

Human-Perceived Temperature Changes in South Korea and Their Association with Atmospheric Circulation Patterns

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ABSTRACT: This study investigates the spatiotemporal characteristics of human-perceived temperature (HPT) data, which describe the joint effects of temperature and humidity on the human body, and examines the related large-scale atmospheric circulation patterns for the summer season (July–August) in South Korea using trend and composite analyses. The increasing trend of HPT was stronger than that of the maximum, mean, and minimum temperatures during 1981–2018. There was an abrupt change in HPT between 1981–2009 and 2010–18, which is likely caused by the northward upper-level subtropical jet, strengthened downward motion, anomalous anticyclones around South Korea, and increased sea surface temperature over the western North Pacific Ocean, which are related to the enhancement and western expansion of the western North Pacific subtropical high (WNPSH). These results highlight the importance of the activity of the WNPSH in the variability of HPT in South Korea. When the western edge of the WNPSH is located in the northwest, a positive geopotential height anomaly at 500 hPa is centered over South Korea, which is associated with high temperatures and low relative humidity. The southwestern extension of the WNPSH modifies the wind circulation pattern and brings warm and moist air from the West (Yellow) Sea along the ridge line of the WNPSH. Eventually, it leads to extreme HPT, associated with high relative humidity and temperature over South Korea, particularly in the southern part of the country. Therefore, we concluded that monitoring and predicting the location of WNPSH and understanding the mechanism and factors influencing the movement of WNPSH under global warming are necessary for predicting and coping with extreme HPT.

KEYWORDS: Atmospheric circulation; Extreme events; Humidity; Surface temperature; Interdecadal variability

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), the global temperature has increased by approximately 0.78°C (0.72°–0.85°C) in 2003–12 relative to that in 1850–1900 (IPCC 2013). Recent increases in the global mean temperature can be linked to an increase in the occurrence of extreme weather events (e.g., heat waves, heavy rainfall) around the world (Pall et al. 2011; King et al. 2015; Perkins and Gibson 2015; Black and Karoly 2016; Hope et al. 2016; Uhe et al. 2016; Xia et al. 2016; van der Wiel et al. 2017; Ding et al. 2019; Im et al. 2019; Xu et al. 2019).

Heat waves can lead to a significant impact on the social and economic losses. According to the World Meteorological Organization (WMO 2013), the number of deaths due to heat waves in 2001–10 increased by 2300% relative to the number of deaths in 1991–2000. The increase in the number of deaths due to heat waves was much larger than the overall increase of 20% due to various extreme weather events, including droughts, storms, and floods. For example, a heat wave over Europe in 2010 caused more than 55 000 deaths and led to a total economic loss of \$15 billion (U.S. dollars; Peters et al. 2010). In the summer of 2015, there were at least 2500 deaths in India due to severe heat (Ratnam et al. 2016; Ghatak et al. 2017).

In future climate change scenarios, extreme weather events are predicted to be more frequent, intense, and persistent across the

globe with significant impacts on human health, infrastructure, industry, and ecosystems (Meehl and Tebaldi 2004; Trewin and Vermont 2010; Schiermeier 2011; Oliver et al. 2018). The World Health Organization (WHO) reported that there will be approximately 92 000 deaths per year from heat waves by 2030 in various parts of the world, especially in sub-Saharan Africa, Latin America, and South and Southeast Asia (WHO 2014).

