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• Original Paper •

The Unprecedented Extreme Anticyclonic Anomaly over Northeast Asia in July 2021 and Its Climatic Impacts

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ABSTRACT

This study investigates the evolution of an extreme anomalous anticyclone (AA) event over Northeast Asia, which was one of the dominant circulation systems responsible for the catastrophic extreme precipitation event in July 2021 in Henan, and further explores the significant impact of this AA on surface temperatures beneath it. The results indicate that this AA event over Northeast Asia was unprecedented in terms of intensity and duration. The AA was very persistent and extremely strong for 10 consecutive days from 13 to 22 July 2021. This long-lived and unprecedented AA led to the persistence of warmer surface temperatures beyond the temporal span of the pronounced 500-hPa anticyclonic signature as the surface air temperatures over land in Northeast Asia remained extremely warm through 29 July 2021. Moreover, the sea surface temperatures in the Sea of Japan/East Sea were extremely high for 30 consecutive days from 13 July to 11 August 2021, persisting well after the weakening or departure of this AA. These results emphasize the extreme nature of this AA over Northeast Asia in July 2021 and its role in multiple extreme climate events, even over remote regions. Furthermore, possible reasons for this long-lasting AA are explored, and it is suggested to be a byproduct of a teleconnection pattern over extratropical Eurasia during the first half of its life cycle, and of the Pacific–Japan teleconnection pattern during the latter half.

Key words: anomalous anticyclone, Northeast Asia, surface air temperatures, sea surface temperatures

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Article Highlights:

- The anomalous anticyclone over Northeast Asia in July 2021 was unprecedented in terms of intensity and duration.
- The anomalous anticyclone over Northeast Asia is thought to be responsible for extreme warming of both surface air temperatures and SSTs beneath it, in addition to the extreme rainfall in Henan.
- The extremely warm surface temperatures persist even after the anomalous anticyclone weakens or disappears.

1. Introduction

A catastrophic extreme precipitation event occurred during 17−22 July 2021 in North China, particularly in Henan Province, which is one of the main grain production and most densely populated areas in China. This infamous weather event was named the “21·7” event in accordance with the “year·month” of its occurrence. During the “21·7” event, 20 national weather stations, accounting for one-sixth of the total number in Henan, renewed their daily rainfall records. Notably, the largest hourly precipitation at the station of Zhengzhou, the capital city of Henan Province, received up to 201.9 mm, breaking the Chinese mainland’s record of hourly precipitation which stood since 1949. The 6-day accumulated rainfall at 10 national weather stations exceeded the annual average rainfall in the area (Ran et al., 2021; Shi et al., 2021). This extremely heavy rainfall event caused devastating flooding with 398 deaths or missing and 120.06 billion RMB Yuan of economic losses according to a government disaster report (http://www.gov.cn/xinwen/2022-01/21/content_5669723.htm).

Previous studies have revealed that the “21·7” event was the result of the combined effect of multiple weather systems. The persistent southeasterly flow in association with the northwardly displaced subtropical high and Typhoon In-

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fa (2021) transported abundant water vapor to Henan, which converged and uplifted on the windward slopes of the Taihang and Funiu mountains, inducing a long-duration, extreme precipitation event in Henan (Ran et al., 2021; Zhang et al., 2021; Wei et al., 2023). In the context of this large-scale background, some studies further illustrate the details of the circulation responsible for the "21·7" event, including the activity of low-level jets (Luo and Du, 2023), anticyclonic wave breaking (Bueh et al., 2022), an upper tropospheric cold low (Cai et al., 2022), and the interaction between Typhoon In-fa (2021) and Typhoon Cempaka (2021) (Xu et al., 2022a).

It has been documented that the AA over Northeast Asia in the mid-to-high latitudes was associated with a northwardly displaced subtropical high that is known to play an important role in inducing extreme rainfall events in North China by establishing a steady moisture conveyor belt that tends to maintain synoptic-scale disturbances (Zhao et al., 2019; Zhang et al., 2022; Hu et al., 2023). Ding et al. (2015) showed that the catastrophic rainfall event from 4 to 8 August 1975, which also affected Henan and caused severe socio-economic losses, was closely linked to a steady ridge to the east of Lake Baikal, which prevented the northward shift of Typhoon Nina (1975), causing the typhoon to hover over Henan for a long time, resulting in abundant water vapor convergence in Henan. Zhang et al. (2022) further performed a clustering analysis to investigate the large-scale circulation patterns responsible for daily precipitation extremes in Henan and found that the circulation pattern most conducive to extreme precipitation is characterized by anticyclonic anomalies to the north of Henan and associated strong easterly anomalies and intense moisture transport to Henan. This pattern well resembles the circulation characteristics for the "21·7" event (Ran et al., 2021; Chyi et al., 2022; Xu et al., 2022b; Zhang et al. 2023), suggesting the important role of the AA over Northeast Asia in inducing heavy rainfall events in North China. Some studies on the "21·7" rainstorm event found that the extreme AA over Northeast Asia in cooperation with Typhoon In-fa (2021) not only enhanced the pressure gradient between them and the consequent westward moisture transport into Henan (Ran et al., 2021; Zhang et al., 2021; Wei et al., 2023; Luo and Du, 2023; Zhang et al., 2023), but also favored the slow movement of Typhoon In-fa (2021) (Kong et al., 2022; Chyi et al., 2023). Therefore, it is necessary to fully explore the evolution of AA over Northeast Asia, which is one of the motivations for this study.

