LETTER

Attribution of the record-breaking heat event over Northeast Asia in summer 2018: the role of circulation

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Abstract

In summer 2018, an extraordinary heat wave with record-breaking high temperatures hit Northeast Asia. However, the contribution of atmospheric circulation to this heat wave remains unknown. In this study, we quantify the contribution of circulation by using the flow analogue method. It is found that Northeast China, Korea and Japan were the most affected areas by the heat event, from daily to monthly timescales. The persistent high temperature was associated with an anticyclonic anomaly over Northeast Asia, related to the record-breaking northward shift of the western Pacific subtropical high (WPSH). The persistent anomalous anticyclone played a dominant role in this heat event, explaining half of the magnitude of the heat event. Both thermodynamical change and dynamical change in recent decades have increased the probability of occurrence of this kind of heat event over Northeast Asia. Specifically, the change in dynamical flow explains a fraction of less than 20% of the increases in probability of heat events. The contribution of thermodynamical changes to heat events generally increases with the rarity of the extreme event.

1. Introduction

Extreme weather events such as heat waves have drawn increasing attention in recent years, due to their great impact on human health, society and natural ecosystems (Perkins Sarah 2015). Associated with global warming, it is likely that the frequency of heat waves has increased in large parts of Europe, Asia and Australia (Stocker and Qin 2013, Lee and Lee 2016, Wang et al 2016). East Asia has suffered severe heat waves in recent years, including the 2013 heat wave in Central and Eastern China, Korea and Japan (Imada et al 2014, Min et al 2014, Zhou et al 2014, Ma et al 2017), the 2014 hot and dry summer in Northeast Asia (Wilcox et al 2015) and the 2017 spring–summer hot and dry extremes over Northeast China (Wang et al 2019). In summer 2018, a record-breaking heat wave swept large areas of Northeast China, Korea and Japan. The China Meteorological Administration issued high-temperature warnings for 33 consecutive days. The Japan Meteorological Agency (JMA) identified the event as a natural disaster and reported ‘unprecedented levels of heat’ (BBC 2018). In Kyoto, temperatures reached above 38 °C for seven consecutive days for the first time since records started in the 19th century (BBC 2018). In South Korea, the whole country was hit by record temperatures unseen in the last 100 years (The Guardian 2018). The extreme heat event caused heat-related mortality and harmed crops and livestock over Northeast Asia. At least 1032 people died from heat-related causes in July 2018 (Imada et al 2019).

Understanding the causes of extreme events is important but is a challenge. Each extreme weather event is unique and driven by the interplay between specific atmospheric dynamics (large-scale circulations) and other physical processes (Vautard et al 2016). The exact timing, location and duration of extreme events can be often driven by the atmospheric circulation, especially in mid-latitudes (Kornhuber et al 2019). Previous studies showed there is a clear link between atmospheric dynamics and heat waves in Europe. For example, the circulation anomaly was the main contributor to the...
recent mega-heat waves over Europe (Jézéquel et al 2018, Sánchez-Benítez et al 2018). Barriopedro et al (2011) identified a blocking anticyclone as the main cause of the 2010 Russian heat wave. Nevertheless, no clear hemispheric increase in blocking is found (Barnes et al 2014). The midlatitude sinuosity linking to extreme events showed a slight increase in recent analyses (Cattiaux and Ribes 2018). Besides, increasing trends in anticyclonic circulations have been identified to contribute to summer/autumn hot extremes over portions of Eurasia and North America (Horton et al 2015).

The variation of summer surface air temperature in Northeast Asia (NEA) can be influenced by the western Pacific subtropical high (WPSH) (Sui et al 2007, Chen and Lu 2014), the Silk Road Pattern or the circum-global teleconnection (CGT) (Hong et al 2017), the East Asia–Pacific/Pacific–Japan (EAP/PJ) tele-connection pattern (Chen et al 2016) and the Arctic oscillation (Tang et al 2014, Lee and Lee 2016). However, barely any study has quantified the contribution of atmospheric circulation to a specific heat wave over NEA in the context of event attribution. Given the huge and record-breaking impact of the 2018 heat wave on NEA, we aim to: (i) reveal the atmospheric circulation features associated with the heat event, and (ii) quantify the contribution of circulation to the extreme high temperatures. In particular, we aim to quantify how the dynamical and thermodynamical changes in recent decades potentially increased the odds of an extreme high-temperature event over NEA, regardless of the relative roles of external forcing and internal variability.