Extreme temperature events have become an important public concern, and recent studies have focused on analyzing the mechanism and atmospheric circulation patterns of extreme temperature events (Lee and Lee 2016; Lu and Chen 2016; Wang et al. 2017; Yeh et al. 2018; Su and Dong 2019). An extreme temperature event is caused by a high pressure system that brings clear skies and enhances the effect of solar radiation. Luo et al. (2020) reported that extreme temperature over China is associated with the Pacific meridional mode on interannual time scales. Lee and Lee (2016) found that circulation anomalies affecting the interannual and decadal variability of heat waves in South Korea are similar. Lee et al. (2020) indicated that the heat wave index that uses large-scale circulation patterns associated with heat waves, defined as the vorticity difference at 200 hPa between the South China Sea and Northeast Asia, can predict the heat waves over South Korea based on The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) data in the medium range. Extreme temperatures over East Asia (South Korea, China, and Japan) have also been attributed to the variations in the western North Pacific subtropical high (WNPSH). Luo and Lau (2017), for example, suggested that the westward movement of the WNPSH is responsible for the

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occurrence of heat waves over the southern part of China. Yoon et al. (2018) used *K*-means cluster analysis to find that severe heat waves over South Korea in 2015 were strongly related to the WNPSH. Extreme heat waves caused the death of more than 80 people in Japan in July 2018 and were directly associated with the northward movement of the WNPSH causing a tropospheric anticyclone with a barotropic structure across northeastern Asia (Liu et al. 2019).

Previous studies have focused only on the effect of temperature even though the combined effects of temperature and humidity pose risks to human health (Sherwood and Huber 2010; Fischer et al. 2012; Willett and Sherwood 2012; Im et al. 2017). Under warm and humid conditions, the human body naturally starts to heat up and release sweat. However, it is difficult to lose heat through evaporation (sweating) when the atmospheric moisture content is high. The combination of environmental heat and internal body heat generated as a by-product of metabolism may cause physical disorders and even death (Sherwood and Huber 2010; WMO 2020).

Recently, a few studies have reported on human-perceived temperature (HPT), considering the effect of the humidity on human body. To the best of our knowledge, those studies have estimated the impacts of HPT under climate change scenarios using global climate models (Fischer and Knutti 2013; Im et al. 2017; Matthews et al. 2017; Russo et al. 2017; Coffel et al. 2018; Lee and Min 2018; W. Li et al. 2019; Sun et al. 2019). Most of these studies have shown that, as a result of the increase in both temperature and humidity, HPT will intensify throughout the twenty-first century at a higher rate than the temperature.

South Korea is one of the countries most affected by heat stress. Summers in South Korea are characterized by hot and humid conditions under the influence of the East Asian monsoon. Yoon et al. (2014) reported that South Korea had a heat-related burden of 6.85 disability-adjusted life years per 1000 people in 2008, and this number is expected to increase in the future. Lee and Min (2018) and Im et al. (2017) projected future intensification of heat stress over South Korea under global warming scenarios. A comprehensive understanding of the spatiotemporal variations in HPT and related large-scale atmospheric circulation patterns as well as future changes in HPT across South Korea is necessary to predict and mitigate the effects of HPT.

In this study, we investigated the spatiotemporal characteristics including long-term trends and changepoints of HPT over South Korea during 1981–2018 based on the observations and analyzed large-scale atmospheric circulation patterns that affect the variations in HPT.

2. Data and method

a. Datasets

The daily minimum, mean, and maximum temperature and relative humidity observations from 45 synoptic weather observation stations (Automated Synoptic Observation System), operated by the Korea Meteorological Administration (KMA), were used in this study. The stations were selected based on the availability of continuous measurements longer than 30 years based on a consistent location and measurement techniques. Basic and extended quality

checks were applied to the data, such as a plausible value check and internal consistency check based on the World Meteorological Organization guide (KMA 2016). In addition, these stations have been used as national climate observation sites to determine the climate variability over South Korea (KMA 2020). The distribution of 45 observational stations is shown in Fig. 1. The analysis was carried out in the summers of 1981–2018. Summers in South Korea typically occur from June to August, but the temperature characteristics in early and late summer vary slightly (Yeo et al. 2017). In early summer, the temperature is controlled by the land–sea thermal contrast in East Asia, whereas late summer temperatures are attributed to the enhanced convective activity over the western tropical Pacific. Therefore, we analyzed the data collected from July to August in this study.

