Influences of tropical circulation and sea surface temperature anomalies on extreme heat over Northeast Asia in the midsummer of 2018

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ABSTRACT

A destructive extreme heat attacked Northeast Asia (NEA) in the midsummer of 2018, characterized by the average midsummer $T_{max}$ (daily maximum air temperature at 2 m) ranking first during the study period. The current study indicates that the cyclonic anomaly over the western North Pacific (WNP) was an important cause, which presents an anomaly of two standard deviations. The cyclonic anomaly over the WNP was accompanied by anomalous convection, which favored descending and anticyclonic anomalies over NEA through a local meridional cell. The anticyclonic anomaly over NEA corresponds to the northwestward extension of the WNP subtropical high and facilitated the occurrence of extreme heat. The tropical sea surface temperature anomaly (SSTA) presents a La Niña decaying episode, but the SSTA over the tropical Pacific and North Indian Ocean was weak in the summer. In contrast, the southeastern tropical Indian Ocean (SETIO) was obviously cool, which was the coolest after detrending. The SETIO cooling triggered a low-level southeasterly anomaly, which turned into a southwesterly after crossing the equator, due to the Coriolis force. The southwesterly anomaly extended eastwards and favored the cyclonic anomaly over the WNP. Meanwhile, the circulation anomalies over the SETIO and WNP were connected via a local meridional cell, with the ascending branch over the WNP. Moreover, the above mechanism also operates for the climate statistics, verifying the robust influence of the SETIO SSTA. Considering the consistency of the SETIO SSTA, it could be a potential predictor for the climate over the WNP and NEA.

1. Introduction

In the midsummer of 2018, a severe extreme heat attacked Northeast Asia (NEA), including Northeast China, Korea, and Japan. For example, Shenyang, a city in Northeast China seldom influenced by extreme heat, suffered from a week of daily maximum temperature exceeding 35°C and witnessed a maximum temperature of 38.4°C, breaking the observational record. The occurrence of extreme heat greatly threatens human health and can often cause fatalities. It was reported that the extreme heat that attacked Japan in July 2018 resulted in about 24 000 hospitalized patients and more than 90 deaths, and the extreme heat that occurred in South Korea during the late July to early August led to thousands of heatstroke victims and dozens of deaths. Such a destructive impact calls for an understanding of the causes of the unusual extreme heat in 2018.

The occurrence of extreme heat is typically caused by a local anticyclonic anomaly, which favors higher temperatures through increasing the adiabatic heating associated with subsidence and the diabatic heating due to less cloud cover (Black et al. 2004; Chen and Lu 2015). For NEA, which is influenced by the East Asian monsoon, the anomalous anticyclone and high temperatures are typically related to the intensification
and northwestward extension of the western North Pacific (WNP) subtropical high (WNPSH) (Cui et al. 2007; Ogasawara and Kawamura 2007). It is known that the temperature over NEA is associated with various teleconnection patterns. Park and Schubert (1997) emphasized that the midlatitude wave pattern over the Eurasian continent was critical for the record-breaking extreme heat and drought conditions over NEA in the summer of 1994. Lee and Lee (2016) suggested that the interannual variation of extreme heat over South Korea is related to a north–south dipole pattern resembling the so-called Pacific–Japan (PJ) pattern. Chen and Lu (2014) proposed that the teleconnection patterns associated with the interannual variation of the summer temperature over NEA show clear month-to-month differences, characterized by a midlatitude wave train in May–June but the PJ pattern in July–August. Tachibana et al. (2010) showed that the positive (negative) phase of the summer Northern Hemisphere annular mode corresponds to abnormal low (high) temperature over NEA. It was deduced that extreme heat over NEA results from multiple factors. Particularly, the extreme heat over NEA in 2018 was accompanied by the strongest cyclonic anomaly over the WNP during the study period. Therefore, the 2018 case is analyzed here in order to highlight the tropical influence and help detect the likely external forcing.

