Heatwave and Blocking in the Northeastern Asia: Occurrence, Variability, and Association

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Abstract The spatiotemporal variation and characteristics of heatwave in Northeastern Asia are investigated on both a grid basis and an event basis. We find that persistent, extensive, and intense heatwave has become more frequent during the last four decades. Such trend is found significantly correlated with the increase of temperature. The association between heatwave and blocking is also analyzed using two leading blocking indices, examining 500-hPa geopotential height (TM index) and vertically averaged potential vorticity anomaly (PV index), respectively. A discrepancy between blocking climatology of TM index and PV index is exhibited, with the former displaying two high-frequency zonal bands at the north and south regions, while the latter only showing one high frequency band in the north. However, grid-based concurrence analysis using the two blocking indices agreeably suggests that blocking favors the occurrence of heatwave, especially in the north region where blocking often occurs. We further explicitly investigate their temporal association with time lags, which has not been done before in the literatures. It reveals that heatwave mostly occurs after or on the onset day of blocking and ends after or at the end of blocking. It indicates that blocking is more of a favorable environmental condition to trigger heatwave than maintain it. Lastly, the impact of blocking on the characteristics of heatwave events is explored on an event basis using a 3-D spatiotemporal object model. Blocking-related heatwave events are more likely to be more persistent, extensive, and intense than unrelated events.

1. Introduction

Heatwave is a disastrous weather hazard with extremely high temperature persistent for days. Severe heatwaves with long duration and overwhelming intensity could cause tremendous financial loss and even deaths (Mora et al., 2017). Frequent dreadful heatwaves were observed across the world since 2000, for example, Europe (2003; Stott et al., 2004), Russia (2010; Miralles et al., 2014), Australia (2013; Bureau of Meteorology, 2013), and China (2013; Y. Sun et al., 2014). According to Intergovernmental Panel on Climate Change 2013, heatwave frequency has increased since the mid-20th century in large part of Europe, Asia, and Australia. Recent studies suggest that the probability of extreme heatwave might further increase under global warming due to the mean temperature shift (Russo et al., 2015; Seneviratne et al., 2018; Sousa et al., 2018) that might offer certain predictability of heatwave occurrence given their observed association, especially for those extreme events observed since 21st century (Black et al., 2004; Ding & Ke, 2015; Dole et al., 2011; Miralles et al., 2014). The most severe heatwaves on record, including European heatwave in 2003, Russian heatwave in 2010, and Chinese heatwave in 2016, were all found driven by such anticyclone anomalies (Black et al., 2004; Ding & Ke, 2015; Miralles et al., 2014). The positive quasi-stationary 500-hPa height anomalies could dynamically produce subsidence, clear skies, light winds, warm-air advection, and prolonged hot conditions at the surface (Meehl & Tebaldi, 2004). Pfahl and
Wernli (2012) showed that up to 80% of summer hot extremes were collocated with blocking. A number of most recent studies (Brunner et al., 2018; Schaller et al., 2018; Sousa et al., 2018) explored the link between blocking and the substantial changes in the frequency of extreme hot days observed in Europe and Russia. Efforts were made to objectively detect blocking based on different meteorological variables with varying hypotheses of underlying mechanisms. The 500-hPa geopotential height ($Z_{500}$) and the potential vorticity (PV) fields are the most widely adopted meteorological proxies for detection. Methods relying on $Z_{500}$ are mainly based on its meridional gradient (Lejenäs & Økland, 1983; Tibaldi et al., 1997; Tibaldi & Molteni, 1990, hereinafter TM90; Trigo et al., 2004) or the maxima (R. M. Dole & Gordon, 1983; Sausen et al., 1995) to capture the omega-shape high pressure system or an in-situ easterly geostrophic flow (Scherrer et al., 2006; Schwierz et al., 2004). On the other hand, PV focuses on a quasi-horizontal wave-turning on the dynamic tropopause in order to capture dynamic features of the phenomenon (Pelly & Hoskins, 2003; Schwierz et al., 2004). Consequently, indices based on either $Z_{500}$, for example, TM90 (Brunner et al., 2018; Buehler et al., 2011; Schaller et al., 2018; Tibaldi & Molteni, 1990; Whan et al., 2016), or PV, for example, APV* (anomaly of vertically averaged PV; Pfahl & Wernli, 2012; Schwierz et al., 2004; Sillmann et al., 2011; Sillmann & Croci-Maspoli, 2009), are now frequently employed to study the association between blocking and heatwave. However, it is still rare to find studies that systematically quantify their association in a probabilistic context that could increase our confidence in explaining the variability (let alone predictability) of heatwave occurrences using blocking. There exists spatiotemporal discrepancy in climatological frequency among these leading blocking indices, due to their different proxies and definitions as expected. For instance, TM90 (Scherrer et al., 2006; Tibaldi & Molteni, 1990) is based on meridional gradient of $Z_{500}$; the resulted climatological frequency often exhibits a meridional high-low-high pattern, that is, higher frequency in lower latitude (<40°N) and higher latitude (>55°N; Schaller et al., 2018). While, the APV*-based blocking indices often show one high-frequency zonal band above 55°N (Pfahl & Wernli, 2012). So we think it is important to study associations between blocking and heatwave occurrence using different indices, considering the aforementioned differences in the blocking climatology. Moreover, previous studies on the relationship between blocking and heatwave are often narrowly confined to preliminary frequency analysis of their concurrences; their exact temporal association with time lags and potential influences of blocking on the characteristics of heatwave events are rarely explored. In order to fill these research gaps, this study first investigates the trend of heatwave frequency on both grid and event bases, then scrutinizes the relationship between heatwave and collocated blocking detected by a 2-D-extension of TM90 (Scherrer et al., 2006) and a dynamical blocking indicator based on PV (Schwierz et al., 2004), respectively. Consistency and discrepancy based on the two blocking indices are discussed. Our work is motivated by two main objectives: (1) investigate the spatiotemporal variation and changes of the occurrence and characteristics of heatwave in the Northeastern Asia and (2) explore the spatiotemporal association between heatwave and blocking, in terms of both occurrence and characteristics, using two leading blocking indices.

The paper is organized as follows. Section 2 describes the data and method used in this study. In section 3, we address the following: section 3.1 discusses the change of heatwave occurrence; section 3.2 presents the climatology of blocking frequency based on two leading blocking indices; section 3.3 describes the association between heatwave and blocking, from concurrent association, to extended temporal association, along with the blocking impact on the characteristics of heatwave events. At the end, a summary is provided. Note that all abbreviations are tabulated in Table S1 in the supporting information for your reference.

2. Data and Method

2.1. Blocking Index

Our study area is defined as 35–75°N and 70–160°E (hereafter referred to as Northeastern Asia), including north China, Inner Mongolia, part of Russian, Korea, and Japan. Two leading blocking indices are considered and compared in this study. The first one is a 2-D-extension (Scherrer et al., 2006) of the TM90 proposed by Tibaldi and Molteni in 1990 based on the daily $Z_{500}$ from ERA-Interim, referred to as the TM index hereinafter. First, northward and southward gradients (GHGN and GHGS) of $Z_{500}$ at each grid point with latitude $\phi = 35^\circ, 35.5^\circ, ..., 75^\circ$ N and longitude $\lambda = 70^\circ, 70.5^\circ, ..., 160^\circ$ E are calculated as following with $\Delta \phi = 15^\circ$:...
Instantaneous blocking at a grid is set to 1 if both GHGN < −10 m/(° latitude) and GHGS > 0 m/(° latitude). Blocking is identified when the instantaneous blocking index remains nonzero for at least consecutive 5 days to detect the persistent system (Brunner et al., 2018).

