Circulation anomalies in the mid–high latitudes responsible for the extremely hot summer of 2018 over northeast Asia

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ABSTRACT
This study investigated the contributions of mid–high-latitude circulation anomalies to the extremely hot summer (July and August; JA) of 2018 over Northeast Asia (NEA). The JA-mean surface air temperature in 2018 was 1.2°C higher than that of the 1979–2018 climatological mean, breaking the record of the past 40 years. This study investigated the contributions of mid–high-latitude circulation anomalies to the extremely hot summer (July and August; JA) of 2018 over Northeast Asia (NEA). The JA-mean surface air temperature in 2018 was 1.2°C higher than that of the 1979–2018 climatological mean, breaking the record of the past 40 years. Countries in NEA have suffered severe challenges such as water shortage, electricity consumption, crop failure, and increase of heat-related illness. Thereby, the summer of 2018, as one extraordinary climate extreme, has aroused wide concerns of society.

1. Introduction
An extremely hot summer (refers to July and August (JA) in this study) occurred in 2018 over Northeast Asia (NEA), including North and Northeast China, southeastern parts of Mongolia, North Korea, South Korea, and southern parts of Japan. The surface air temperature was 1.2°C higher than its climatological mean (1979–2018), breaking the record of the past 40 years. Countries in NEA have suffered severe challenges such as water shortage, electricity consumption, crop failure, and increase of heat-related illness. Thereby, the summer of 2018, as one extraordinary climate extreme, has aroused wide concerns of society.

The summer temperature over NEA has exhibited a rising trend in the past few decades (e.g. Schaefer and Domroes 2009; Zhu et al. 2012). Particularly, an amplified warming has been identified from the mid-1990s (Chen and Lu 2014a; Dong et al. 2016; Hong, Lu, and Li 2017). Various mechanisms have been documented to explain this decadal warming, such as the increase in precipitation over South China (Chen and Lu 2014a), the decadal changes of the Silk Road Pattern (SRP) and Atlantic Multidecadal Oscillation (Hong, Lu, and Li 2017), and anthropogenic forcing (Dong et al. 2016). Accompanied by the warming of summer mean temperature, the occurrence frequency of extreme heat events over NEA has increased considerably (e.g. Choi et al. 2009; Wei and Chen 2011).
The warming background favors the occurrence of extremely hot summers, but it is not the only contributor (Lu and Chen 2016). The NEA summer temperature was found to be greatly affected by large-scale circulation anomalies. Usually, warm summers are associated with local positive anomalies of geopotential height (Gong, Pan, and Wang 2004; Zhu et al. 2012; Gao et al. 2014; Chen and Lu 2015; Chen et al. 2016). There are exceptions, however, such as the extraordinarily hot summer of 2016, during which a negative geopotential height anomaly was identified to cover the region of anomalous warming (Yeh et al. 2018). These local circulation anomalies related to the temperature variability over NEA may be induced by teleconnection patterns. For instance, the teleconnection patterns over the Eurasian continent can induce anomalous temperature over NEA (Sato and Takahashi 2006; Chen et al. 2016; Li and Ruan 2018). In addition, the Arctic variability (Gu and Yang 2006; Lee and Lee 2016) and the Okhotsk high (Sato and Takahashi 2007) have also been suggested to be associated with NEA summer temperatures. These studies highlight the important role of mid–high-latitude circulation in modulating the summer temperature over NEA.

Therefore, this study focused on the mid–high-latitude circulation anomalies responsible for the anomalous warming over NEA in JA 2018. We ignored tropical factors that may also affect NEA summer temperature, such as the Pacific–Japan pattern (Chen and Lu 2014b; Lee and Lee 2016), western North Pacific subtropical high (Cui et al. 2007; Imada et al. 2014), and local or remote SST forcings (e.g. Ham and Na 2017; Zhuang et al. 2018).

The paper is organized as follows: The datasets used in this study are described in section 2. The main results, including the local characteristics of temperature and circulation anomalies in JA 2018 and the remote influences of circulation from upstream regions are stressed in section 3. The final section summarizes our conclusions.

2. Data

The daily air temperature at 2 m and monthly circulation and temperature data at multiple levels were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis-1 dataset (Kalnay et al. 1996), extending from 1979 to 2018. The daily data were on the T62 Gaussian grid, and the monthly data had a horizontal resolution of 2.5° × 2.5°. The climatological mean of these 40 years was removed from the original daily or monthly data to calculate corresponding anomalies.