Furthermore, it is well known that AA can lead to warmer surface temperatures beneath it by inducing anomalous subsidence and promoting additional solar radiation due to reduced cloud cover. Therefore, it can be expected that the AA over the mid-high latitudes of Northeast Asia, which is to be shown in this study as unprecedented, may result in extremely warm surface temperatures. For instance, Xu et al. (2019) indicated that the AA played an important role in the extreme heat in South Korea and south-central Japan, based on 38 years of data from 1979 to 2016. Furthermore, a persistent AA in the extratropics can reduce ocean heat loss by suppressing surface wind speeds (Bond et al., 2015; Rodrigues et al., 2019), thus enhancing sea surface temperatures (SSTs). This effect, together with more solar radiation can even trigger a marine heatwave, defined as a coherent area of extremely warm SST that persists for days to months (Frölicher and Laufkötter, 2018; Rodrigues et al., 2019; Holbrook et al., 2020). The marine heatwave not only affects weather and climate through air-sea interaction (Bond et al., 2015; Di lorenzo et al., 2016) but also results in a devastating impact on marine ecosystems (Frölicher and Laufkötter, 2018; Wyatt et al., 2023). For instance, in the summer of 2021, an unprecedented marine heatwave occurred in the Japan/East Sea and the western North Pacific (Kuroda and Setou, 2021; Li et al., 2023), which triggered a widespread outbreak of harmful algae in the coastal waters and led to catastrophic damage of marine ecosystems (Kuroda et al., 2021, 2022). A record-breaking monetary loss to Japanese coastal fisheries, equivalent to over 8.19 million U.S. dollars, resulted (Iwataki et al., 2022). Kuroda and Setou (2021) suggested that this marine heatwave was closely related to a similar AA that this study focuses upon. In their study, they excluded the Japan/East Sea from their interest region and focused on the western North Pacific to explore the features of this marine heatwave. However, this study will show that the marine heatwave in the Sea of Japan is comparable to, or even stronger than, the heatwave in the western North Pacific. In summary, another motivation of this study is to explore the evolution of surface temperatures in Northeast Asia, including SSTs in the Japan/East Sea, in association with the East Asian AA in the summer of 2021.

The remainder of this paper is organized as follows. Section 2 describes the data and methodology. Section 3 presents the unique features of the AA over Northeast Asia in July 2021. The anomalies of surface air temperatures and SSTs induced by the AA are investigated in section 4. Section 5 explores the possible mechanism responsible for the extreme AA over Northeast Asia. Section 6 provides concluding remarks.

2. Data and methodology

The daily precipitation data from 2400 stations in the Chinese mainland were obtained from the National Meteorological Information Center, China Meteorological Administration (http://data.cma.cn/data/index/f0fb4b55508804ca.html). The daily horizontal winds, geopotential heights, 2-m air temperatures, total precipitation, total cloud cover, and surface inbound solar radiation came from the fifth generation of the European Center for Medium-Range Weather Forecast atmospheric reanalysis data (ERA5) with a horizontal resolution of 0.75° × 0.75° from 1979 to 2021 (Hersbach et al., 2020). Daily SSTs used in this study are from the daily Optimum Interpolation Sea Surface Temperature V2 (OISST V2) dataset managed by the National Oceanic and Atmospheric Administration (NOAA) with a horizontal resolution of 0.25° × 0.25° for 1982–2021 (Huang et al., 2021), which has been available since 1982 when the satellite measurements of global SSTs started. The 2-m air temperatures over land and sea are calculated by the NCAR Command Language function (landsea_mask). (https://www.ncl.ucar.edu/Document/Functions/Shea_util/landsea_mask.shtml). In this study, the geopotential heights, 2-m air temperatures, total precipitation, total cloud cover, surface inbound solar radiation, and SSTs are detrended prior to the analyses to eliminate possible effects of global warming. The Student's *t*-test is employed to determine the significance of the composite anomalies.

3. The features of the anomalous anticyclone over Northeast Asia

The heavy rainfall in Henan lasted for six consecutive days, from 17 to 22 July 2021; the most intense rainfall occurred during 19–21 July (Bueh et al. 2022). Figure 1a shows the spatial distribution of cumulative precipitation from 17 to 22 July 2021. Heavy rainfall, with cumulative precipitation exceeding 200 mm, appears to the east of the Taihang Mountains. The extreme nature of this rainstorm process is most pronounced in Zhengzhou (34.8°N, 113.6°E, marked by a star in Fig. 1a). The maximum daily precipitation at Zhengzhou station was 624.1 mm, more than triple its historical maximum daily precipitation (184.1 mm) (Chyi et al. 2022). Moreover, the total precipitation during the six consecutive days from 17 to 22 July was 820 mm, which exceeds its annual climatological precipitation (641 mm).

Figure 1b shows the anomalies of 500-hPa geopotential heights and 850-hPa horizontal winds averaged over 17–22 July 2021. The circulation anomalies are characterized by an AA over Northeast Asia and a cyclone over the subtropical western North Pacific. There are easterly wind anomalies, as strong as 10 m s^{-1}, from the western North Pacific to North China, as a result of the combination of the AA and cyclone. The strong easterly anomalies transport abundant water vapor into North China, which represents an important circulation-related factor responsible for the heavy rainfall event (e.g., Xu et al., 2022b; Zhang et al., 2021). The anomalous cyclone over the subtropical western North Pacific is induced by Typhoon In-fa (2021), as is well documented in previous studies (e.g., Xu et al., 2022a; Rao et al., 2022). In this study, we focus on the AA over Northeast Asia, which has been somewhat ignored in previous studies.

Figure 2 shows the daily evolution of 500-hPa geopotential heights averaged over Northeast Asia (35°–55°N, 120°–150°E) in July 2021. The geopotential heights experienced a pronounced increase from 9 to 15 July before the heavy rainfall event and remained at a high amplitude until the end of the event. This indicates that the AA over Northeast Asia existed before the occurrence of the heavy rainfall event, and maintained a considerably high amplitude for a long time before and during the heavy rainfall event. It is noted that the daily geopotential heights are higher than their corresponding daily climatological means by two interannual standard deviations for the 10 consecutive days from 13 to 22 July 2021. Here, the daily climatological means and standard deviations are obtained based on the corresponding days from 1979 to 2020.

Figure 3a shows the 500-hPa geopotential heights and their anomalies averaged over the ten days of 13–22 July 2021. There is an extreme AA over Northeast Asia. This AA is even stronger than that averaged over the period of the heavy rainfall event (17–22 July 2021) as evidenced by the 500-hPa height anomalies averaged over the region (35°–55°N, 120°–150°E), being 92.3 and 82.6 gpm for 13–22 July and 17–22 July, respectively. It was primarily