The other blocking index, based on daily vertically averaged potential vorticity (VAPV) between 500 and 150 hPa obtained from ERA-interim, follows the method proposed by Schwierz et al. (2004), hereafter referred to as the PV index. VAPV anomalies (in pvu [Gill, 1982]) are calculated against the monthly climatological value for each grid. A tracking algorithm using VAPV anomalies with prescribed blocking intensity and overlap ratio (OR) between two consecutive time steps is applied (Scherrer et al., 2006); thus, the movement of the blocking pattern and its dynamic core can be captured. Previous studies (Pfahl & Wernli, 2012; Schwierz et al., 2004) used several thresholds for VAPV anomaly (e.g., −0.7, −1.2, and −1.3 pvu) to detect blocking with desirable intensities. While, the choice of OR often varies with different temporal resolutions of the data used in previous studies, for example, Schwierz et al. (2004) set OR=0.7 for the 6-hourly dataset and Castanheira and Barriopedro (2010) reduced OR to 0.45 when applied to the daily data. In this study, we provide an assessment of the detection sensitivity to different combinations of these two key parameters (i.e., PV-based intensity and OR for temporal continuity). Results are attached in the supporting information. In the main manuscript, we use −1.2 pvu and OR=0.4 to carry out the comparison with TM-index based results. Because they (i.e., −1.2 pvu and OR=0.4) represent the commonly used neutral thresholds and exhibit comparable frequency of blocking with that detected by the TM-based. It is worth noting that the spatial pattern of PV-based blocking is in fact not sensitive to different choices of the two parameters but only the magnitude showing some difference (Figure S1 in the supporting information). With prescribed PV intensity and OR value, a PV-based blocking event is thus identified once the spatial extent of the blocking pattern ≥1.8×10^6 m^2, and a 5-day persistency criterion is met. The required spatial extent (≥1.8×10^6 m^2) and duration (≥5 days) ensure the spatial-temporal quasi-stationarity of the captured system. Note that the main difference between the PV-based and the TM-based procedures is that a grid has PV-based blocking index = 1 when there is a qualified blocking event, where the blocking region could move with continuity between time steps for at least 5 days, while TM-based approach qualifies a grid-based blocking only when the fixed grid satisfies both the GHGN and GHGS conditions for at least 5 days, which requires a more rigorous spatial stationarity of the system (Scherrer et al., 2006).

2.2. Heatwave Index

Heatwave is defined based on the summertime (June–August) daily maximum temperature using CPC global air temperature data with a 0.5°×0.5° spatial resolution from 1979 to 2017. On a grid basis, we define a day with a heatwave index = 1 if the daily maximum temperature exceeds the 90 percentile of the long-term June-July-August daily temperature record over a 15-day window (from 7 days ahead to 7 days after the day of interest) for at least three consecutive days (Raei et al., 2018); otherwise, the heatwave index is equal to 0. This definition is more robust than those with absolute threshold. It takes persistency of the characteristics of heatwave into consideration, as well as the spatial variance in daily maximum temperature over the study region. A heatwave event is detected based on the heatwave index and their connectivity condition measured as following. Firstly, at each time step, we find all of the nonzero grids to identify clusters of connected grids. Any two nonzero grids are connected when they share a side. Then, consistent with PV-based blocking definition, we use OR = 0.4 on consecutive days to monitor the evolution of the spatial extent of heatwave events and their durations. Other OR values, including 0.35, 0.45, and 0.5, are also employed to assess the sensitivity of the results to OR values. According to the sensitivity test result, our conclusion is quite robust among the prescribed OR values (results not shown). Lastly, selected heatwave events have to last for at least 3 days. As a result, a heatwave event with its dynamic location, specific shape, and affecting area can be described using a 3-D spatiotemporal object (Figure 1a). Previous definitions of heatwave event usually utilized regular shapes for sliding scan,
for example, a square. If heatwave grids within the scanning area exceed a certain fraction, and a prescribed percentage of overlapping areas between consecutive days is met, the scanning process continues (Lopez et al., 2018; Stefanon et al., 2012). This method might miss comparatively smaller or spatially irregular events. However, with a 3-D spatiotemporal object representing a heatwave event as presented in this study, we can quantify their duration, spatial extent, volume, and intensity, referred to as HWD, HWE, HWV, and HWI, respectively. HWD is defined as the number of days between the onset and the end day; HWE is the largest number of affected grids during the event at any day; HWV is the total number of grids, that is, the volume of the 3-D object by counting the total number of grids; and HWI is measured by the sum of daily maximum temperature exceeding the corresponding 90 percentile divided by the interquartile range of the 15 moving days centering on the corresponding calendar day (equation (3)). Besides, the center location of each event is defined by the barycentric coordinates (only including longitude and latitude) of the 3-D object.

\[ \text{HWI} = \sum \frac{T_d - T_{15d90p}}{T_{15d75p} - T_{15d25p}} \] (3)

2.3. Association Analysis

We use conditional probability analysis at each grid point to investigate the concurrent association between heatwave and collocated blocking. First, summertime June-July-August climatology of heatwave (blocking) frequency is expressed as P (heatwave; P [blocking]). While the frequency of heatwave (blocking) under blocking (heatwave) is expressed as P (heatwave|blocking; P [blocking|heatwave]). If heatwave is not associated with blocking, the heatwave frequency during blocking days should be similar (statistically indistinguishable) to the climatological frequency of heatwave; otherwise, their association can be implied. To quantify the extent of concurrent association, relative anomaly (HWF\textsubscript{anom}) proposed by Brunner et al. (2018) is calculated at each grid as following:

\[ \text{HWF}_{\text{anom}} = \frac{P(\text{heatwave}|\text{blocking})}{P(\text{heatwave})} \] (4)

When \( \text{HWF}_{\text{anom}} \) is significantly greater than 1, it indicates that blocking favors the occurrence of heatwave. The larger the \( \text{HWF}_{\text{anom}} \) is, the greater impact of blocking on heatwave frequency is suggested. While, when \( \text{HWF}_{\text{anom}} \) is significantly smaller than 1, the suppression of blocking on heatwave frequency can be implied. For convenience, all days constituting heatwave/blocking are referred to as heatwave days (HWDy)/blocking days (BLDy) hereinafter.
Considering the temporal persistence of both heatwave and blocking, we group consecutive HWDy/TM-based BLDy into one heatwave/TM-based blocking sequence (referred to as HWS/TMS respectively) and dissect the 3-D PV-based blocking event to each grid (hereinafter PVS) to explore the exact temporal association with time lags between the two. TMS and PVS are together referred to as blocking sequence (hereinafter BLS). Besides, we also investigate the influence of blocking on the characteristics (HWD, HWE, HWV, and HWI) of heatwave events. We divide all identified heatwave events into blocking-related heatwave events (BRH) and blocking-unrelated heatwave events (BURH). BRH are those temporally associated with collocated blocking within certain time lag, with their mean duration and extent overlap ratio (MDEOR) over certain threshold. We perform a complete assessment over different time lags and MDEOR; results are elaborated in sections 3.3.2 and 3.3.3, respectively. As shown in the schematic diagram (Figure 1), for a given heatwave event (blue 3-D object in Figure 1a), the orange grids are overlapped by blocking in both space and time (Figure 1b). We denote the ratio of the temporal projection of orange grids to HWD as $R_{\text{HWD}}$ and the ratio of spatial projection of the orange grids to HWE as $R_{\text{HWE}}$. MDEOR is defined as the average of $R_{\text{HWD}}$ and $R_{\text{HWE}}$. The complement of BRH is BURH. Then, empirical cumulative distribution function (ECDF) of their characteristics is calculated for BRH and BURH, respectively, under different thresholds of MDEOR.