To investigate the associated large-scale atmospheric circulation patterns and physical processes, the daily dataset from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al. 2011) was used, covering a period of 38 years from 1981 to 2018. The dataset includes the geopotential height, specific humidity, horizontal and meridional wind, and vertical velocity data at different pressure levels at a horizontal resolution of $1.5^\circ \times 1.5^\circ$. The 2-m temperature, precipitation, and outgoing longwave radiation data at the surface level are also included in the dataset. In addition, the Optimum Interpolation Sea Surface Temperature (OISST) dataset provided by the Climate Diagnostics Center of the U.S. National Oceanographic and Atmospheric Administration (NOAA) was used (Reynolds et al. 2007).

b. HPT indicators

Various heat stress indices that account for the potential impact of the combined temperature and relative humidity on the human body depending on the environment have been devised (Buzan et al. 2014). Among them, wet bulb globe temperature index is the International Organization for Standardization (ISO) standard for quantifying human thermal comfort (ISO 1989), but it is not easy to calculate using the station data. Recent research has focused on the wet bulb temperature (WBT) index as a measure of discomfort (Buzan et al. 2014; Coffel et al. 2018); however, WBT is more sensitive to humidity according to Sherwood (2018). Therefore, in this study, we used HPT as the heat index, known as apparent temperature, to measure how the human body feels in response to changes in the relative humidity combined with ambient temperature (Steadman 1979). The heat index is issued by the NOAA National Weather Service (NWS) and is widely used by the general public (Sherwood and Huber 2010; Russo et al. 2017; W. Li et al. 2019). It is easily calculated using temperature (T ; $^\circ\text{C}$) and relative humidity (RH; %) observations as follows:

$$\begin{aligned} \text{HPT} = & -8.7849 + 1.6114T - 0.012308T^2 \\ & + (2.3385 - 0.14612T + 2.2117 \times 10^{-3}T^2) \times \text{RH} \\ & + (-0.016425 + 7.2546 \times 10^{-4}T \\ & - 3.582 \times 10^{-6}T^2) \times \text{RH}^2. \end{aligned} \quad (1)$$

We used the daily maximum temperature and daily minimum relative humidity to calculate the HPT (Russo et al. 2017). Figure 2 shows the relationship between temperature and relative humidity.