ENSO is the major external forcing modulating the circulation over the WNP and NEA. El Niño has a cooling effect on the summer temperature over NEA and La Niña has a warming effect (Wu et al. 2010; Takahashi, Watanabe, and Shiogama et al. 2016). During the summer following an El Niño (La Niña) episode, an anomalous anticyclone (cyclone) is observed over the WNP, which modifies the local convection and further induces a meridional wave pattern with an anomalous cyclone (anticyclone) over NEA (Wang, Wu, and Lau 2001; Xie et al. 2016). The sea surface temperature anomaly (SSTA) over the central–eastern tropical Pacific and the local SSTA over the WNP facilitate the circulation anomaly over WNP persisting from winter to the subsequent early summer, via the Rossby wave response and a local positive air–sea feedback (Wang, Wu, and Fu 2000; Wu, Li, and Zhou 2010). As the central–eastern tropical Pacific SSTA vanishes and the WNPSH weakens, the maintenance of the circulation anomaly over the WNP throughout summer is favored by the eastward-propagating Kelvin wave excited by the Indian Ocean basin-wide SSTA (Yang et al. 2007; Xie et al. 2009; Wu, Li, and Zhou 2010). The SSTA over the North Indian Ocean is further emphasized as the most important factor (Xie et al. 2009). As for the 2018 case, the tropical SSTA was characterized by a La Niña decaying episode. However, neither the tropical Pacific nor the North Indian Ocean showed an obvious SSTA in the summer. Therefore, what was the dominant external forcing for the anomalous summer climate in 2018? Our analyses indicate that the SSTA over the southeastern tropical Indian Ocean (SETIO) was important. Thereby, the 2018 case could provide insight into the influence of the SETIO SSTA on the climate over the WNP and NEA.

The rest of the paper is organized as follows: Section 2 describes the data and methods. Section 3 analyzes the influence of the cyclonic anomaly over the WNP on the extreme heat over NEA in 2018. Section 4 reveals the role of SETIO cooling. Section 5 gives the conclusions.

2. Data and methods

The daily data in June–August were extracted from NCEP–NCAR Reanalysis 1 (Kalnay et al. 1996). The variables included wind, geopotential height, daily maximum air temperature at 2 m ($T_{\text{max}}$), and surface precipitation rate. The variables had a spatial grid resolution of 2.5°, except the latter two variables, which are stored in Gaussian grids. The surface precipitation rate was converted to daily precipitation amounts. The SST data were extracted from NOAA’s daily OISSTv2, with a horizontal resolution of 0.25° (Reynolds et al. 2007). The analyzed period was 1982–2018 because the daily SST data start from 1982.

The daily $T_{\text{max}}$ data were used to define extreme heat. An extreme-heat day over a grid was defined when the $T_{\text{max}}$ exceeded the 90th percentile of the climate series during June to August, so each grid on average had approximately nine extreme-heat days in one summer. An extreme-heat day over NEA was defined in the same way but using the $T_{\text{max}}$ averaged over NEA. The average from 1982 to 2018 was calculated as the climatology, and the anomalies were computed by subtracting this climatology. Correlation analysis was applied, and the Student’s t-test was employed for significance testing. Time series were detrended by removing the linear trend when excluding the signal associated with global warming.

3. Influence of the cyclonic anomaly over the WNP

Figure 1 shows the $T_{\text{max}}$ and extreme-heat frequency over NEA. Anomalous high temperature and extreme heat prevails over Northeast China, the Korean Peninsula, and South Japan (Figure 1(a) and (b)). The maximum extreme-heat frequency exceeds 30 days over NEA, which is about
20 days more than the climatology. Accordingly, the center of extreme-heat frequency was selected as the core region of NEA, covering (30°–50°N, 110°–145°E) (rectangles in Figure 1(a) and (b)). The evolutions of $T_{\text{max}}$ and extreme heat over the core region were analyzed (Figure 1(c)). Climatologically, the $T_{\text{max}}$ peaks in early August and stays at large amplitudes from July to August. In 2018, the $T_{\text{max}}$ over NEA was persistently above-normal during the midsummer from 13th July to 11th August, and 18 extreme-heat days occurred in this period, accounting for more than 50% of all days. In an historical context, the $T_{\text{max}}$ anomaly in the midsummer of 2018 reaches 1.7 standard deviations and ranks first during the study period (Figure 1(d)). Therefore, the midsummer of 2018 was characterized by extreme high $T_{\text{max}}$ and frequent extreme heat. The following analyses focus on the midsummer spanning from 13th July to 11th August.

Figure 2 shows the geopotential height and wind field in the midsummer of 2018. A barotropic anticyclonic anomaly occurred over NEA, with the intensity enhancing and the center tilting westwards as height increases (Figure 2(a)–(c)). The anticyclonic anomaly over NEA was associated with the northwestward expansion of the WNPSH (Figure 2(b)). Climatologically, the WNPSH is located to the east of South Japan. In 2018, the WNPSH extended northwestwards greatly and split into several parts, with the western part stretching to Northeast China. The WNPSH dominated over NEA and led to the occurrence of extreme heat. The anomalies of the position and intensity of the WNPSH were also analyzed in an historical context (not shown). It turns out that the anomaly of the WNPSH was prominently characterized by northwestward expansion, which reached its most northwards over NEA in 2018. In contrast, the intensity of the WNPSH only presents a moderately positive anomaly, ranking ninth during the study period.