2.4. Statistical Significance

As both blocking and heatwave are persistent system and phenomenon, strong autocorrelation is expected. Monte Carlo test (Metropolis & Ulam, 1949) is employed to test the significance of their association. A detailed example of applying Monte Carlo test to investigate the concurrent association between heatwave and blocking can be traced in Brunner et al. (2018). In this study, the test is conducted with 1,000 random draws and on 0.05 significance level. Kolmogorov-Smirnov goodness-of-fit (KS) test is utilized to examine the significance of differences between distributions, that is, ECDFs, BRH, and BURH. Statistically significant differences indicate substantial influence of blocking on the characteristics of heatwave.

3. Results

3.1. Increase of Heatwave Occurrence

Climatological summertime heatwave frequency (from June to August, 92 days) during 1979–2017 is quite evenly distributed over the Northeastern Asia with a regional average frequency of 0.05 (0.01 corresponds to approximately one heatwave day in each summer). Only the high-latitude region (55°–75°N) exhibits a slightly higher frequency around 0.06 (Figure 2a). We first conduct trend analysis on the occurrences at each grid (Figures 2c and 2d). Note that all the trends discussed below are statistically significant on the 0.05 level. We find that there are increasing trends of heatwave days (HWDy) at almost all the grids. About one quarter of the study area exhibits increase of >2.5 day/decade. If the increasing rate remains constant, then two decades later, heatwave frequency is expected to double in these areas. By grouping consecutive heatwave days into one sequence, an increasing trend is also exhibited (>0.5 HWS/decade for half of the study area), with the most rapid increase in the zonal band between 45° and 55°N. Further, we investigate the changes associated with the temporal and spatial distributions of heatwaves over the study area. Figure 2e shows the ratio of HWDy over each summer that have affecting area (connectivity in space is not imposed) exceeding 160 (black), 320 (blue), and 480 (orange) grids relative to the annual average during 1979–2017. Although all three time series show substantial increasing trends, HWDy with larger affecting area escalates more. Up to this point, we find that not only our study area is experiencing more HWDy in the summer but also more area is experiencing heatwave on the same day. Moreover, Figure 2f illustrates the annual ratio of grids (heatwave index = 1) that are affected by heatwave more than 3 (black), 6 (blue), and 9 (orange) days (continuity in time is not imposed). It reveals that more grids are experiencing more HWDy, particularly in the recent decade, with a substantial change point detected in the middle of 1990s using Pettitt test method (Pettitt, 1979).

Apart from the above grid-based results, where connectivity is not imposed, we further conduct a series of event-based analyses using the detected 3-D heatwave events. Comparing to the grid-based results, we can identify how the number of heatwave events with specific characteristics (duration, extent, volume, and intensity) is changing. The number of events that exceeding different thresholds of HWD, HWE, HWV, and HWI is thus analyzed. Significantly increasing trends of heatwave events are found, especially those
Figure 2. Spatial distribution of (a) heatwave frequency; (b) number of heatwave sequence; (c) trend of heatwave frequency; (d) trend of heatwave sequence; (e) annual ratio of heatwave days for each summer with affecting area exceeding 160 (black), 320 (blue), and 480 (orange) grids; (f) annual ratio of grids that are affected by heatwave more than 3 (black), 6 (blue), and 9 (orange) days; (g) annual ratio of heatwave events with duration (HWD) exceeding 3 (black), 4 (blue), and 5 (orange) days; (h) annual ratio of heatwave events with volume (HWV) exceeding 100 (black), 300 (blue), and 1000 (orange) grids; (i) annual ratio of heatwave events with extent (HWE) exceeding 30 (black), 100 (blue), and 300 (orange) grids; (j) annual ratio of heatwave events with intensity (HWI) exceeding 100 (black), 300 (blue), and 1,000 (orange).
with large extent (HWE), long duration (HWD), and high intensity (HWI), as shown in Figures 2g–2j. In another word, persistent, extensive, and intense heatwave events have become more frequent. This result is consistent with the previous studies (Meehl & Tebaldi, 2004; Perkins et al., 2012) but from a novel and more robust event-based perspective with imposed connectivity in both space and time.

According to Brunner et al. (2017), the increase of heatwave frequency is mainly attributed to the global warming. To further verify this claim and our procedures, we remove the long-term linear trend (significant on the 0.05 level) of daily maximum temperature from 1979 to 2017 at each grid and recalculate the heatwave occurrence and statistics of characteristics following the same procedures above. After removing the temperature trends, both the grid-based and the event-based heatwave frequencies show no significant increasing trends over the entire study region (results not shown), consistent with the conclusion from Brunner et al. (2017). Further, the removal of temperature trend does not alter the temporal distribution of heatwaves as illustrated by the heatmap and calendar day sum (right panel) in Figures 3a and 3b. The removal of temperature trend only leads to disappearance of trend in seasonal totals (bottom panels in Figures 3a and 3b). Note that the following results about the association between heatwave and blocking are all based on the recalculated heatwave derived from the detrended temperature (Brunner et al., 2017).

### 3.2. Blocking Climatology

As stated in Scherrer et al. (2006), the geographic distribution of blocking frequency largely depends on the definition and the selected spatiotemporal criteria of each blocking index. In our study, the discrepancy between the summer climatological blocking frequency resulted from TM index and PV index is also observed (Figures 4a and 4b). TM-based blocking (Figure 4a) exhibits two high-frequency zonal bands, that is, 35–45°N (hereinafter as south region) and 55–75°N (hereinafter as north region), with their corresponding frequencies around 0.1 (~10 days per summer) and 0.05 (~5 days per summer), respectively. The zonal band between these two high-frequency regions, that is, 45–55°N (hereafter as middle region), shows extremely low frequency (<0.01). This pattern is consistent with Schaller et al. (2018) as we introduced in the beginning. While, PV-based blocking (Figure 4b) exhibits south-to-north increasing frequency with only one high-frequency band. Notably, there is barely no blocking being detected below 40°N. Apart from the identification criteria, this discrepancy in spatial pattern may be physically attributed to the different features captured by these two blocking indices. Specifically, TM index explicitly accounts for easterly flow (Pinheiro et al., 2019), whereas PV index captures the shape of the dynamic tropopause and indicates anticyclonic circulation (Pinheiro et al., 2019; Scherrer et al., 2006). Furthermore, low-latitude blockings are frequently detected by TM index but rarely detected by PV index because the VAPV anomalies relative to the seasonal mean climatology are comparatively larger here than in the high-latitude region, while the TM index has no reference to the mean climatology. Besides, the numbers of TMS and PVS exhibit discrepancy as well (Figures 4c and 4d). Since the TM-based blocking follows more rigorous criterion for spatial
Figure 4. Spatial distribution of (a) TM-based blocking frequency, (b) PV-based blocking frequency, (c) number of TM-based blocking sequence, and (d) number of PV-based blocking sequence. Spatial distribution of P (heatwave|blocking) based on (e) TM index and (f) PV index. Spatial distribution of P (blocking|heatwave) based on (g) TM index and (h) PV index. Spatial distribution of relative anomaly based on (i) TM index and (j) PV index.
stationary and the speed of PV-based blocking is higher than the TM-based (Pinheiro et al., 2019), the number of TMS is relatively smaller than PVS given their similar frequencies in the north region. Such difference also reflects in their respective temporal association with heatwave, which will be further discussed in section 3.3.2. The climatologies of PV-based blocking resulted from other combinations of PV intensity and OR value are displayed in Figure S1. Similar patterns are observed among different combinations with some differences in magnitudes as expected, suggesting the insensitivity of the spatial patterns of PV-based blocking to these two parameters, at least in our study region.