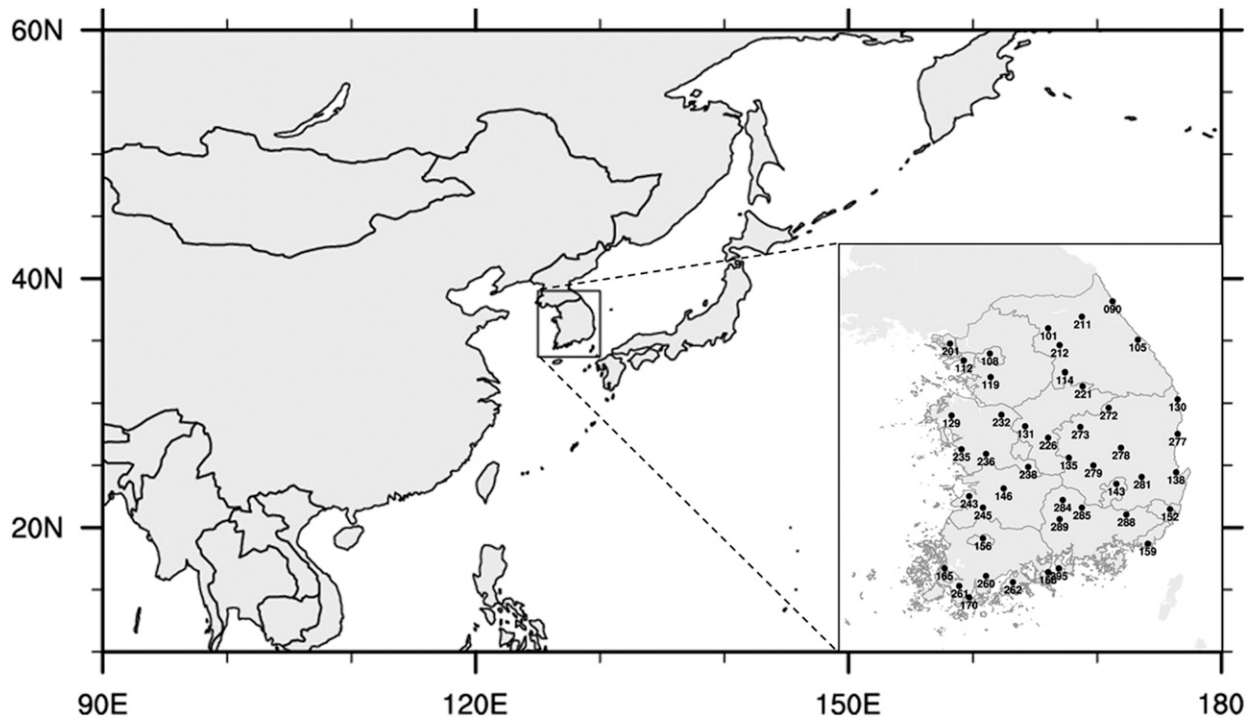


FIG. 1. Location of the research area, showing the distribution of surface observational stations. The numbers indicate weather station numbers. Refer to Table 1 for more details.

There is a direct relationship among temperature, relative humidity, and HPT: as temperature and relative humidity increase, the HPT exponentially increases, and, as they decrease, the HPT exponentially decreases. The effects of HPT, which can lead to severe heat disorders with prolonged exposure and/or physical activity, can be classified into four categories: caution, extreme caution, danger, and extreme danger (NWS 2020) (Table 1).

c. Method

To analyze the long-term trends in the temperature data, the Mann–Kendall test was applied in this study. The Mann–Kendall test has been widely used to detect statistically significant trends in the time series of climatic variables (Mann 1945; Kendall 1975; Im et al. 2011; Jung et al. 2011). Because it is a nonparametric test and does not require the data to be normally distributed, it can be robust to outliers and nonlinear trends. It can also be used for data with missing values. Moreover, the statistical changepoint analysis based on Student's t test was applied to the time series of temperature including minimum, mean, maximum temperature, and HPT to diagnose the variations in temperature in South Korea in the 2000s (Wilks 1995). The statistical t value for two independent time series is

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}, \quad (2)$$

where x_1 and x_2 are the average of the two time series, s_1 and s_2 are standard deviations of the two time series, and n_1 and n_2 are the number values for the two time series. When the absolute

value of t is the largest on the basis of running year interval in the time series, the year is determined to be a changepoint.

We used a composite analysis to estimate the impact of the variations in large-scale atmospheric circulation patterns on the spatiotemporal variations in extreme HPT during the study period and employed Student's t test to determine the statistical significance levels. The extreme HPT days were defined as extreme caution, danger, and extreme danger categories in Table 1 (i.e., with the value of HPT exceeding 32°C).

Composite analysis, which defines the average field on pre-identified dates, provides the physical mechanism and meteorological patterns in observations and climate models at various scales

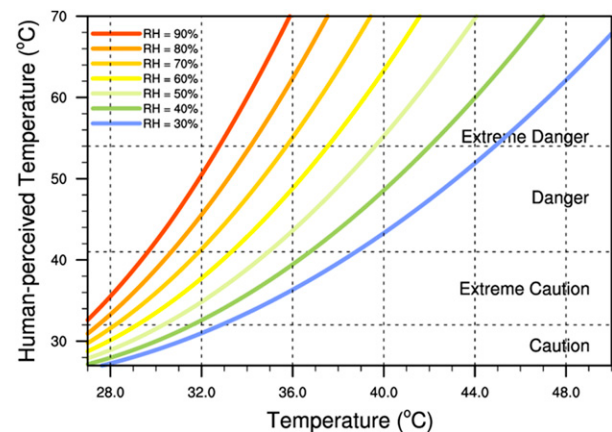


FIG. 2. Relationship between temperature (°C) and relative humidity (%) for human-perceived temperature (°C).

