology of 1979–2014.
anomaly pattern in East Asia, via changes of the WPSH and East Asian trough and via the PJ pattern. Conversely, the EU pattern from north Europe to midlatitude East Asia, represented by the geopotential height anomalies at 500 and 200 hPa, was closely associated with the Arctic Ocean sea ice extent anomalies. The SVD analysis showed high correlation between the sea ice extent and the EU pattern. In addition, the strong warming in the Caspian Sea and the surrounding European Continent contributed to the SR teleconnection pattern and further resulted in a deepening of the East Asian trough and, thus, insufficient precipitation in NCNEA.

The SSTA in the Northern Hemisphere Pacific and the Arctic Ocean, sea ice anomalies, and the temperature in the Caspian Sea and European Continent have shown dramatic anomalies simultaneously in recent decades. As for the impact of global warming on the drought in the region, there have been indications that warming may lead to a southward shift of EASM in the future based on phase 3 of the Coupled Model Intercomparison Project (CMIP3), model simulations (Li et al. 2010). However, some regional model projections do not agree with such results. Here, we analyzed the 34 CMIP5 model results on the July–August precipitation change in the region (figures not shown). Results show that the east (west) part of NCNEA may have more (less) precipitation during 2016–35 and 2046–65, with considerable spread among models. Most of the models project significant increased precipitation in the whole region during 2080–99. Therefore, the joint result of Pacific SSTA anomalies, Arctic sea ice anomalies, and warming over the European Continent and Caspian Sea resulted in the strong atmospheric circulation anomalies that led to severe drought in north China and northeast Asia. One or two of these factors alone may not have resulted in such a severe drought in NCNEA. Therefore, seasonal prediction of NCNEA summer precipitation must consider not just the tropical Pacific SSTA, as is sometimes the case operationally, but also the North Pacific SSTA, the Arctic sea ice extent, and the thermal state in the Caspian Sea. Furthermore, as revealed by a number of other studies, the tropical Indian SSTA could also have an impact upon the WPSH and NCNEA precipitation, and the temperature in the south Indian Ocean (30°S–0°, 50°–110°E) also reached its highest in summer 2014 since 1958 (figure not shown). Therefore, the SSTA in the Indian Ocean should also be taken into account in seasonal precipitation predictions.

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