Besides, different from heatwave (Figures 3a and 3b), both TM-based and PV-based summer blocking show no significant trend but certain subseasonality according to calendar day sum of blocking grids (Figures S1k and S1l). It shows that TM-based blocking peaks in late July, while PV-based blocking does in late June. Such difference in subseasonality further leads to the similar discrepancy in subseasonality between the occurrence of heatwave and TM-/PV-based blocking (Figures S1m and S1n).

### 3.3. Association Between Heatwave and Blocking

#### 3.3.1. Concurrent Association

The comparison between the climatological heatwave frequency P (heatwave; Figure 2a) and the one during blocking days P (heatwave|blocking; Figures 4e and 4f) clearly reveals that blocking favors occurrence of heatwave. P (heatwave) exhibits relatively small values, less than 0.1 in the entire study area, while P (heatwave|blocking) displays significantly higher values, larger than 0.3 in most area under both blocking indices. Spatially, in the north region with frequent blocking, the regional mean likelihood of heatwave during blocking is 0.34 and 0.25 for TM-based and PV-based blockings, respectively, which approximately correspond to increases of heatwave frequency with a factor of 7 and 5 measured by the relative anomaly (Figures 4i and 4j). In the middle region, particularly high values of P (heatwave|blocking; > 0.5) are exhibited, indicating that once blocking is detected by either index, heatwave is very likely to occur. However, blocking frequency is comparatively low here; hence, only a small portion of heatwave can be accounted for and biases might be larger. As for the south region, during TM-based blocking, heatwave frequency increases by a factor of 3 in most area, while PV index detects barely no blocking in this region, let alone establishing the association between blocking and heatwave here. On the other hand, up to 50% of the identified heatwave is concurrent with TM-based blocking in parts of north and south regions, while the likelihood of PV-based blocking given heatwave is comparatively low (less than 35%). All of these results indicate that TM-based blocking exhibits somewhat stronger concurrence with heatwave than the PV-based blocking. In addition, the value of P (heatwave|blocking) is apparently larger than P (blocking|heatwave) over most study regions. It indicates that blocking is more of a sufficient than a necessary condition to heatwave. It is also worth noting that since the likelihood of heatwave (blocking) under blocking (heatwave) is somewhat subjective to the detection algorithm of blocking, this conclusion may also possess certain sensitivity to the choice of blocking index. Strong concurrent association between warm extremes (temporal continuity is not imposed) and collocated blocking was also reported by Pfahl and Wernli (2012) in the midlatitude to high latitude in the northern hemisphere, but only based on single PV index from a partial perspective of P (blocking|heatwave). By calculating the relative anomaly, Brunner et al. (2018) also found that heatwave frequency doubled during blocking in the northern Europe based on TM index only. Our study advances by using two leading blocking indices with climatological discrepancy to explore and assess the robustness of concurrent association between heatwave and blocking. Meanwhile, the differences in the association between these two blocking indices are also revealed.

Moreover, an additional spatial filter for TM index has been applied to select large-scale blocking events with desired spatial scale as conducted in several latest studies (Brunner et al., 2018; Schaller et al., 2018; Woollings et al., 2008). More details about the spatial filter can be found in Schaller et al. (2018). Due to the permission of the meridional and zonal movements, the blocking frequency becomes comparatively higher than the one without spatial filter. As a result, the higher blocking frequency leads to higher P (blocking|heatwave) and lower P (heatwave|blocking), as shown in the conditional probability maps (Figure S2) with varying PV and TM indices.

To further explore the variability of the concurrent association between heatwave and blocking, we investigate the likelihood of heatwave (blocking) under blocking (heatwave) using both blocking indices on an annual basis (Figure 5). Note that the figure displays results calculated for the entire study region.
Figures 5a and 5b clearly show that before removing the long-term daily temperature trend, the likelihoods of heatwave under blocking increase significantly for both blocking indices. While after removing the temperature trend, the increasing trends of the likelihood also disappear. It again implies that the increasing occurrence of heatwave might be related to global warming.

3.3.2. Extended Temporal Association

Most of previous studies focus on concurrent association; exploration of exact temporal association between heatwave and blocking considering time lags is lacking. To fill this gap and provide a better profile of their temporal relationship, we calculate the gaps between the start/end dates of HWS and BLS at each grid (hereinafter as Gap_ss/Gap_ee). After examining the number of HWS-BLS pairs with $|\text{Gap}_\text{ss}/\text{Gap}_\text{ee}| < 30$ days (result not shown), we find that most of the pairs have their Gap_ss/Gap_ee lie between $-7$ and $7$ (Figure 6). There are only 4,908 temporally overlapped HWS-TMS pairs, containing 2.7% (1.0%) individual TMS (HWS), and 2,776 temporally overlapped HWS-PVS pairs, containing 0.8% (0.5%) individual PVS (HWS), with their Gap_ss/Gap_ee falling outside $[-7, 7]$. Thus, in the following discussion, we focus on the HWS-BLS pairs falling within $[-7, 7]$. However, if the readers want to focus on a narrower time lag such as $[-4, 4]$, this figure can still serve the purpose. It is also worth pointing out that any individual HWS can be paired with several individual BLS and vice versa.

The percentages of unique individual HWS/BLS and HWDy/BLDy accounted by HWS-BLS pairs are listed in Table 1. Generally, comparing to the concurrent pairs, the time-lagged HWS-BLS pairs account for much more HWDy and BLDy, suggesting the importance of having this deeper insight into their temporal association other than just concurrent scenario. For instance, in the north region, about 49.3% PV-based BLDy are temporally associated with HWS with time lags $\text{Gap}_\text{ss}/\text{Gap}_\text{ee} \in [-7, 7]$, but only 23.9% exhibit concurrence. On the other hand, 42.5% HWDy are temporally related to PVS with $\text{Gap}_\text{ss}/\text{Gap}_\text{ee} \in [-7, 7]$; only 17.8% are concurrent. The intercomparison between two blocking indices shows substantial difference. The ratios (the numbers inside the brackets, Table 1) of HWDy in concurrent pairs to those in the time-lagged pairs are significantly lower based on PV index (~0.4) than TM index (~0.8). It suggests that the PV-based concurrent scenario might only capture a small proportion of the full temporal association; thus, conducting this extended temporal analysis is more imperative for PV-based blocking.
Figure 6. The number of HWS-TMS/HWS-PVS pairs in the (a/b) north region; (c/d) middle region; (e/f) south region, and the (g/h) whole study region with $\text{Gap}_{ss}/\text{Gap}_{ee} \in [-7, 7]$. The heatmaps show the pair count for each combination of $\text{Gap}_{ss}$ and $\text{Gap}_{ee}$. The bottom panels in (a)–(h) show the sum of HWS-BLS pairs for each $\text{Gap}_{ee}$; the right panels in (a)–(h) show the sum of HWS-BLS pairs for each $\text{Gap}_{ss}$. 