2. Data and methods

We used 6-hour data from the Japanese 55 year Reanalysis (JRA-55) on a $1.25^\circ \times 1.25^\circ$ grid from 1958 to 2018 (Kobayashi et al 2015). Variables used include 2 m mean temperature (T2 m), maximum temperature, geopotential height at 500 hPa (Z500), and wind fields. Daily mean data were obtained by averaging 6-hour data in each day. Daily anomalies were calculated relative to the 1981–2010 mean of each calendar day.

To characterize the magnitude and spatio-temporal evolution of this event, we identified areas with record-breaking temperatures at different timescales over NEA over land (denoted as dashed blue boxes in figure 1(a)) for summer (June–July–August) 2018. Following Barriopedro et al (2011), we calculated the moving average of T2 m with windows from 1 to 40 d, for each summer (June–July–August) day of 1958–2018. For each calendar day and timescale in 2018 summer, a grid with the highest temperature during the period of 1958–2018 was identified as the record-breaking one. We then calculated the area with record-breaking temperature in each day and timescale during the summer of 2018. At the same time, for each timescale, the period with the largest record-breaking area in summer 2018 can be detected (e.g. for 21-day running mean, there are largest areas with record-breaking temperature during 16th July–5th August). Based on the identified spatial and temporal evolution, we finally obtained the spatial patterns of the temperature anomalies at different timescales (from weekly to monthly) in summer 2018.

To characterize the atmospheric circulation, we specifically investigated the anomalous WPSH. Following previous studies (He et al 2015), the WPSH is measured by eddy geopotential height, defined as the deviation of geopotential height from the regional average over 0–40$^\circ$N, 180$^\circ$W–180$^\circ$E. We used two indices to describe the characteristics of WPSH based on the eddy geopotential height at 500 hPa: (i) the Western Ridge Point Index, which is defined as the longitude where the most western end of the 0 m contour of eddy geopotential height lies over regions within 10$^\circ$N–60$^\circ$N and 90$^\circ$E–180$^\circ$E; (ii) the Ridge Line Position Index, which is defined as the average latitude where the following conditions were satisfied: (a) zonal wind was zero and (b) the meridional shear of zonal wind was above zero, over regions within 10$^\circ$N–60$^\circ$N and 110$^\circ$E–150$^\circ$E. These two indices were recommended by the National Climate Center of China Meteorological Administration for operational monitoring use.

To extract the circulation contribution to the extreme high temperatures over NEA, we used the ‘flow analogue method’ (Yiou et al 2014, Jézéquel et al 2018) with the circulation proxy eddy geopotential height at 500 hPa (here eddy Z500, denoted as zonal mean removed from geopotential height at 500 hPa). For each day, we search the 20 analogue days with the most similar eddy Z500 field over NEA (35$^\circ$N–50$^\circ$N, 115$^\circ$E–140$^\circ$E, denoted as the black rectangle in figure S2 (stacks.iop.org/ERL/15/054018/mmedia)) among the days of other years. The similarity was measured by the Euclidean distance. To avoid the impact of the seasonal cycle on both temperature and circulation, we only look for analogue days within a moving window of 61 d ($\pm$30 d) centered around the day of interest. Different choices in the number of circulation analogues or moving window and datasets were tested, with similar results. We then reconstructed ‘flow-conditioned’ temperature (hereafter referred to as ‘uchronic temperature’) anomalies by the following steps: (i) For each day, we randomly picked one of the 20 best analogue days and then obtained a sequence of temperature anomalies during the research period; (ii) we then calculated the average of the sequence of temperature anomalies; (iii) we repeated the above two steps 1000 times and finally got the probability distribution of temperature anomalies conditional on the observed anomalous circulation of 2018 summer (hereinafter referred
to as ‘uchronic temperature’). In addition, we also reconstructed the distribution of temperature anomalies from a randomly picked series of observed days (same length as this event) regardless of circulation as a control group. The distributions of uchronic temperatures over two reference periods (1958–1990 and 1991–2017) were compared with each other as well as the control group.

To assess the relative contributions of dynamical and thermodynamical changes to high temperature over NEA, given the 2018 atmospheric circulation, following Sánchez-Benítez et al (2018),

Figure 1. (a) Maximum mean temperature anomalies (relative to 1981–2010, units: °C) for 21-day average in summer 2018, which is during 16th July–5th August. (b) Numbers of hot days (shading) during 16th July–5th August. (c) Temporal evolution of the spatial extent (in $10^3$ km$^2$) of areas with record-breaking temperatures at different time scales, but only the areas within dashed blue box (figure 1(a)) are considered. The black dots indicate regions with record-breaking temperature anomalies (a) and hot days (b), respectively.
Figure 2. (a) Geopotential height (contour, unit: gpm) at 500 hPa and their anomalies (relative to 1981–2010, shadings) for the 16th July–5th August 2018 period. The 0 m contour of eddy geopotential height, which indicates the location of the WPSH, are highlighted in blue (climatology) and in red (2018). (b) Scatter plot of WPSH western ridge point (x-axis) and ridge line position (y-axis) during 16th July–5th August from 1958 to 2018. Red scatter highlights the 2018 values. The horizontal and vertical dashed lines denote the 1958–2018 mean of the WPSH western ridge point and ridge line position, respectively.