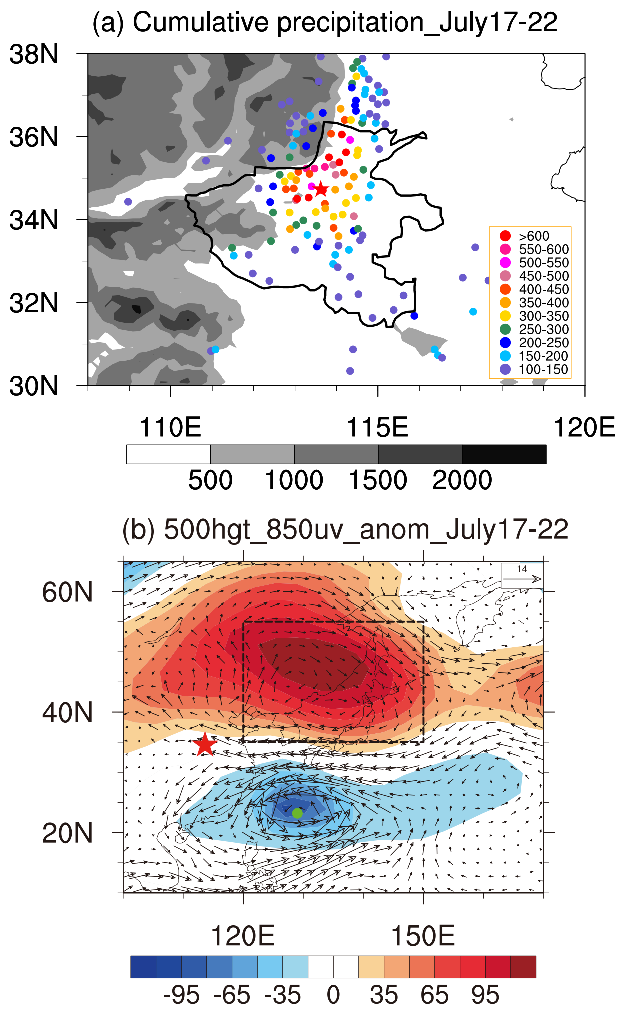

Fig. 1. (a) Distribution of cumulative precipitation from 17 to 22 July 2021 (colored dots; units: mm). The shading represents the topography (units: m). Henan province is outlined by the thick black line. (b) The 850-hPa horizontal wind anomalies (vector, units: m s^{-1}) and the 500-hPa geopotential height anomalies (shading, units: gpm) averaged from 17 to 22 July 2021. The red star represents the location of Zhengzhou city, the green dot represents the mean location of Typhoon In-fa (2021) during 17–22 July, and the rectangle with dashed lines denotes the region where strong positive geopotential height anomalies are located.

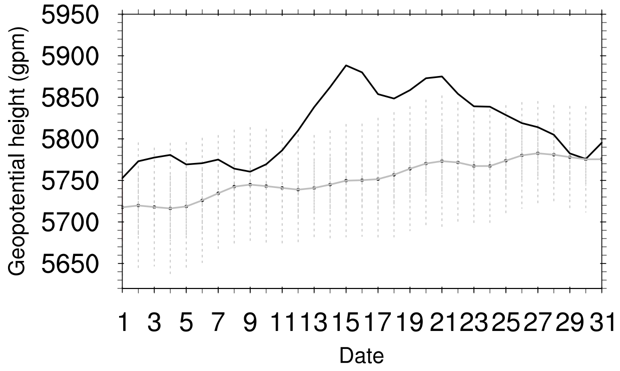

Fig. 2. The daily evolution of the regional mean 500-hPa geopotential heights (units: gpm) over Northeast Asia in July 2021 (black line) and corresponding daily climatological mean for the time period 1979–2020 (gray line). Here, Northeast Asia denotes the area of interest (35°–55°N, 120°–150°E, depicted by the rectangle outlined by the dashed line shown in Fig. 1b). The dotted lines represent the two interannual standard deviations greater or less than the daily climatological means for each day.

caused by stronger anticyclonic anomalies during 13–16 July (Fig. 3b) compared to that during 17–22 July. In addition, there is also an anomalous cyclone over the subtropical western North Pacific during 13–22 July. However, this cyclonic anomaly is weaker than that for 17–22 July, without the strong impacts of Typhoon In-fa (2021) during 13–16 July as shown in Fig. 3b. Corresponding to these height anomalies, the western Pacific subtropical high, represented by the 5880 gpm isoline, shifts significantly northward compared to the climatology. The ridge line of the western Pacific subtropical high reaches 40°N during 13–22 July 2021, while the ridge line is located at about 25°N in climatology. In addition, corresponding to the anomalous cyclone over the subtropical western North Pacific, the western Pacific subtropical high also exhibited a significant eastward retreat.

The geopotential heights over Northeast Asia during 13–22 July 2021 were extreme anomalies (Fig. 3c). The height anomalies averaged over the region (35°–55°N, 120°–150°E) during 13–22 July 2021 were 92.3 gpm, above normal, corresponding to more than three interannual standard deviations. The regionally averaged height anomalies were more than double that of the second highest ones, which were 42.8 gpm, and occurred in 2018. In July 2018, North China also experienced heavy rainfall; in particular, Beijing received accumulated rainfall of 386 mm during 15–18 July 2018, more than half of its climatological annual precipitation (Lei et al., 2020).

Furthermore, we extended the period of comparison to July and August, which is the rainy season in North China (e.g., Ding et al., 2015), and examined the probability distribution of 500-hPa geopotential height anomalies averaged over Northeast Asia for 10 consecutive days in these two months from 1979 to 2020, and illustrate the extreme degree of the AA over Northeast Asia during 13–22 July