TABLE 1. Categories and specific health risk of HPT (NWS 2020).

Categories	HPT	Health risk
Caution	27°–32°C	Fatigue is possible with prolonged exposure and/or physical activity
Extreme caution	32°–41°C	Sunstroke, heat cramps, and heat exhaustion are possible with prolonged exposure and/or physical activity
Danger	41°–54°C	Sunstroke, heat cramps, or heat exhaustion are likely and heat stroke is possible with prolonged exposure and/or physical activity
Extreme danger	>54°C	Heat stroke is highly likely with continued exposure

(Grotjahn and Faure 2008; Dole et al. 2011; Lee et al. 2016; Lee and Lee 2016). Freychet et al. (2017) constructed a time-lagged composite analysis to analyze the characteristics of the circulation associated with heat waves in China. Loikith and Broccoli (2015) used composite analysis to evaluate the large-scale atmospheric circulation associated with temperature extremes in a suite of global climate models contributing to the CMIP5 and found that the ensemble reproduced large-scale atmospheric circulation patterns on extreme temperature days over North America. Tomczyk and Owczarek (2020) showed that high pressure systems block zonal circulations on days with strong and very strong heat stress levels in Poland.

3. Results and discussion

a. Variability of temperature and relative humidity

Figure 3 and Table 2 indicate the average values of maximum temperature, HPT, and relative humidity over South Korea from 1981 to 2010. The maximum temperature ranged from 26.50° to 30.65°C, and HPT ranged from 28.33° to 34.55°C. The difference between the HPT and the maximum temperature caused by the combined effect of relative humidity and maximum temperature on the HPT ranged from 1.83° to 4.64°C. From the relationship between temperature, relative humidity, and HPT shown in Fig. 2, at high temperatures even a slight increase in temperature can lead to a considerable

increase in HPT. The spatial distribution between the maximum temperature and HPT was similar (Fig. 3), depicting the influence of the complex mountainous topography of South Korea. For example, the maximum temperature and HPT are relatively low in the high-altitude area and eastern South Korea [e.g., Sokcho (station No. 90), Gangneung (105), and Uljuin (130)]. On the contrary, inland regions of the southern parts of the country [e.g., Daegu (143), Uiseung (278), Miryang (288), and Yeongcheon (281)] show the climatologically highest values of maximum temperature and HPT and lowest levels of humidity because of the southerly winds that bring warm and dry air in the summer due to topographic effects (Table 2).

The average long-term minimum, mean, and maximum temperature, HPT, and relative humidity for 45 stations from 1981 to 2018 are shown in Fig. 4. The minimum, mean, and maximum temperatures and HPT increased by 0.36°, 0.30°, 0.27°, and by 0.29°C decade^{−1} for minimum, mean, and maximum temperatures and for HPT, respectively, during 1981–2018. The change in relative humidity was −1.10% decade^{−1}. Overall, the results showed a clear interdecadal variation and an increasing trend in temperature and HPT. The relative humidity showed a decreasing trend. Note that the increasing trend of HPT, which measures the combined effect of temperature and relative humidity on the human body, was more pronounced than the trends in the maximum, mean, and