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We also find that the HWS-BLS pairs distribute unevenly within the selected \( \text{Gap}_{\text{ss}}/\text{Gap}_{\text{ee}} \) range (Figure 6). We first examine \( \text{Gap}_{\text{ss}} \) and \( \text{Gap}_{\text{ee}} \) separately. All distributions of \( \text{Gap}_{\text{ee}} \) over the three subregions in Figure 6, except the one for HWS-TMS in the south region (Figure 6e), are negatively skewed, suggesting that HWS mostly ends after or at the end of BLS. While, there is slight difference between the distributions of \( \text{Gap}_{\text{ee}} \) for HWS-TMS and HWS-PVS pairs. Specifically, HWS mostly ends 0 or 1 (1 or 2) day after the onset day of TMS (PVS), implying a larger gap between the end of HWS and PVS on average. For regions with relatively high number of HWS-BLS pairs, such as the north region (Figures 6a and 6b) and south region with TM index (Figure 6e), HWS inclines to start no earlier than BLS, that is, \( \text{Gap}_{\text{ss}} \geq 0 \). While for the region with rather fewer HWS-PVS pairs, such as the middle and south regions (Figures 6d and 6f), this result may not hold. When we pool all the data in the three subregions, we reach the same conclusion that HWS inclines to starts after or on the onset day of PVS/TMS and ends after or at the end of PVS, except that the distribution of \( \text{Gap}_{\text{ee}} \) for TMS shows no apparent skewness. The variabilities of the \( \text{Gap}_{\text{ss}}/\text{Gap}_{\text{ee}} \) distributions over the entire study region are further explored and displayed in Figure 7, with the red/blue solid lines denoting the annual mean. Although there is apparent variability from year to year, the phenomenon that most of the HWS start after or on the onset day of blocking and end after or at the end of BLS is still notable. The narrow interquartile range of \( \text{Gap}_{\text{ss}}/\text{Gap}_{\text{ee}} \) in Figure 7b also supports this result. All these suggest that blocking is more of a necessary condition to trigger heat-accumulating process, but not imperative to maintain it.

The separate analysis of \( \text{Gap}_{\text{ss}} \) and \( \text{Gap}_{\text{ee}} \) accents the possible triggering role of blocking in the occurrence of heatwave. To further verify this, we consider \( \text{Gap}_{\text{ss}} \) and \( \text{Gap}_{\text{ee}} \) jointly and separate all of the HWS-BLS pairs into four cases. Case 1: \( \text{Gap}_{\text{ss}} < 0 \) and \( \text{Gap}_{\text{ee}} > 0 \), in this case, blocking days are fully contained by HWS and the role of blocking in triggering or maintaining heatwave is hard to tell; Case 2: \( \text{Gap}_{\text{ss}} < 0 \) and \( \text{Gap}_{\text{ee}} \leq 0 \), the effect of blocking in maintaining heatwave is highlighted in this case; Case 3: \( \text{Gap}_{\text{ss}} \geq 0 \) and \( \text{Gap}_{\text{ee}} \leq 0 \), the role of blocking to trigger or maintain heatwave is not clear; Case 4: \( \text{Gap}_{\text{ss}} \geq 0 \) and \( \text{Gap}_{\text{ee}} > 0 \), this case emphasizes the primary role of blocking in triggering heatwave than maintaining it. All these four cases are illustrated in Figure 8. And the corresponding numbers of HWS-BLS pairs for the aforementioned four cases are summarized in Table 2. The largest number of pairs is in bold.

The result shows that for HWS-PVS pairs in the north region, there are totally 69,971 pairs with \( \text{Gap}_{\text{ss}} \geq 0 \), \( \text{Gap}_{\text{ee}} > 0 \) (Case 4), significantly outnumbering the other cases. It articulates the triggering role of blocking. In the middle region, same conclusion is reached. In the south region, although HWS intends to start earlier and ends no later than BLS, the sample size is quite small. If we look at the entire study region, Case 4 is certainly of statistical dominance. For the HWS-TMS pairs, the situation is somewhat different. In all of the three subregions, most pairs fall in Case 3 (\( \text{Gap}_{\text{ss}} \geq 0 \) and \( \text{Gap}_{\text{ee}} \leq 0 \)), upon which the role of blocking in the occurrence of heatwave is hard to tell. However, if we look at the remaining three cases, Case 4 significantly outnumber the other two cases over the entire study region, within which the north region contributes the most. This discrepancy between HWS-PVS and HWS-TMS pairs might be attributable to their different criteria on duration. As we state before, TM-based blocking requires a more rigorous stationarity of the system over space, and its speed is lower than the PV-based. Thus, the resultant TMS tends to be

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**Table 1**

The Total Percentages of Individual HWS/BLS and HWDy/BLDy Accounted by the HWS-BLS Pairs Falling in the \( \text{Gap}_{\text{ss}}/\text{Gap}_{\text{ee}} \) Range ([−7,7]) Based on TM Index and PV Index Over the Three Subregions

| Pair type | Subregion | Concurrent association | Extended temporal association |
|-----------|-----------|------------------------|------------------------------|
|           |           | HWDy (%) | BLDy (%) | HWDy (%) | BLDy (%) | HWS (%) | BLS (%) |
| HWS-PVS   | North     | 17.8     | 23.9     | 42.5(0.42) | 49.3     | 39.1     | 38.4     |
|           | Middle    | 7.4      | 28.3     | 19.0(0.39) | 48.3     | 16.4     | 41.9     |
|           | South     | 1.0      | 24.6     | 3.4(0.29)  | 47.3     | 2.7      | 41.7     |
| HWS-TMS   | North     | 21.7     | 32.0     | 26.7(0.81) | 56.0     | 23.3     | 50.2     |
|           | Middle    | 3.0      | 58.5     | 3.8(0.79)  | 83.5     | 3.1      | 78.3     |
|           | South     | 14.1     | 22.0     | 15.8(0.89) | 37.2     | 13.6     | 36.6     |

Note: The percentages of HWDy/BLDy accounted by the concurrent pairs are also listed for comparison. The values inside the brackets denote the ratios of the HWDy accounted by the concurrent pairs (concurrent association) relative to the time-lagged pairs (extended temporal association). For instance, \( \frac{17.8}{42.5} = 42\% \).
more persistent than PVS on the grid basis. Consequently, the proportion of TMS that fully contains HWS tends to be higher than PVS, and the percentage of HWS-TMS pairs falling within Case 3 is correspondingly higher. However, if we increase the heatwave duration threshold to 5 days (same as blocking duration threshold), the number of HWS-TMS pairs falling with Case 3 plunges, and Case 4 becomes the most typical case (Figure S3 and Table S2). To sum up, after examining all cases under two blocking indices with different duration thresholds of heatwave, we can reach the conclusion that blocking is more of a favorable environmental condition to trigger heatwave than maintain it, especially based on PV index and with long-duration heatwave.

As we discussed in section 3.3.1, TM-based blocking exhibits stronger concurrence with heatwave than the PV-based. However, the profile of temporal association between TM/PV-based blocking and heatwave is quite comparable. As shown in Table 1, in the north region, the percentages of BLDy (HWDy) accounted by HWS-TMS/PVS pairs are 56.0%/49.3% (26.7%/42.5%), respectively. How does the

Figure 7. (a) The distributions of Gap_{ss}/Gap_{ee} for each year under TM-/PV-based blocking. (b) The interquartile ranges of Gap_{ss}/Gap_{ee} under TM-/PV-based blocking. The orange/blue lines in (a) and (b) show the distributions for Gap_{ss}/Gap_{ee}, respectively. The red/blue bold solid lines in (a) and (b) denote the annual mean.