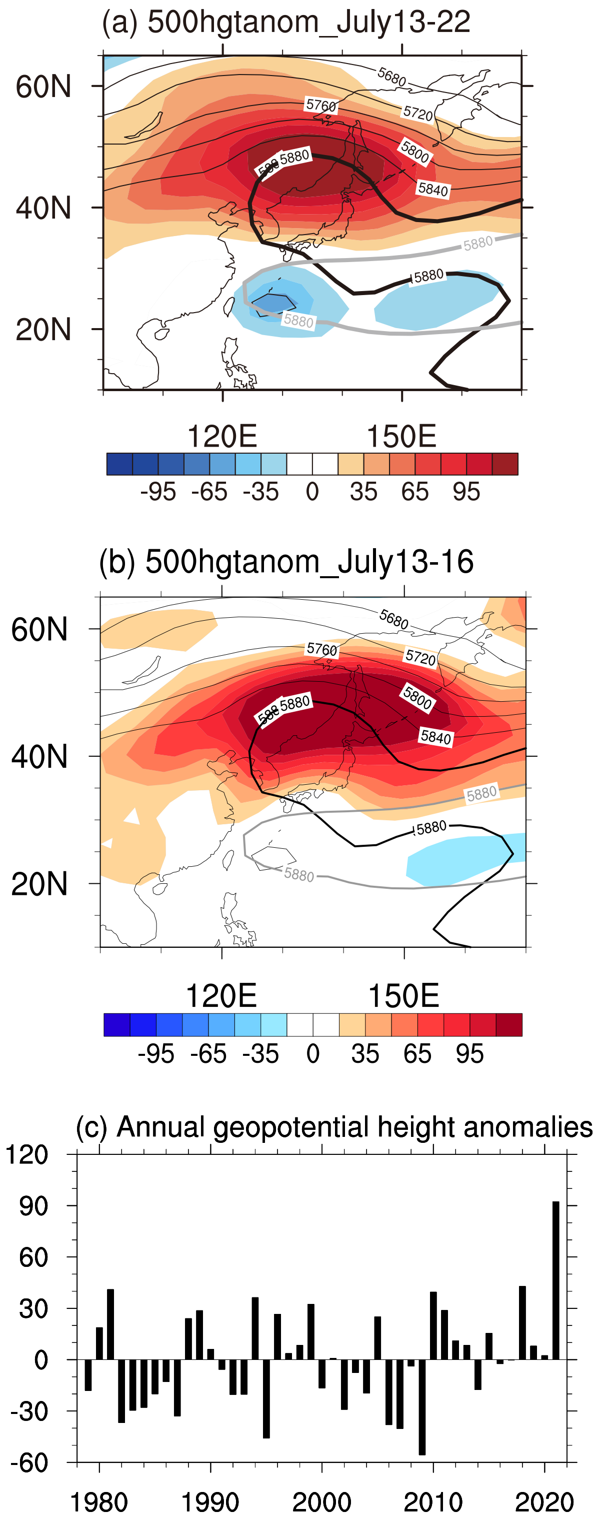

Fig. 3. The 500-hPa geopotential heights (black contours, interval is 40 gpm) and their anomalies (shading) averaged for (a) 13–22 and (b) 13–16 July 2021 (units: gpm). (c) The interannual 500-hPa geopotential height anomalies over Northeast Asia were averaged over 13–22 July from 1979 to 2021 (units: gpm). The gray solid lines in Figs. 3a and 3b indicate the climatological mean 5880 isoline for 1979–2020. Northeast Asia denotes the interest area (35°–55°N, 120°–150°E) depicted by the rectangle outlined by the dashed line shown in Fig. 1b.

2021 (Fig. 4a). There are 53 sets of consecutive 10 days during July and August in one year, and thus total 2226 sets during 1979–2020. These 2226 sets are used to calculate the probability density function (PDF) of 10-consecutive-day-mean height anomalies averaged over Northeast Asia (35°–55°N, 120°–150°E). The result indicates that the height anomalies are mainly concentrated in the range from –50 to 50 gpm, with the 1st and 99th percentiles being –57.2 and 51.6 gpm, respectively. Therefore, the anomaly of 13–22 July 2021 (92.3 gpm) is considerably larger than the 99th percentile. It is even larger than the 99.9th percentile (64.3 gpm), although the precision of this percentile is uncertain due to the limited sampling number (2226 sets of consecutive 10 days) in this study.

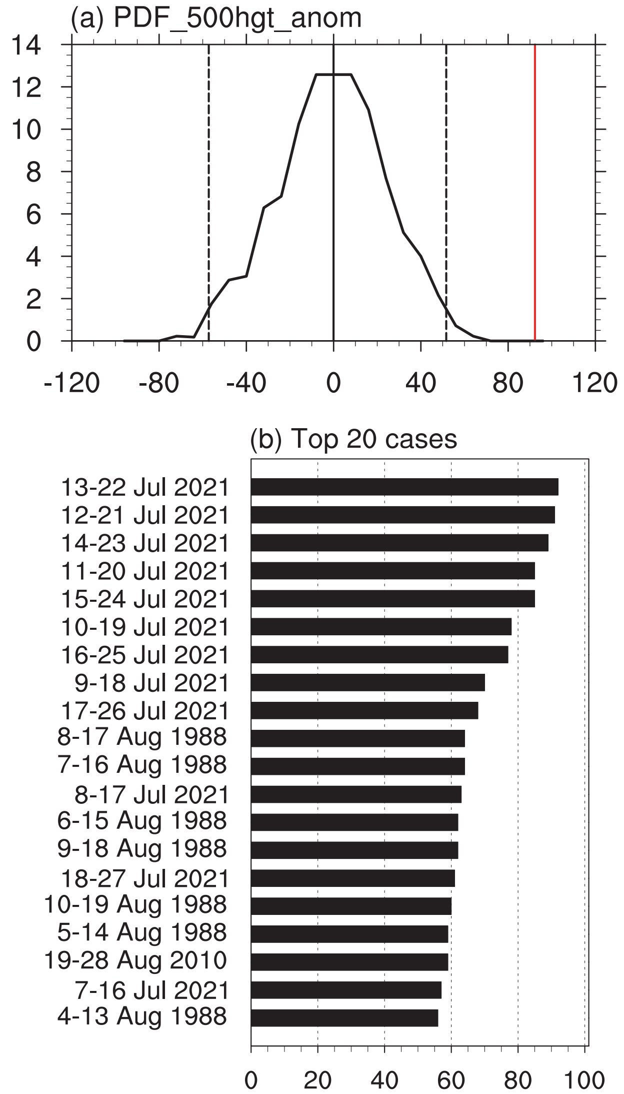

Fig. 4. (a) The probability density function (PDF; curves; %) and median (vertical solid line) of the 500-hPa geopotential height anomalies over Northeast Asia averaged for 10 consecutive days in July and August from 1979 to 2020. Vertical dashed lines indicate the 1% and 99% percentiles. The vertical red line represents the intensity of 500-hPa geopotential height anomalies averaged over Northeast Asia and over 13–22 July 2021. (b) The top 20 cases with the highest 500-hPa geopotential height anomalies averaged over Northeast Asia for 10 consecutive days in July and August from 1979 to 2021.

Figure 4b shows the top 20 cases with the highest 500-hPa geopotential height anomalies averaged over Northeast Asia for 10 consecutive days during July and August from 1979 to 2021. The top one is 13–22 July 2021, and the following eight cases all occur around this time. Among the top 20 cases, 12 cases occurred in July 2021, all overlapping with 13–22 July. The result demonstrates that the extreme AA over Northeast Asia is not only limited to the period of 13–22 July 2021 but extends over a longer period, consistent with the result shown in Fig. 3. The anticyclonic anomaly over Northeast Asia in July 2021 was not only unprecedented but also persisted for a long period. Aside from the cases in 2021, there were seven cases during early and middle August of 1988 and one case in late August of 2010. We examined the accumulated precipitation during these two periods and found that North China, including Henan, also experienced heavy rainfall (not shown), albeit relatively weak compared to the heavy rainfall during 17–22 July 2021.