3. Results

Figure 1(a) shows the spatial distribution of the 2-m air temperature anomaly in JA 2018. This study focuses on JA because the temperature over NEA usually reaches its annual peak in these two months, during which the occurrence probability of extreme heat is the highest. Moreover, the temperature anomalies in JA 2018 were notably stronger compared to the adjacent June and September (figures not shown). The anomalous high temperature exhibited a band structure over NEA, stretching eastwards from 100°E to 135°E along 32.5°–47.5°N (marked by the rectangle in Figure 1(a)), covering North and Northeast China, southeastern parts of Mongolia, North Korea, South Korea, and southern parts of Japan. Temperatures in most of this domain were higher than local climatological means by more than 1°C. Particularly, the anomalies over southeastern parts of Mongolia, North and Northeast China were more than two times larger than local standard deviations. In addition to NEA, abnormal warming also appeared over Europe, West Asia, and northern Africa in JA 2018. The most significant warming, with an amplitude of above 3°C, was observed in northern Europe (60°–72.5°N, 15°–45°E), where the area-averaged anomaly was the largest of the past few decades, which is shown by the result in this section.

Figure 1(b) shows the time series of the JA-mean 2-m air temperature anomaly averaged over NEA (32.5°–47.5°N, 100°–135°E; NEA_TI). There was a significant increasing trend of surface air temperature during 1979–2018, with a rate of 0.3°C/decade. Summer of 2018 was the warmest of the past 40 years, with the temperature anomaly being 1.2°C, almost double the standard deviation of the temperature anomaly. Particularly, the JA-mean temperature was, respectively, 0.3°C and 0.12°C higher than in 1994 and 2016, two of the most extraordinarily hot summers ever reported in NEA countries (Lee and Lee 2016; Park and Schubert 1997; Yeh et al. 2018). Figure 2 illustrates the 200-hPa geopotential height anomaly in JA 2018. NEA was dominated by a strong positive anomaly of geopotential height, with the maximum center (more than 150 m) over North China. The positive anomaly of larger than two standard deviations occupied a large domain, corresponding well to the area of remarkable warming (Figure 1(a)). This is consistent with previous studies in that a local-intensified geopotential height facilitates the occurrence of a hot summer over NEA (e.g. Gong, Pan, and Wang 2004; Zhu et al. 2012; Chen et al. 2016), and suggests that the anomalous warming in 2018 was largely attributable to the circulation anomaly. The positive anomaly of geopotential height existed throughout the troposphere, exhibiting...
the strongest intensity at the upper level (figures not shown). It indicated a deep anticyclonic circulation anomaly locally, which favored atmospheric warming through enhancing downward solar radiation and adiabatic heating by subsidence. Accordingly, the high-temperature anomaly was not limited to the surface, but occurred in a thick atmospheric layer up to 200 hPa (figures not shown).

In addition, significant positive anomalies of geopotential height also appeared over northern Europe and the Caspian Sea, where abnormal high temperatures were detected. But was the enhancement of the geopotential height over NEA related to the circulation anomalies over those upstream regions? To examine the relationships between them, three circulation indexes were defined as the area-averaged geopotential height anomaly, respectively, over northern Europe (60°–72.5°N, 15°–45°E; NEU_ZI), the Caspian Sea (32.5°–47.5°N, 40°–65°E; CS_ZI), and NEA (35°–50°N, 100°–135°E; NEA_ZI). These regions are denoted as dashed rectangles in Figure 2.

The regressions of 200-hPa geopotential height anomaly onto NEU_ZI and CS_ZI are shown by Figure 3(a,b), respectively. Significant positive anomalies of geopotential height are found over NEA, indicating that the positive geopotential height anomalies over both northern Europe and the Caspian Sea favor the enhancement of geopotential height over NEA. The anomalies regressed onto NEU_ZI are characterized by a tripolar structure, with two significant positive anomalies, respectively, over northern Europe and NEA, and a negative anomaly between them. The associated wave activity flux, calculated as in Takaya and Nakamura (2001), clearly indicates that the wave train propagates from northern Europe to NEA. On the other hand, the regression onto CS_ZI is characterized by significant anticyclonic anomalies over the Caspian Sea and NEA, respectively. These anticyclonic anomalies resemble SRP-related anomalies (Hong and Lu 2016). Various previous studies have demonstrated that SRP-related wave trains show a feature of eastward propagation along the Asian jet (e.g. Lu, Oh, and Kim 2002; Enomoto, Hoskins, and Matsuda 2003; Ding and Wang 2005), despite the wave activity flux shown in Figure 3(b) being somewhat weak over central Asia. As illustrated above, the spatial distributions of the wave-like pattern related to NEU_ZI and CS_ZI are distinct, implying that the impacts of the circulation anomalies over northern Europe and the Caspian Sea on the NEA circulation may be independent. Considering the contribution of 2018, we repeated the above regression analysis by using the data of 1979–2017 and derived similar results (figures not shown), which confirms that the two teleconnection patterns shown in Figure 3 are statistically reliable.