Figure 8. (a) The Gap_{ss}/Gap_{ee} range for the four cases of HWS-BLS pairs. Case 1: Gap_{ss} < 0, Gap_{ee} > 0; Case 2: Gap_{ss} < 0, Gap_{ee} ≤ 0; (Maintain) Case 3: Gap_{ss} ≥ 0, Gap_{ee} ≤ 0; (Indistinct) Case 4: Gap_{ss} ≥ 0, Gap_{ee} > 0; (b) the schematic diagram for the illustration of the four cases.
Table 2
The Number of HWS-BLS Pairs for the Four Cases (Case 1: Gap_ss < 0, Gap_ee > 0; Case 2: Gap_ss < 0, Gap_ee ≤ 0; Case 3: Gap_ss ≥ 0, Gap_ee ≤ 0; and Case 4: Gap_ss ≥ 0, Gap_ee > 0) Over the Three Subregions Under Two Blocking Indices

| Pair type | Subregion | Case 1 | Case 2 | Case 3 | Case 4 |
|-----------|-----------|--------|--------|--------|--------|
| HWS-PVS   | North     | 8,617  | 19,607 | 12,826 | 69,971 |
|           | Middle    | 4,155  | 7,079  | 1,792  | 7,175  |
|           | South     | 640    | 1,284  | 89     | 799    |
|           | Total     | 13,412 | 27,970 | 14,644 | 77,945 |
| HWS-TMS   | North     | 1,023  | 9,578  | 30,359 | 22,583 |
|           | Middle    | 306    | 1,065  | 1,121  | 2,359  |
|           | South     | 224    | 3,283  | 7,325  | 2,407  |
|           | Total     | 1,553  | 13,926 | 38,805 | 26,081 |

Note. Dp0; and Case 4: Gap_ss – value less than 0.05. ** – value less than 0.01.

Table 3
The P-Values and D Statistics Obtained From the Kolmogorov-Smirnov (KS) Test for Detecting the Differences Between the Heatwave Event Duration (HWD), Extent (HWE), Volume (HWV), and Intensity (HWI) of Blocking-Related Heatwave Events (BRH) and Blocking-Unrelated Heatwave Events (BURH)

| MDEOR | HWD | HWE | HWV | HWI | HWD | HWE | HWV | HWI | HWD | HWE | HWV | HWI | HWD | HWE | HWV | HWI | HWD | HWE | HWV | HWI |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TM    | 0.0 | 0.24** | 0.38** | 0.35** | 0.32** | 0.55** | 0.57** | 0.55** | 0.32** | 0.21** | 0.22** | 0.22** | 0.22** | 0.22** | 0.22** | 0.22** | 0.22** | 0.22** | 0.22** |
| PV    | 0.0 | 0.16** | 0.18** | 0.20** | 0.13** | 0.17** | 0.16** | 0.10** | 0.29** | 0.17** | 0.18** | 0.18** | 0.18** | 0.18** | 0.18** | 0.18** | 0.18** | 0.18** | 0.18** |
|       | 0.2 | 0.13** | 0.15** | 0.15** | 0.09** | 0.11** | 0.11** | 0.12** | 0.03** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** |
|       | 0.4 | 0.09** | 0.10** | 0.10** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** | 0.05** |
|       | 0.6 | 0.17** | 0.19** | 0.18** | 0.19** | 0.09** | 0.12** | 0.13** | 0.17** | 0.08** | 0.09** | 0.09** | 0.09** | 0.09** | 0.09** | 0.09** | 0.09** | 0.09** | 0.09** |
|       | 0.8 | 0.24** | 0.60** | 0.58** | 0.62** | 0.40** | 0.95** | 0.96** | 0.94** | 0.55** | 0.57** | 0.57** | 0.57** | 0.57** | 0.57** | 0.57** | 0.57** | 0.57** | 0.57** |

Note. D statistics is the largest distance (in absolute value) between the ECDFs for BRH and BURH. N denotes no detected BRH.
*p-value less than 0.05. **p-value less than 0.01.

3.3.3. Impact of Blocking on the Characteristics of Heatwave Events
Apart from their temporal association, the impact of blocking on the spatiotemporal characteristics of heatwave events is rarely investigated in previous studies. To explore the potential influence of blocking presence on the characteristics of heatwave, we firstly divide the whole set of heatwave events into BRH and BURH based on MDEOR. Extended from the method introduced in section 2.3, considering the identified time-lagged temporal association above, we define BRH with an extended [−7, 7] time window of a heatwave event. The calculation of MDEOR is adjusted accordingly. Note that the characteristics are still based on the original heatwave events; the extended time window is only to relate blocking to heatwave. The affiliation of a heatwave event to a certain region (north, middle, or south) is based on its center location as defined in section 2.2. The significance of differences in characteristics (HWD, HWE, HWV, and HWI) of BRH versus BURH is tested by KS test. We perform such test considering varying thresholds of MDEOR ranging from 0 to 0.8. The ECDFs of the characteristics of BRH and BURH with MDEOR > 0.2 in the north region are shown in Figure S4 as an example for illustration. Figure S4 shows that BRH is more likely to be persistent, extensive, and intense than BURH in this case (north region, MDEOR > 0.2). The p-values and D statistics of KS test for different regions and MDEOR values are summarized in Table 3. Note that HWD is a discrete variable with relatively narrow value range, to which the KS test may be not applicable. Based on the TM index, all characteristics in the north and south regions are significantly different (at the 0.05 level) between BRH and BURH regardless of different MDEOR values. While in the middle region, the distinctions between BRH and BURH are substantial as long as the MDEOR is not too large (≤0.6). As for the PV index, BRH and BURH again exhibit significant differences in their characteristics in the north region, with all p-values < 0.01. It reveals that the presence of blocking does show substantial influence on the characteristics of heatwave. However, whether the difference between BRH and BURH for a certain region is significant or not is also subjective to the blocking identification criteria, for example, TM versus PV, as different criteria lead to discrepancies in blocking climatology in space and time. For example, for regions with high blocking frequency, that is, the comparable or even stronger temporal linkage between HWS-PVS associate with a weaker concurrence? The answer may root in the shorter duration of PVS relative to TMS. Given the comparable Gap_ss between HWS-PVS/TMS pairs, the short duration of PVS could lead to larger Gap_ee of HWS-PVS pairs than those of HWS-TMS pairs. Hence, the smaller proportion of concurrence relative to those with time lags is expected based on PV index, resulting in a weaker concurrence. Therefore, rather than conducting concurrent analysis alone, the new approach presented in this study provides a more nuanced understanding of the exact temporal association between heatwave and blocking.
north and south regions based on the TM index and north region based on the PV index, we simply have more BRH to construct the ECDFs. While for the other regions, limited BRH samples lead to unreliable ECDFs.

4. Summary

Based on the ERA-interim reanalysis daily maximum temperature, we investigate the spatiotemporal variation and the changes of summertime heatwave occurrence with both grid-based and event-based analyses between 1979 and 2017 over the Northeastern Asia. The association between blocking and heatwave is further explored in terms of both occurrence and their characteristics using two leading blocking indices.

During the study period, the frequency of heatwave significantly increases on both grid and event bases. More notably, persistent, extensive, and intense heatwave events have become more frequent over the entire region, consistent with some previous studies (e.g., Perkins et al., 2012; Zampieri et al., 2016). However, most of them drew conclusion on a grid or station basis. Few ever explored the trend from an event-based perspective by imposing connectivity in both space and time as presented in this study. Our study also reveals that the increase of heatwave occurrence is significantly correlated with the warming temperature, in agreement with Brunner et al. (2017) and Perkins (2015). As reported by Fischer and Knutti (2015), heatwave frequency might further increase an additional fivefold under the 2° global warming. It is imperative to abide by the Paris agreement to hold the global warming well below 2°, and better to limit it to 1.5°, considering the striking increasing rate of heatwave frequency already observed in our study.