3. Results

3.1. Observed characteristics of the 2018 heat wave over Northeast Asia

To characterize the spatio-temporal evolution and magnitude of the 2018 heat event, we examine the time evolution of the spatial extension of areas over the

‘thermodynamically adjusted’ temperature distributions were calculated by repeating the above flow analogue method, but with detrended temperature and detrended eddy Z500 fields, since the trend on Z500 is generally led by thermodynamics (e.g. Z500 rises by warming in lower levels). The detrending is similar to Jézéquel et al (2018). The contribution of dynamical change was then estimated as the difference of ‘thermodynamically adjusted’ temperature distributions between the past (1958–1990) and present periods (1991–2017), while the thermodynamical change was estimated as the difference between the total change and the dynamical change (see SI Method).
NEA with simultaneously record-breaking temperatures for any period of 1 to 40 d in summer 2018 (figure 1(c)). The record-breaking temperatures were first observed in early June at a daily timescale, but did not last longer. Starting from mid-July, record high temperatures hit a large area over NEA and lasted at timescales ranging from daily to monthly. The exceptionally high temperatures over NEA started in mid-July and ended by mid-August. Analyses of the maximum mean temperature anomalies for moving averages of 7 days, 15 days, 21 days, and 31 days during summer 2018 (figure S1) indicate that NEA was located in the center of the extreme high temperatures at all timescales. The temperature over Northeast China, Korea and the south of Japan was 3 °C warmer than the 1981–2010 mean. For the 21-day moving average, persistent high temperature over NEA was detected from 16th July to 5th August. During this period, at least 71 266 people required hospitalization for heat stroke in Japan, while North Korea witnessed crop destruction (The Guardian 2018). The regional average of 21-day temperature anomalies over NEA (35°N–50°N, 115°E–140°E, rectangle in figure 1(a)) reached a record high of 2.35 °C. This was almost three standard deviations of the interannual variability above the 1981–2010 mean and was the highest since 1958. During 16th July–5th August 2018, large areas over Northeast China, Korea and the south of Japan experienced record-breaking hot days, defined as days with daily temperature above the 95th percentile of 1958–2018. The most affected area had more than 12 record-breaking hot days (figures 1(b), (c)). Based on this evidence, we focus on the persistent high temperature over NEA during the period of 16th July–5th August 2018 in the following analysis, similar to the definition of an extreme event of Cattiaux and Ribes (2018).

3.2. Circulation pattern associated with extreme high temperature

The corresponding atmospheric circulation features a persistent anticyclonic anomaly over NEA (figure 2(a)). The anomalous pattern is indicative of a northwestward shift and intensification of the WPSH in the mid-troposphere. As evidenced by the closed 0 m contour of eddy geopotential height over Northeast China, Korea and the south of Japan, the ridge line of WPSH was located unprecedentedly at 37.5°N,
which is almost 8° north of the climatological position. This was the most extreme northward shift in historical records since 1958. In addition, the western ridge point of the WPSH shifted to 116°E, which is about 4° west of the normal position (figure 2(b)). Hence both the northwestward shift and intensification of the WPSH have provided favorable circulation background for the heat wave.

3.3. Circulation contribution to the high temperature
To quantify the role of circulation in the magnitude of the heat event, we measure the contribution of the anomalous anticyclone to the temperature anomalies over NEA using the flow analogue method (Yiou 2014, Jézéquel et al 2018). Figure 3(a) shows the distributions of T2 m anomalies averaged over NEA land for randomly picked days and eddy Z500 flow analogue (similar eddy Z500 circulation denoted as rectangle in Figure S2) days in the past (1958–1990) and present (1991–2017) period. There are significantly larger uchronic temperature anomalies compared to the randomly picked ones during both time periods, confirming the role of circulation that is favorable for extreme high temperature. The anomalous anticyclone could explain half of the observed temperature anomalies (2.35 °C), as the median of uchronic T2 m anomalies is 1.11 °C during 1958–2017 (figure 3(a)). The remaining temperature anomaly could be partially explained by other factors not accounted for by the circulation, such as the soil moisture through land–atmosphere feedback (Li et al 2018) and the Tibetan Plateau snow cover (Wu et al 2012). Further comparison reveals that the temperature anomalies accounted for by circulation in the present period are higher than in the past. This difference could be attributed to (i) thermodynamical changes, as indicated by different randomly picked T2 m between the two periods (figure 3(a)); or (ii) dynamical changes, as indicated by the different Euclidean distances of flow analogues between the two periods under the ‘thermodynamically adjusted’ condition (figure S3).