At the same time, an anomalous cyclone appeared over the WNP, showing a large zonal scope. The cyclonic anomaly was the strongest in the lower troposphere and weakens as height increases (Figure 2(a)–(c)). The lower-

![Figure 1](image1.png)

**Figure 1.** (a) Average $T_{\text{max}}$ (units: °C) and (b) extreme-heat frequency (units: days) in June–August 2018. The contours (shading) denote the original values (anomalies). The blue rectangles denote NEA. (c) Evolutions of the climatological $T_{\text{max}}$ (gray line) and $T_{\text{max}}$ anomaly in 2018 (black line). The red dots denote the extreme-heat days over NEA. The blue dashed lines denote the midsummer from 13th July to 11th August. (d) Standardized anomaly of the midsummer $T_{\text{max}}$ averaged over NEA during 1982–2018.
tropospheric cyclonic anomaly was so strong that the circulation was clearly modified. Climatologically, southerly flow prevails over the WNP and thrusts into NEA (Figure 2(d)). In comparison, a cyclone occurred to the east of the Philippines and Taiwan in 2018 (Figure 2(e)). The cyclonic anomaly over the WNP and the anticyclonic anomaly over NEA formed a meridional dipole pattern, which were connected via a local meridional cell.

Figure 2. Anomalies of wind and geopotential height at (a) 200 hPa, (b) 500 hPa, and (c) 850 hPa for the midsummer of 2018. In (b), the blue contours of 5880 gpm depict the domain of the WNPSH, with the dashed contours denoting the climatology and solid contours denoting 2018, and the red rectangle is used to define H500. In (c), the blue rectangle is used to define L850. (d) Climatological wind field and (e) wind field in the midsummer of 2018. (f) Anomalous meridional vertical circulation averaged between 120°E and 130°E. The units for geopotential height, horizontal wind, and vertical velocity are m, m s$^{-1}$, and −10$^{-4}$ hPa s$^{-1}$, respectively.
(Figure 2f). Associated with the cyclonic anomaly, convection was enhanced over the tropical region. The abnormal updraft diverged in the upper troposphere and the northward outflow descended in the subtropical region north of 30°N. The descending branch favored the formation of an anticyclonic anomaly over NEA and the northward expansion of the WNPSH.

Two indices, named H500 and L850, were defined to depict the cyclonic anomaly over the WNP and the anticyclonic anomaly over NEA. The two indices were calculated as the standardized anomalies of 500-hPa geopotential height averaged over (35°–50°N, 105°–140°E) and 850-hPa geopotential height averaged over (15°–30°N, 110°–150°E), respectively. The key regions were selected according to the anomaly centers in 2018 (Figure 2b and c). The correlation coefficient between H500 and L850 reaches −0.32 (Figure 3a), which is significant at the 0.05 level and verifies their intimate relationship. In 2018, the H500 (L850) index reaches near +3 (−2) standard deviations, ranking as the most positive (negative) anomaly. Since the H500 index presents an obvious increasing trend, the time series were further detrended (Figure 3b). The correlation coefficient decreased slightly after detrending. The detrended H500 became the second largest but the detrended L850 was still the most negative in 2018. The strong cyclonic anomaly over the WNP implies a prominent influence from the tropics to NEA.

4. Influence of the SSTA over the SETIO

In the midsummer of 2018, no obvious SSTA occurred over the central-eastern tropical Pacific, WNP or North Indian Ocean (Figure 4a). The evolutions of the SSTA over these three key regions (the key regions are identical to those in Xie et al. (2016)) illustrates a La Niña episode matured in the late autumn to winter of 2017 and dissipated in the summer of 2018 (Figure 4e). Therefore, the cyclonic anomaly over the WNP might have been forced by the SSTA in other regions. Notably, an obvious negative SSTA and below-normal precipitation occurred over the SETIO (Figure 4a and b), indicating a plausible influence from this region.

The abnormal cooling and depressed convection over the SETIO would have enhanced the local pressure in the lower troposphere and led to an anomalous pressure gradient, which could be validated by the divergent wind (Figure 4b). Under the combined effect of the pressure gradient force and the Coriolis force, an anomalous southeasterly blew from the SETIO towards the equator and then turned into a southwesterly after crossing the equator (Figure 4a). The southwesterly extended eastwards into the WNP and favored the formation of the cyclonic anomaly. The lower-tropospheric divergent flow shows obvious divergence over the SETIO, with a large part converging over the WNP (Figure 4b). The upper-tropospheric divergent flow is characterized by opposite signs (not shown). Thus, the SETIO and WNP were also connected via a meridional circulation (Figure 4c). The ascending branch corresponds to the precipitation and cyclonic anomalies over the WNP. These anomalies are consistent with the findings of Chen et al. (2018), who indicated that SETIO warming contributed to the anomalous anticyclone over the South China Sea in the summer of 2016. However, the anticyclonic anomaly in the 2016 summer was weak and confined to the South China Sea.