4. The surface air temperature and SST anomalies induced by the anomalous anticyclone

The long-lived AA in July 2021 would naturally increase the surface temperatures beneath, in addition to promoting heavy rainfall in North China. Figure 5a shows the anomalies of 2-m air temperatures averaged over 13–22 July 2021. There are significantly positive anomalies over Northeast Asia well corresponding to the AA shown in Fig. 3a. Specifically, the air temperature anomalies are generally above 2°C over Northeast Asia, and even above 4°C over some regions including northern Japan, the central Sea of Japan, and the northeast coast of Northeast Asia. In addition, the SSTs also exhibit remarkably positive anomalies in the majority of the Japan/East Sea, i.e., its central and southern regions (Fig. 5b). These surface temperature anomalies can be explained by the anomalous precipitation, total cloud cover, and surface inbound (downward) solar radiation averaged over 13–22 July 2021 (Figs. 5c and 5d). Figure 5c shows the precipitation anomalies averaged over 13–22 July 2021 near Northeast Asia. Broad negative anomalies (i.e., anomalous subsidence) are observed over Northeast Asia, consistent with the AA there. Correspondingly, the cloud cover is significantly reduced and the surface inbound solar radiation is increased over Northeast Asia (Fig. 5d). As a result, the surface temperatures over Northeast Asia are significantly warmed.

The region specified as Northeast Asia in this study, (35°–55°N, 120°–150°E), includes roughly equivalent areas of land and sea, and it is expected that the surface air temperatures may evolve differently between the land and sea, due to the different magnitudes of the surface heat flux and heat content between land and sea. Figure 6 shows the daily evolu-

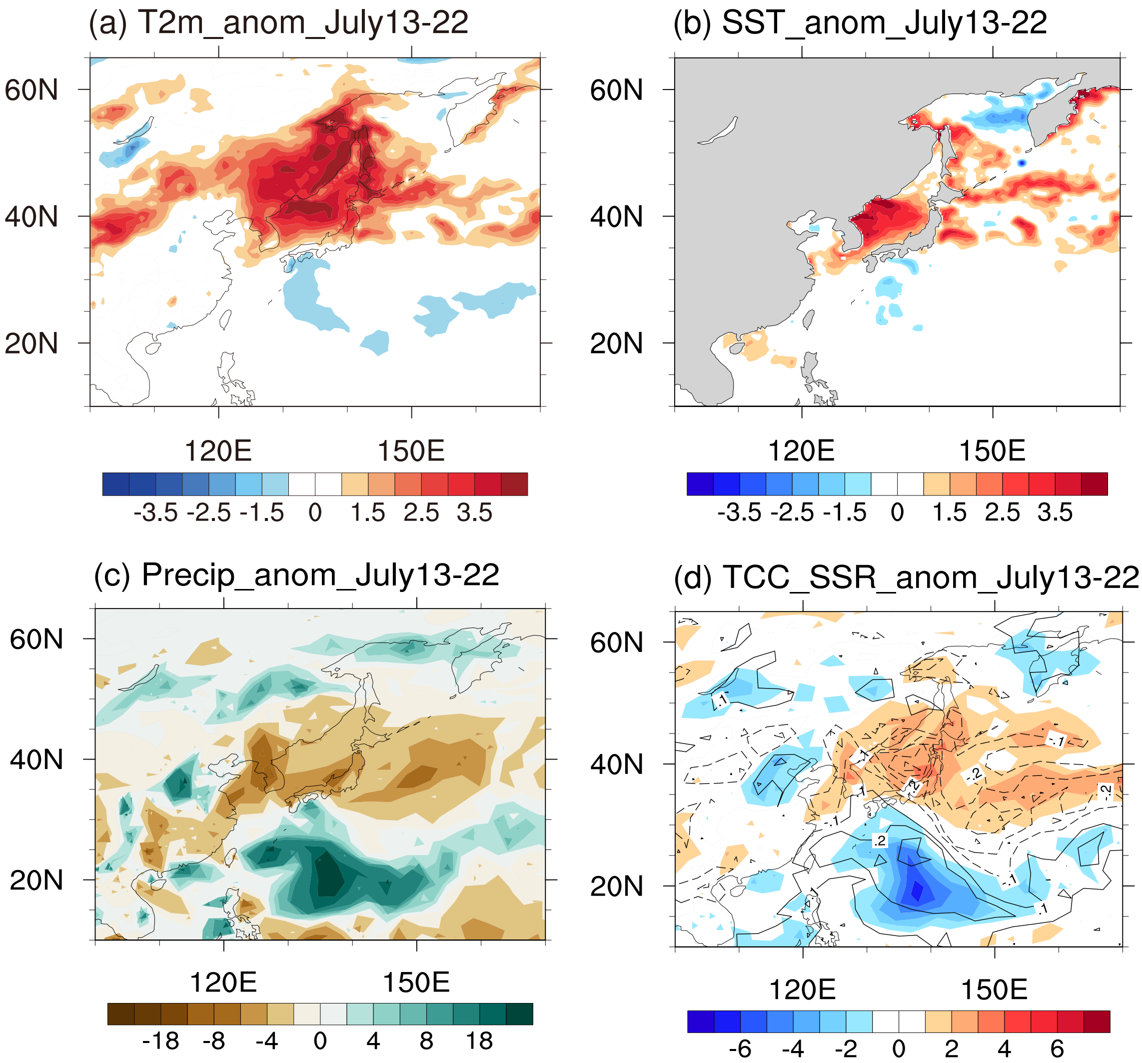

Fig. 5. The anomalies of (a) 2-m air temperatures (units: °C), (b) sea surface temperatures (units: °C), (c) precipitation (units: mm d^{-1}), and (d) total cloud cover (contours; interval is 0.1) and surface inbound solar radiation (shading, units:10^5 J m^{-2}), averaged over 13–22 July 2021.