The concurrent analysis in a probabilistic context based on both blocking indices (TM index and PV index) consistently suggests that blocking favors the occurrence of heatwave. Such relation is most prominent in the north region where blocking frequently occurs: areal mean heatwave frequency increases by a factor of 7 and 5 during TM-based blocking and PV-based blocking, respectively. In the middle region, once the blocking is detected by either index, heatwave is very likely to occur, although only a small portion of heatwave can be accounted for. In the south region, heatwave frequency increases by a factor of 3 in most area during TM-based blocking, while PV index detects barely no blocking here. This finding is consistent with previous studies that have linked blocking to the increased collocated and concurrent heatwave in summertime and attributed this phenomenon to the increased radiative heating, the absence of precipitation, and the anomalous soil moisture at the location under blocking (Brunner et al., 2018; Pfahl & Wernli, 2012; Sousa et al., 2018). Besides, stronger concurrence between heatwave and TM-based blocking than the PV-based is observed. We further investigate their extended temporal association with time lags, which accounts for much more heatwave days and blocking days than the concurrent analysis. The difference is particularly obvious for the PV index, suggesting the importance of performing this extended temporal analysis. Based on the separate analysis of Gap_ss and Gap_ee, we find that HWS mostly starts after or on the onset day of BLS and ends after or at the end of BLS, which implies that blocking is more important to trigger heat-accumulating process than maintaining it. The joint examination of Gap_ss and Gap_ee also supports the conclusion. Once the heat-accumulating process is triggered, the depletion of soil moisture and the subsequent reduction in evaporative cooling may further amplify the temperature (Miralles et al., 2014). This soil moisture-temperature feedback may help maintain the heatwave. Partially similar result in winter was reported by a few studies (Brunner et al., 2017; Buehler et al., 2011) that certain time lags between the onset of cold spell and blocking were needed for the development of cold spell. However, they only conducted regional analysis without considering the time lag between the end of extreme temperature and blocking. Besides, with the clearer profile of temporal linkages between TM-based/PV-based blocking and heatwave, we could explain the weaker concurrence based on PV index with the shorter duration of PVS. Therefore, the new approach presented in this study provides a deeper and more complete picture of the temporal association between heatwave and blocking.

Last but not least, comparison between the characteristics of BRH and BURH suggests that the blocking-related heatwave events are more likely to be persistent, extensive, and intense than those unrelated ones. However, the significance of their distinction is subjective to the blocking detection criteria. For regions with frequent blocking, such as the north and south regions based on TM index and the north region regrading to PV index, the number of BRH is sufficiently large to generate reliable ECDFs. While, the rest may suffer from limited samples of BRH. Schaller et al. (2018) also revealed a significant
correlation between summer heatwave magnitude and number of collocated blocking days in the northern Europe but on a grid basis. But they only focused on the magnitude. In this study, we take a look at a more complete selection of heatwave characteristics to explore the impact of blocking on heatwave, not only its occurrence but also its full characteristics. Besides, in addition to blocking, the association between heatwave and other atmospheric controls like the western North Pacific Subtropical High (Luo & Lau, 2017) or climate modes (e.g., ENSO, PDO; Liu et al., 2019; Luo & Lau, 2019) may also worth further investigations with the newly proposed approach of this study in the future. Such multivariate, likely nonlinear associations, might also require to employ advanced data mining techniques as exemplified by Lu et al. (2016).

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References
Black, E., Blackburn, M., Harrison, G., Hoskins, B., & Methven, J. (2004). Factors contributing to the summer 2003 European heatwave. Weather, 59(8), 217–223. https://doi.org/10.1256/wea.74.04
Brunner, L., Hegerl, G. C., & Steiner, A. K. (2017). Connecting atmospheric blocking to European temperature extremes in spring. Journal of Climate, 30(2), 585–594. https://doi.org/10.1175/JCLI-D-16-0518.1
Brunner, L., Schaller, N., Anstey, J., Stillmann, J., & Steiner, A. K. (2018). Dependence of present and future European temperature extremes on the location of atmospheric blocking. Geophysical Research Letters, 45, 6311–6320. https://doi.org/10.1029/2018GL077837
Buehler, T., Raible, C. G., & Stocker, T. F. (2011). The relationship of winter season North Atlantic blocking frequencies to extreme cold or dry spells in the ERA-40. Tellus A: Dynamic Meteorology and Oceanography, 63(2), 174–187. https://doi.org/10.1111/j.1600-0787.2010.00942.x
Bureau of Meteorology (2013). Australia’s warmest September on record Special Climate Statement 46. [Available at http://www.bom.gov.au/climate/current/statements/46/46.pdf]
Castanheira, J. M., & Barriopedro, D. (2010). Dynamical connection between tropospheric blockings and stratospheric polar vortex. Geophysical Research Letters, 37, L13809. https://doi.org/10.1029/2010GL043819
Cowan, T., Purich, A., Perkins, S., Pezza, A., Boschat, G., & Sadler, K. (2014). More frequent, longer, and hotter heat waves for Australia in the twenty-first century. Journal of Climate, 27(15), 5853–5871. https://doi.org/10.1175/JCLI-D-14-00992.1
Ding, T., & Ke, Z. (2015). Characteristics and changes of regional wet and dry heat wave events in China during 1960–2013. Theoretical and Applied Climatology, 122(3–4), 651–665. https://doi.org/10.1007/s00704-014-1324-9
Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., et al. (2011). Was there a basis for anticipating the 2010 Russian heat wave? Geophysical Research Letters, 38, L06702. https://doi.org/10.1029/2010GL046582
Dole, R. M., & Gordon, N. D. (1983). Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: Geographical distribution and regional persistence characteristics. Monthly Weather Review, 111(8), 1567–1586. https://doi.org/10.1175/1520-0493(1983)111<1567:PAOTEN>2.0.CO;2
Fischer, E. M., & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy precipitation and high-temperature extremes. Nature Climate Change, 5(6), 560. https://doi.org/10.1038/nclimate2617
Gill, A. E. (1982). Atmosphere-Ocean dynamics (International Geophysics Series). San Diego, CA: Academic Press.
Lau, N. C., & Nath, M. J. (2012). A model study of heat waves over North America: Meteorological aspects and projections for the twenty-first century. Journal of Climate, 25(14), 4761–4784. https://doi.org/10.1175/JCLI-D-11-00575.1
Lau, N. C., & Nath, M. J. (2014). Model simulation and projection of European heat waves in present-day and future climates. Journal of Climate, 27(10), 3713–3730. https://doi.org/10.1175/JCLI-D-13-00284.1
Lejenäs, H., & Oikland, H. (1983). Characteristics of Northern Hemisphere blocking as determined from a long time series of observational data. Tellus A, 35(3), 350–362. https://doi.org/10.1111/j.1600-0787.1983.tb02010.x
Liu, Q., Zhou, T., Mao, H., & Fu, C. (2019). Decadal variations in the relationship between the Western Pacific subtropical high and summer heat waves in East China. Journal of Climate, 32(5), 1627–1640. https://doi.org/10.1175/JCLI-D-18-0993.1
Lopez, H., West, R., Dong, S., Gonji, G., Kirtman, B., Lee, S. K., & Atlas, R. (2018). Early emergence of anthropogenically forced heat waves in the western United States and Great Lakes. Nature Climate Change, 8(5), 414–420. https://doi.org/10.1038/s41558-018-0116-y
Lu, M., Lai, U., Kawaje, J., Liess, S., & Kumar, V. (2016). Exploring the predictability of 30-day extreme precipitation occurrence using a global SST–SLP correlation network. Journal of Climate, 29, 1013–1029. https://doi.org/10.1175/JCLI-D-14-00452.1
Luo, M., & Lau, N. C. (2017). Heat waves in southern China: Synoptic behavior, long-term change, and urbanization effects. Journal of Climate, 30(2), 703–720. https://doi.org/10.1175/JCLI-D-16-0269.1
Luo, M., & Lau, N. C. (2019). Amplifying effect of ENSO on heat waves in China. Climate Dynamics, 52(5–6), 3277–3289. https://doi.org/10.1007/s00382-018-4322-0
Meeth, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. Science, 305(5686), 994–997. https://doi.org/10.1126/science.1098704
Metropolis, N., & Ulam, S. (1949). The Monte Carlo method. Journal of the American Statistical Association, 44(247), 335–341. https://doi.org/10.1080/01621459.1949.10501532
Miralles, D. G., Teuling, A. J., Van Heerwaarden, C. C., & De Arellano, J. V. G. (2014). Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nature Geoscience, 7(5), 345. https://doi.org/10.1038/ngeo2141
Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., et al. (2017). Global risk of deadly heat. Nature Climate Change, 7(7), 501. https://doi.org/10.1038/nclimate3322
Pelly, J. L., & Hoskins, B. J. (2003). A new perspective on blocking. Journal of the Atmospheric Sciences, 60(5), 743–755. https://doi.org/10.1175/1520-0469(2003)060<0743:ANPOB>2.0.CO;2
Perkins, S. R. (2015). A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale. Atmospheric Research, 164, 242–267. https://doi.org/10.1016/j.atmosres.2015.05.014
Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophysical Research Letters, 39, L20714. https://doi.org/10.1029/2012GL053361
Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. Journal of the Royal Statistical Society: Series C (Applied Statistics), 28(2), 126–135. https://doi.org/10.2307/2346729
Plahm, S., & Wernli, H. (2012). Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-) daily time scales. Geophysical Research Letters, 39, L12807. https://doi.org/10.1029/2012GL052261
Pinheiro, M. C., Ullrich, P. A., & Grotjahn, R. (2019). Atmospheric blocking and intercomparison of objective detection methods: Flow field characteristics. *Climate Dynamics*, 53(7-8), 4189–4216. https://doi.org/10.1007/s00382-019-04782-5