Figure 4 shows the normalized time series of NEU_ZI, CS_ZI, and NEA_ZI. A striking feature is that these three indexes synchronously reached their largest values in 2018. Particularly, the normalized NEU_ZI and CS_ZI were both 2.4, and the normalized NEA_ZI was 3.0.
The correlation coefficients between the former two indexes and NEA_ZI were both significantly high: 0.61 between NEU_ZI and NEA_ZI, and 0.59 between CS_ZI and NEA_ZI, confirming the profound impacts of circulation anomalies over northern Europe and the Caspian Sea on the NEA circulation. However, NEU_ZI and CS_ZI were weakly related, with the correlation coefficient being 0.28 during 1979–2018. This is consistent with the speculation drawn from Figure 3. Therefore, it was very particular that the geopotential heights over the two upstream regions concurrently reached their highest values in JA 2018. These extreme anomalies over the upstream regions jointly resulted in the pronounced positive geopotential height anomaly over NEA.

The 2-m temperature anomaly regressed onto NEA_ZI is shown in Figure 5. The spatial distribution of the regressed temperature anomaly over NEA coincides well with the temperature anomaly in JA 2018 (Figure 1(a)), confirming the role of the local positive geopotential height anomaly in inducing the anomalous warming. In addition, significant positive temperature anomalies are apparent over northern Europe and the Caspian Sea, suggesting that anomalous warming over these two regions tends to occur concurrently with that over NEA. The area-averaged temperature anomalies over northern Europe and the Caspian Sea (marked by rectangles in Figure 1(a)) were further calculated (NEU_TI and CS_TI). The correlation coefficient between NEU_TI (CS_TI) and NEA_TI was 0.58 (0.36), significant at the 0.01 (0.05) level based on the Student’s t-test. This close relationship of temperature anomalies is established through the two teleconnection patterns over the Eurasian continent shown in Figure 3. The fact of simultaneous warming over northern Europe, the Caspian Sea, and NEA in JA 2018 (Figure 1(a)) coincided with this relationship. The temperature anomalies over northern Europe and the Caspian Sea (NEU_TI and CS_TI) both reached record-breaking highs in JA 2018 (Figure 4(d,e)), affected by the extremely intensified geopotential heights there (Figure 4(a,b)). Further, we repeated the above analysis using extended data (1968–2018) and another dataset (ERA-Interim), and derived consistent results (figures not shown) with the present ones.

4. Conclusion and discussion

This study investigated the circulation anomalies associated with the extraordinarily hot summer (JA) of 2018 over NEA. The 2-m air temperature in JA 2018 was 1.2°C warmer than its climatological mean, being the highest during the analysis period 1979–2018. The temperature anomalies were more than two times larger than the local interannual standard deviation over large parts of NEA, especially over southeastern Mongolia, North and Northeast China.

The anomalous warming over NEA in JA 2018 was caused by a local positive anomaly of geopotential height, which is consistent with previous studies (e.g. Gong, Pan, and Wang 2004; Zhu et al. 2012; Chen et al. 2016). Concurrently, anomalous high geopotential heights also appeared over northern Europe and the Caspian Sea in JA 2018. It was found that the upper-tropospheric geopotential heights over the two upstream regions and over NEA synchronously reached their strongest levels in JA 2018.

The circulation anomalies over both northern Europe and the Caspian Sea make crucial impacts on the circulation over NEA through initiating downstream wave trains, based on the results of regression analysis over 1979–2018. Particularly, the enhancement of geopotential height over northern Europe induces decreasing geopotential height to its south-east but increasing geopotential height over NEA, constituting a tripolar teleconnection pattern over the Eurasian continent. On the other hand, the geopotential height anomaly over the Caspian Sea can
cause an SRP-like teleconnection, with two consistent circulation anomalies appearing respectively over the Caspian Sea and NEA. Therefore, during JA 2018, the extremely intensified geopotential heights over both of the two upstream regions made joint contributions to forming the profound anticyclonic anomaly over NEA. This implies that to comprehensively understand the temperature variability over NEA, the role of both teleconnections should be emphasized. Furthermore, the sources of these two wave trains will be helpful for improving forecasts of extremely high temperatures over NEA, which is worthy of further exploration, especially for the wave train originating from northern Europe, which is not been well documented in the literature.

Due to the above two teleconnection patterns over the Eurasian continent, the temperature anomalies in NEA are closely related to those in both northern Europe and the Caspian Sea. As happened in JA 2018, under the control of the strongest anticyclonic anomaly locally, the two upstream regions also experienced their hottest summers on record.

This study, focusing on the extreme warming over NEA in 2018, did not distinguish decadal and interannual variations. However, as mentioned in the introduction, the temperatures over NEA show clearly strong decadal and interannual variations, which can also be found in the present results. The variations on these two-time scales may be due to different physical processes and therefore need investigating separately.

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