tions of surface air temperatures over the land and sea, and SSTs in the Sea of Japan/East Sea during July and August 2021. The surface air temperatures over the landmass of Northeast Asia had significantly increased since 12 July, and remained high until 29 July, followed by a rapid decrease before regressing to normal on 31 July (Fig. 6a). This evolution is consistent with that of the regionally averaged geopotential heights shown in Fig. 2, but the extremely high surface air temperatures, estimated to be higher than two interannual standard deviations, persisted for a longer time than the geopotential heights, implying the existence of positive feedback related to air-land interaction. On the other hand, the surface air temperatures over the sea show a similar evolution but increase in a slower manner and the warm anomalies are maintained, being extremely high until early August (Fig. 6b), which is later than the cessation of extremely high temperatures over land (Fig. 6a). Specifically, the temperatures higher than two interannual standard deviations persisted for 26 consecutive days (12 July to 6 August) over sea, while this condition was satisfied for 18 consecutive days (from 12 to 29 July) over land. In addition, the air temperatures over sea tended to be relatively stable compared with those over land. These differences between land and sea can be attributed to a larger heat content of ocean water and a stronger air-sea interaction. It may be surmised that the long-lived AA over Northeast Asia in July induces warmer SSTs beneath. The above-mentioned phenomenon is clearly evident in Fig. 6c, which illustrates that extremely warm SSTs in the Sea of Japan/East Sea persisted for a longer duration than surface air temperatures.

Figure 7a shows the SST anomalies averaged over 30 days from 13 July to 11 August 2021, during which time the daily SST anomalies in the Sea of Japan/East Sea are more than two interannual standard deviations above the mean (Fig. 6c). These positive anomalies are strong, with the maximum anomaly as high as 6.4°C. These positive anomalies are even stronger than those averaged over 13–22 July 2021 (Fig. 5b), when the extreme AA persisted over Northeast

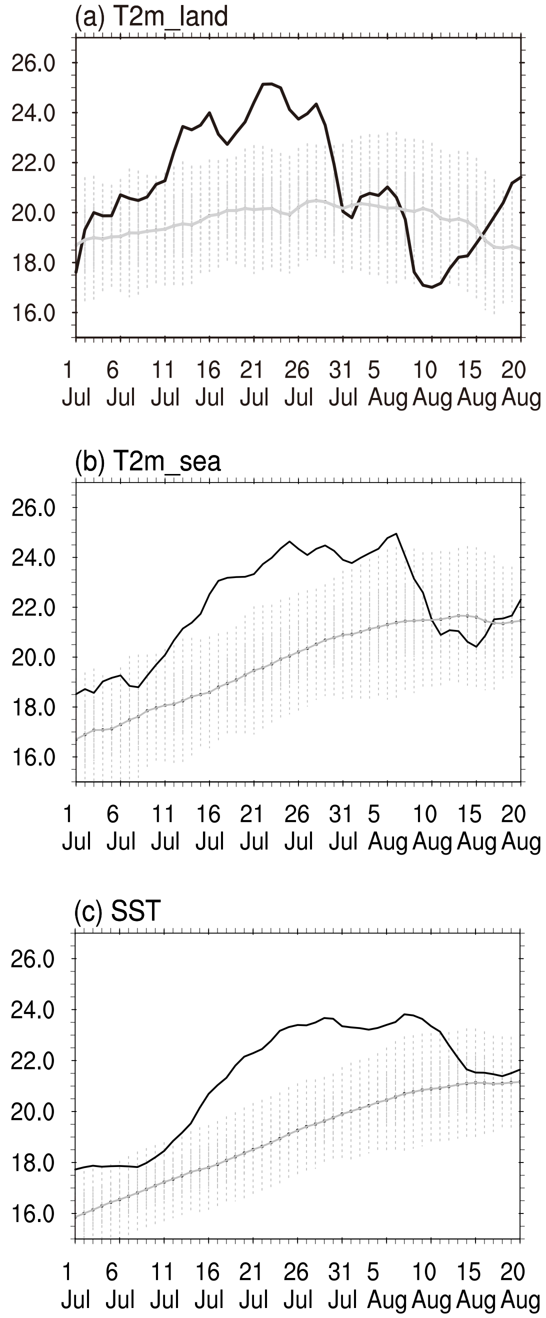

Fig. 6. The daily evolution of the regional-mean 2-m air temperatures (units: °C) averaged over the (a) land and (b) sea of Northeast Asia (35°–55°N, 120°–150°E) and (c) SSTs in the Sea of Japan/East Sea (units: °C) from 1 July to 20 August 2021 (black line) and the corresponding daily climatological mean (gray line). The dotted lines represent the two interannual standard deviations greater or less than climatological means.

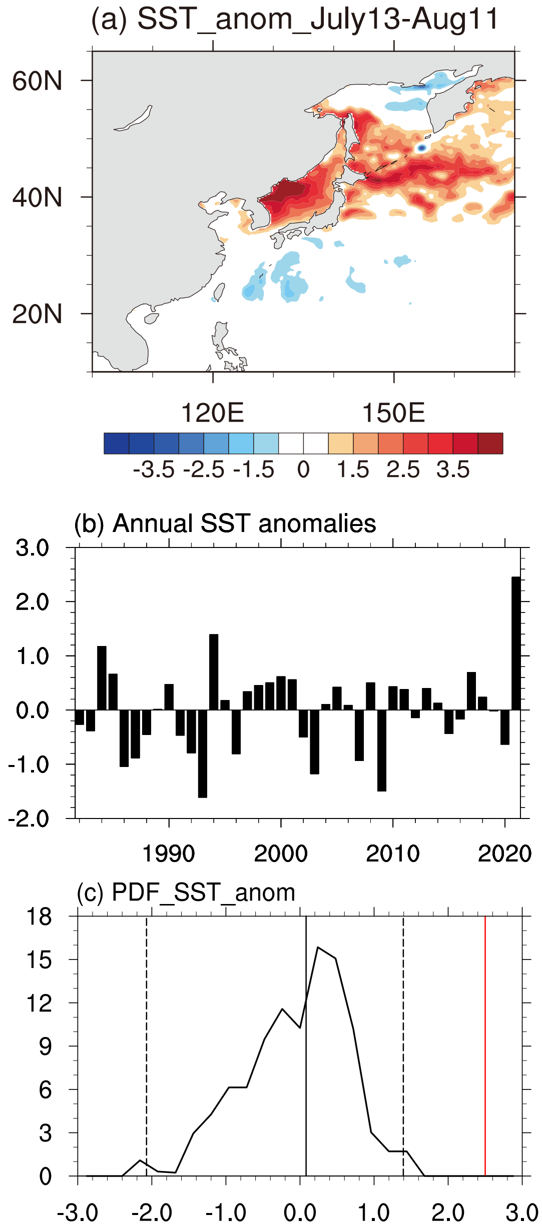

Fig. 7. (a) The SST anomalies averaged for 13 July to 11 August 2021 (shading, units: °C). (b) The interannual SST anomalies in the Sea of Japan/East Sea averaged for 13 July to 11 August from 1982 to 2021 (units: °C). (c) The probability density function (PDF; curves; %) and median (vertical solid line) of SST anomalies in the Sea of Japan/East Sea averaged for 30 consecutive days in July and August from 1982 to 2020. Vertical dashed lines indicate the 1% and 99% percentiles. The vertical red line represents the intensity of SST anomalies averaged over the Sea of Japan/East Sea and from 13 July to 11 August 2021.