Raei, E., Nikoo, M. R., AghaKouchak, A., Madjdyanl, O., & Sadegh, M. (2018). GHWR, a multi-method global heatwave and warm-spell record and toolbox. *Scientific Data*, 5, 180206. https://doi.org/10.1038/sdata.2018.206

Russo, S., Sillmann, J., & Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, 10(12), 124003. https://doi.org/10.1088/1748-9326/10/12/124003

Sausen, R., Koenig, W., & Sillmann, F. (1995). Analysis of blocking events from observations and ECHAM model simulations. *Tellus A*, 47(4), 421–438. https://doi.org/10.1034/j.1600-0870.1995.t01-3-00003.x

Schaller, N., Sillmann, J., Anstey, J., Fischer, E. M., Grans, C. M., & Russo, S. (2018). Influence of blocking on Northern European and Western Russian heatwaves in large climate model ensembles. *Environmental Research Letters*, 13(5), 054015. https://doi.org/10.1088/1748-9326/aaba55

Scherrer, S. C., Croci-Maspoli, M., Schwierz, C., & Appenzeller, C. (2006). Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 26(2), 233–249. https://doi.org/10.1002/joc.1250

Schwarz, S., Croci-Maspoli, M., & Davies, H. C. (2004). Perspicacious indicators of atmospheric blocking. *Geophysical Research Letters*, 31, L06125. https://doi.org/10.1029/2003GL019341

Seneviratne, S. I., Donat, M. G., Mueller, B., & Alexander, L. V. (2014). No pause in the increase of hot temperature extremes. *Nature Climate Change*, 4(3), 161. https://doi.org/10.1038/nclimate2145

Sillmann, J., & Croci-Maspoli, M. (2009). Present and future atmospheric blocking and its impact on European mean and extreme climate. *Geophysical Research Letters*, 36, L10702. https://doi.org/10.1029/2009GL038259

Silva, L., Croci-Maspoli, M., Hulla, B., & Katz, R. W. (2013). Extreme cold winter temperatures in Europe under the influence of North Atlantic atmospheric blocking. *Journal of Climate*, 26(22), 5899–5913. https://doi.org/10.1175/2013JCLI4075.1

Sousa, F. M., Trigo, R. M., Barriopedro, D., Soares, P. M., & Santos, J. A. (2018). European temperature responses to blocking and ridge regional patterns. *Climate Dynamics*, 50(1-2), 457–477. https://doi.org/10.1007/s00382-017-3620-2

Stefanon, M., D’Andrea, F., & Drobinski, P. (2012). Heatwave classification over Europe and the Mediterranean region. *Environmental Research Letters*, 7(1), 014023. https://doi.org/10.1088/1748-9326/7/1/014023

Stott, P. A., Stone, D. A., & Allee, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature*, 432(7017), 610–614. https://doi.org/10.1038/nature03089

Sun, Q., Miao, C., & Duan, Q. (2016). Extreme climate events and agricultural climate indices in China: CMIP5 model evaluation and projections. *International Journal of Climatology*, 36(1), 43–61. https://doi.org/10.1002/joc.4328

Sun, Y., Zhang, X., Zwiers, F. W., Song, L., Wan, H., Hu, T., et al. (2014). Rapid increase in the risk of extreme summer heat in Eastern China. *Nature Climate Change*, 4(12), 1082. https://doi.org/10.1038/nclimate2410

Tibaldi, S., d’Andrea, F., Tosi, E., & Roeckner, E. (1997). Climatology of Northern Hemisphere blocking in the ECHAM model. *Climate Dynamics*, 13(9), 649–666. https://doi.org/10.1007/s003820050188

Tibaldi, S., & Molteni, F. (1990). On the operational predictability of blocking. *Tellus A*, 42(3), 343–365. https://doi.org/10.1034/j.1600-0870.1990.001-2-00003.x

Trigo, R. M., Trigo, I. F., DaCama, C. C., & Osborn, T. J. (2004). Climate impact of the European winter blocking episodes from the NCEP/NCAR Reanalyses. *Climate Dynamics*, 23(1), 17–28. https://doi.org/10.1007/s00382-004-0410-4

Whan, K., Zwiers, F., & Sillmann, J. (2016). The influence of atmospheric blocking on extreme winter minimum temperatures in North America. *Journal of Climate*, 29(12), 4361–4381. https://doi.org/10.1175/JCLI-D-15-0491.1

Woodings, T., Hoskins, B., Blackburn, M., & Berrisford, P. (2008). A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. *Journal of the Atmospheric Sciences*, 65(2), 609–626. https://doi.org/10.1175/2007JAS3247.1

Zampieri, M., Russo, S., di Sabatino, S., Michetti, M., Scoccimarro, E., & Gualdi, S. (2016). Global assessment of heat wave magnitudes from 1901 to 2010 and implications for the river discharge of the Alps. *Science of the Total Environment*, 571, 1330–1339. https://doi.org/10.1016/j.scitotenv.2016.07.008