We further quantified how these changes influence the probability of extreme high temperature over NEA as in the summer of 2018. Figure 3(b) shows the probability of uchronic temperatures exceeding a given threshold in the past and present periods. We find that given circulation similar to 2018, the probability of T2 m anomalies larger than 1 °C has increased from 5.2% in the past (1958–1990) to 69.9% in the present (1991–2017), by a factor of 14. Likewise, a heat event with temperature anomalies exceeding 1.2 °C has become 70-fold more likely in the present, for the same anomalous anticyclone.

We finally quantified the contributions of dynamical change and thermodynamical change in recent decades to the probability of heat events over NEA. The dynamical change is estimated as the difference in ‘thermodynamically adjusted’ distributions between the past and present periods (figures 3(c), (d)), while the thermodynamical change is calculated as the remaining part of the total change (figure 4, see SI Method). The change in

![Figure 4. Cumulated dynamical change (orange) and thermodynamical change contributions (green) to the increases in probabilities of heat events in recent decades over NEA.](image-url)
dynamical flow since the 1990s explains a fraction of less than 20% of the increased probabilities of high-temperature events. The contribution of thermodynamical change generally increased with the rarity of extreme high temperature, with a contribution of at least 80%.

4. Conclusions and discussions

The July–August 2018 extreme heat wave lasted almost one month, affected a wide area in Northeast China, the Korean Peninsula and Japan, and displayed a record-breaking highest intensity since 1958. NEA (35°N–50°N, 115°E–140°E) was in the center of the abnormally high temperature at timescales from daily to monthly. The extreme heat wave started in mid-July and ended by mid-August. The dominant atmospheric circulation pattern features a persistent anticyclonic anomaly over NEA, which is indicative of a northward shift and intensification of the WPSH. The exceptional northward shift of the subtropical high was the greatest on record since 1958. A quantitative estimation of the contribution of circulation using the flow analogue method shows that the anomalous anticyclone explains more than half of the observed magnitude in T2 m anomalies. Both thermodynamical change and dynamical change in recent decades are favorable towards the occurrence of the 2018 extreme heat events. Depending on the magnitude of the temperature anomalies, the change in dynamical flow in recent decades explains a fraction of less than 20% of the increased probability of heat events over NEA. The contribution of thermodynamical changes generally increases with the rarity of the extreme event.

While both thermodynamical and dynamical contributions to this heat wave over NEA were detected, we acknowledge that we did not consider the interaction between the thermodynamical and dynamical change, as stressed by Horton et al (2015). We are also unable to attribute these changes solely to climate change due to the limitation of 60 years of data. Besides, the observed circulation was so extreme that it would be impossible to reconstruct the 1958 temperature anomalies close to the observed temperature (Jézéquel et al 2018).

Summer 2018 witnessed several concurrent record-breaking heat and extreme precipitation events in the northern hemisphere mid-latitudes (NOAA 2018) and these events have been connected by an amplified wave-7 tele-connection pattern (Kornhuber et al 2019). The record-breaking northward shift of the WPSH in July 2018 was found to be associated with an eastward-propagating wave train along the subpolar westerly jet over the Eurasian continent, originating from the strongest positive tri-pole pattern of sea-surface temperature anomaly in the North Atlantic (Liu et al 2019). When the anticyclonic node of this wave train reached NEA, this region was hit by extreme high temperature. Some recent studies have shown the influence of human-induced dynamical change on a singular extreme event (Schaller et al 2016, Vautard et al 2016). The increasing occurrence of extreme heat events over NEA may be related to human-induced dynamical change (i.e. Arctic amplification with increasing frequency of slower and increased-amplitude eastward progression of Rossby waves (Francis et al 2012)). Besides, the heat wave over NEA has also exhibited decadal changes, especially the abrupt warming in the mid-1990s (Su and Dong 2019). Further analysis is needed to fully understand the relative roles of external forcing and internal natural variability in the thermodynamical and dynamical contribution to extreme heat events over NEA.

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