Asia (Fig. 3a), evidenced by the SST anomalies averaged in the Japan/East Sea, being 2.5°C and 2.2°C for 13 July–11 August and 13–22 July, respectively. These long-lasting extreme warm SST anomalies around Northeast Asia during July–August 2021 were also noted by Kuroda and Setou (2021), who identified this phenomenon as a marine heatwave. However, their analysis excluded the Sea of Japan/East Sea and focused on the western North Pacific (40°–50°N, 143°E–180°) to explore the features of this marine heatwave. Actually, the maximum SST anomalies averaged throughout this marine heatwave (i.e., from mid-July to mid-August) are located in the Sea of Japan/East Sea, as shown in Fig. 7a. In addition, from 30 July to 1

August when the marine heatwave over the western North Pacific reached its peak, according to Kuroda and Setou (2021), the regionally averaged SST anomalies in their interest area, the western North Pacific, was 2.7°C, smaller than those in the Sea of Japan/East Sea which were 2.9°C.

Moreover, the SST anomalies averaged in the Sea of Japan/East Sea over the period 13 July to 11 August 2021 are much greater than those during the same period of previous years from 1982 to 2020 (Fig. 7b), exceeding the climatological value by more than three interannual standard deviations. There are 33 sets of consecutive 30 days during July and August in one year, and thus a total 1287 sets during 1982–2020. This indicates that the SST anomalies are mainly concentrated in the range from –2.1°C to 1.4°C, corresponding to the 1st and 99th percentiles, respectively. Therefore, the anomaly during the period of 13 July to 11 August 2021 (2.5°C) far exceeds the 99th percentile. This result further confirms that the SST anomalies in the Japan/East Sea during the period of 13 July through 11 August 2021 are unprecedented.

5. Possible causes of the anomalous anticyclone over Northeast Asia

The results shown in the previous sections reveal the extreme nature of the AA over Northeast Asia evidenced by its unprecedented intensity and duration, and the role of this AA in inducing extreme climate events over two widely separated regions. Several unprecedented weather or climate events may occur simultaneously over the remote regions as a consequence of the anomalous circulation shown in this study, or via teleconnection patterns (e.g., Hu et al., 2023; Na and Lu, 2023). Considering these results, it would be of great scientific significance to illustrate the physical mechanism responsible for the formation and maintenance of this extreme AA over Northeast Asia. The unprecedented enhancement of atmospheric convection over the tropical western North Pacific in July 2021 is one candidate mechanism, as suggested by Hu et al. (2023). In addition, atmospheric processes in the extratropics may be another candidate. For instance, some previous studies suggested that wave trains in the mid-high latitudes over the Eurasian continent can induce an AA over East Asia (e.g., Enomoto et al. 2009; Xu et al. 2019).

To investigate the possible mechanism responsible for the formation and maintenance of the extreme AA over Northeast Asia, we examined the daily evolution of the 500-hPa geopotential height anomalies in July 2021 (not shown). Evidently, the AA over Northeast Asia corresponds to different teleconnection patterns in two stages of its lifecycle, i.e., 13–16 July and 17–22 July. During 13–16 July (Fig. 8a), there tends to be a teleconnection pattern over the Eurasian continent with an AA centered over northern Europe, an anomalous cyclone to the east of the Ural Mountains, and an AA over Northeast Asia. During 17–22 July (Fig. 8b), although there are strong circulation anomalies over the North Atlantic, they may not be responsible for the AA over Northeast Asia. During this period, a cyclonic anomaly exists over the subtropical western North Pacific, which together with the AA over Northeast Asia, resembles the

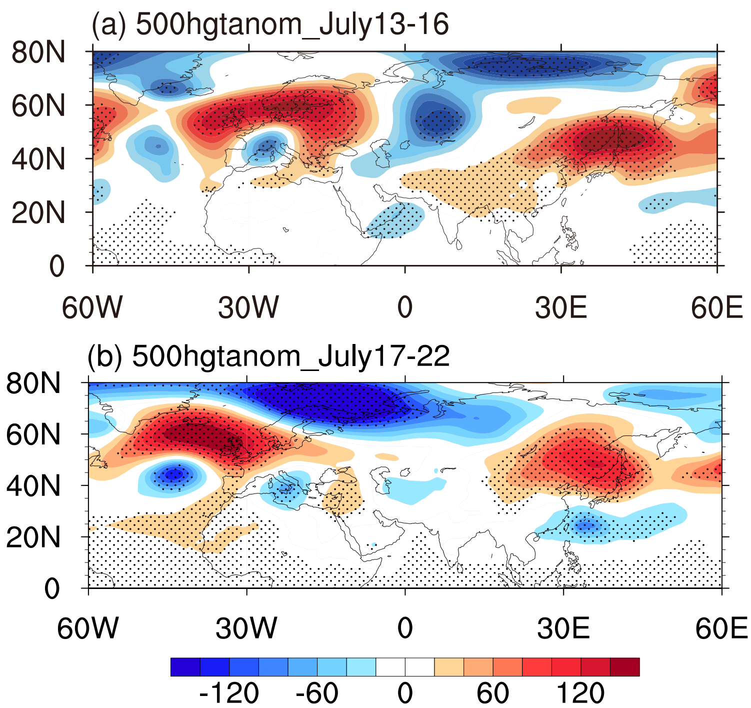

Fig. 8. The 500-hPa geopotential height anomalies (units: gpm) averaged for (a) 13–16 and (b) 17–22 July 2021. Dotted areas denote statistical significance exceeding the 95% confidence level using a *t*-test.