In contrast, the cyclonic anomaly in 2018 was strong and covered a wide area of the WNP, indicating that the influence of the SETIO SSTA can be remarkable.

The connection between the SETIO SSTA and the circulation anomaly over the WNP also appears in the climate statistics. We selected the region over (15°S–0°, 70°–110°E) to represent the SETIO and calculated the standardized time series of the corresponding SSTA (Figure 3). The correlation coefficient between the SETIO SSTA and L850 was 0.35 before detrending and 0.52 after, both of which were statistically significant, thus confirming their intimate relationship. The SETIO SSTA presents an obvious increasing trend, and the SETIO cooling in 2018 ranks third before detrending but first after. The strong SETIO cooling contributed to the extreme cyclonic anomaly over the WNP in 2018.

Figure 4d shows the correlation coefficients between the detrended SETIO SSTA and circulation field, with the SSTA multiplied by −1 to demonstrate the cooling effect clearly. Associated with the SETIO cooling, a lower-tropospheric southeasterly anomaly appears over the SETIO and turns into a southwesterly after crossing the equator. The southwesterly extends eastwards and favors a significant cyclonic anomaly over the WNP. Meanwhile, the anticyclonic anomaly over NEA is significant. These results resemble the anomalies in 2018, verifying the mechanisms deduced from the case study. Moreover, the SETIO cooling could be observed since the preceding autumn (Figure 4e). Hence, the SETIO SSTA could be used as a predictor for the summer climate over the WNP and NEA, which might be important when the tropical Pacific and North Indian Ocean present weak signals.

5. Conclusions

NEA was influenced by extreme high temperatures and frequent extreme heat in the midsummer of 2018. The average midsummer $T_{\text{max}}$ anomaly reached 1.7 standard deviations and ranked first during the study period, and
extreme-heat days accounted for more than 50% of all midsummer days. In this study, the tropical circulation and SST anomalies responsible for the severe extreme heat were explored. The results show that the extreme heat resulted from a barotropic anticyclonic anomaly, which was associated with the northwestward extension of the WNPSH. Meanwhile, there was a strong lower-tropospheric cyclonic anomaly over the WNP, which covered a large scope. The anticyclonic anomaly over NEA and the cyclonic anomaly over the WNP formed a meridional dipole pattern and were connected via a local meridional cell. The intensity of the cyclonic

Figure 3. (a) Original and (b) detrended time series of three standardized indices: L850 (blue line), H500 (red line), and SETIO SSTA (black line). The correlation coefficients between the indices are marked below the lines, with *, **, and *** denoting the confidence level of 90%, 95%, and 99.9%, respectively.
anomaly over the WNP reached two standard deviations and ranked first during the analyzed period, implying a prominent influence from the tropics to NEA.

The SSTA evolution was characterized by a La Niña decaying episode. The SSTAs over the tropical Pacific and North Indian Ocean were quite weak in summer. In contrast, obvious cooling and below-normal precipitation occurred over the SETIO. The cooling and depressed convection resulted in a lower-tropospheric southeast anomaly, which turned into a southwesterly after crossing the equator, due to the Coriolis force. The southwesterly anomaly extended eastwards and facilitated the cyclonic anomaly over the WNP. Meanwhile, the SETIO and WNP were connected via a local meridional cell. The SETIO cooling in 2018 ranked first after detrending, indicating a prominent influence on the cyclonic anomaly over the WNP.

The mechanism deduced from the 2018 case also applies to the climate statistics. It is thus verified that the SETIO SSTA can influence NEA through modulating the circulation over the WNP. Moreover, the SETIO SSTA is continuous and thus could serve as a predictor for the climate over the WNP and NEA, which might be important when weak signals are observed over the tropical...
Pacific and North Indian Ocean. On the other hand, anthropogenic forcing may also be important for the occurrence of extreme heat, such as in the summer of 2013 (Sun et al. 2014). Our results show that the midsummer $T_{\text{max}}$ over NEA demonstrates a remarkable increasing trend (Figure 1(d)), which is likely related to anthropogenic forcing. The specific role of anthropogenic forcing in extreme heat over NEA needs further investigation.

**Disclosure statement**

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