Pacific–Japan (PJ) teleconnection pattern proposed by Nitta (1987) and Huang (1992).

The anomalous cyclone over the subtropical western North Pacific can be explained by the enhanced collocated convective activity or precipitation (Fig. 9a). The enhanced convection can excite a PJ pattern and thus favor the AA over Northeast Asia, as documented by Hu et al. (2023). The daily evolution of precipitation anomalies averaged over the subtropical western North Pacific (15°–25°N, 125°–150°E) shows that the significant positive precipitation anomaly started from 17 July and persisted into 27 July with values above the 95th percentile of the precipitation anomalies (9.96 mm d^{-1}) over the same region during July and August from 1979 to 2020 (Fig. 9b). The peak rainfall enhancement appears in 21 and 22 July, corresponding to Typhoon In-fa (2021). In addition, Hu et al. (2023) found that the existing La Niña also contributes to the formation of the AA over Northeast Asia based on both observation and numerical model analyses. La Niña-induced suppressed convection over the tropical Pacific results in a tropical anticyclonic anomaly, and this anticyclonic anomaly strengthens the precipitation over the tropical western Pacific by intensifying the monsoonal circulations and inducing the positive moisture and enthalpy advection anomalies. Consequently, the enhanced precipitation and convective activity over the western tropical Pacific trigger a PJ-like pattern and a resultant AA over Northeast Asia.

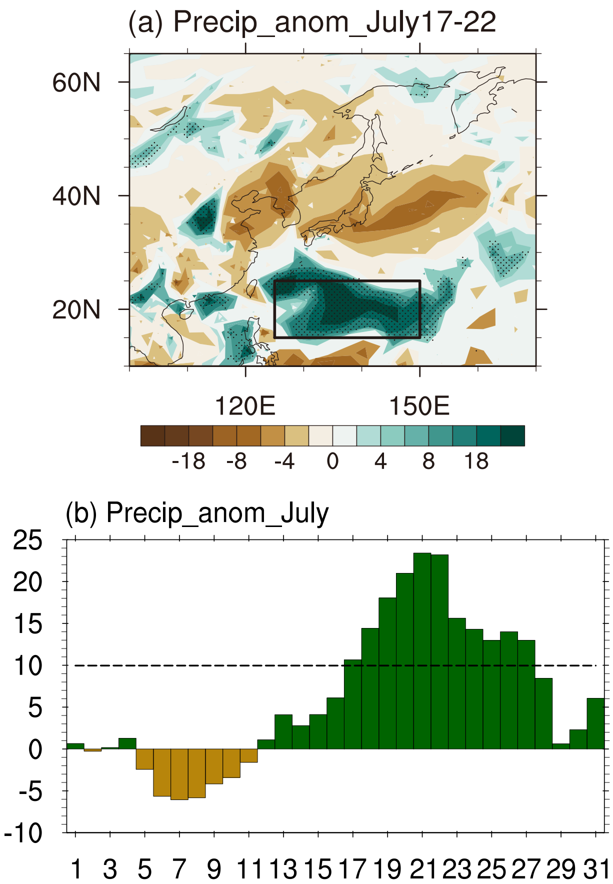

Fig. 9. (a) The precipitation anomalies (units: mm d^{-1}) averaged from 17 to 22 July 2021. Rectangle denotes the key convective region (15°–25°N, 125°–150°E). Dotted areas denote statistical significance exceeding the 95% confidence level using a *t*-test. (b) The daily evolution of the precipitation anomalies averaged over the key convective region in July 2021 (units: mm d^{-1}, green and yellow bars refer to the positive and negative precipitation anomalies, respectively). The dashed line denotes the 95% percentile of regionally averaged precipitation anomalies (9.96 mm d^{-1}) over the same region during July and August from 1979 to 2020.

6. Conclusions

This study investigates the evolution of an extreme AA over Northeast Asia, which is associated with a significant northward shift of the western Pacific subtropical high and plays an important role in the "21·7" severe rainfall event in Henan. Moreover, we also investigated the impacts of this AA on the surface temperatures in Northeast Asia, including surface air temperatures over land and SSTs in oceans. Furthermore, we explored the possible causes of the extreme AA over Northeast Asia.

The extreme AA over Northeast Asia exhibited unprecedented intensity and duration since 1979. It existed before the heavy rainfall event and maintained a considerably high amplitude for a long time before and during the heavy rainfall event. Specifically, from 13 to 22 July 2021, the daily geopotential heights for 10 consecutive days were higher than their corresponding daily climatological means by two interannual standard deviations. The rarity of this AA is further evidenced by the following facts. First, the 500-hPa geopotential height anomalies averaged over Northeast Asia and over 13–22 July 2021 are much greater than those during the same period of previous years from 1979 to 2020, exceeding the normal by more than three interannual standard deviations. Second, the averaged anomalies are considerably larger than the 99.9th percentile for the 10consecutive-day-mean height anomalies over the same region during July and August from 1979 to 2020. Finally, among the top 20 cases with the highest 10-consecutive-day-mean geopotential heights in Northeast Asia during July and August from 1979 to 2021, 12 cases occurred in July 2021 with the most extreme value recorded during 13–22 July 2021.

The AA over Northeast Asia also leads to extreme warming for both surface air temperatures and the SSTs beneath, in addition to supporting the extreme rainfall in Henan. The surface air temperatures notably increased in Northeast Asia, concurrent with the evolution of the AA. In addition, the SSTs beneath the AA are considerably warmer for a longer duration, i.e., the warmer SSTs persist even after the AA weakens and disappears. In particular, the SSTs in the Sea of Japan/East Sea, for 30 consecutive days, i.e., from 13 July to 11 August 2021, are higher than their corresponding daily climatological means by two interannual standard deviations, further noting that the maximum SST anomalies averaged over this period are up to 6.4°C. The regional-mean SST anomalies in this region averaged from 13 July to 11 August in 2021 are much higher than that during the same period from 1982 to 2020, and are above normal by more than three interannual standard deviations, far exceeding the 99th percentile of 30-consecutive-day-mean SST anomalies over the same region during July and August from 1982 to 2020.

The AA over Northeast Asia tends to be induced by different teleconnection patterns, dependent on the first and second halves of its maintenance stages, i.e., a teleconnection pattern over the Eurasian continent during the first half (13–16 July) and the PJ pattern triggered by the enhanced precipitation or diabatic heating over the subtropical western North Pacific during the latter half (17–22 July).

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