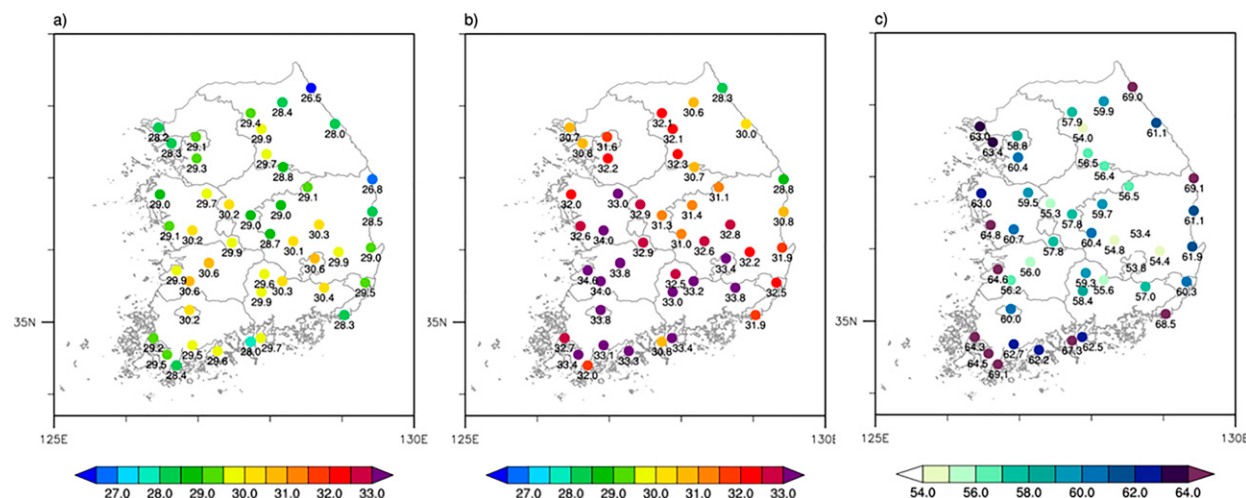


FIG. 3. Average of (a) maximum temperature (°C), (b) HPT (°C), and (c) minimum relative humidity (%) over South Korea from 1981 to 2010.

minimum temperature during 1981–2018. These results are consistent with the findings of several recent studies (Russo et al. 2017; Li et al. 2018; Luo and Lau 2019).

In this study, the changepoint analysis was applied to the HPT time series to determine whether there is a climate regime shift. The analysis periods were divided into two periods around 2010 at 95% confidence level: 1981–2009 and 2010–18, with the largest absolute value of t (Fig. 5). The HPT has increased significantly in recent years when compared with the last three decades. The average HPT was 32.56°, 32.17°, 31.53°, and 33.66°C in 1981–90, 1991–2000, 2001–09, and 2010–18, respectively. The increasing trend in HPT was approximately 1.95°C decade⁻¹ at a 70% confidence level during the period 2010–18 (Fig. 4). Furthermore, we performed a similar trend analysis to compare the effect of global warming on the averaged maximum temperature and HPT over the land region within a latitudinal band from 30° to 40°N similar to South Korea (Fig. 4) and the Northern Hemisphere (not shown). Because the daily data were available to calculate HPT over land region, we created the time series by replacing the trend of maximum temperature in South Korea with global maximum temperature based on monthly Hadley Centre Climatic Research Unit Temperature (HadCRUT) data. The HPT in land region increased at rate of 0.37° and 0.28°C decade⁻¹ in 1981–2018 and 1981–2009, whereas it decreased -0.59°C decade⁻¹ in 2010–18. In 1981–2018, the trend of HPT in South Korea is approximately 5 times that of land region. The increasing HPT trend in South Korea may also be a part of global warming, but the HPT variability in South Korea in recent times could not be fully explained by global warming. Moreover the maximum temperature in South Korea increased by 1.59°C decade⁻¹ in 2010–18 relative to that in the land region (0.45°C decade⁻¹). Zeng et al. (2019) reported that wind speed has been increasing rapidly across the globe since 2010 due to ocean–atmosphere oscillations. This led us to believe that the changes in large-scale atmospheric circulation patterns around 2010 likely have an impact on HPT in South Korea.

Figure 6 shows the spatial distribution of the HPT trends in 1981–2018, 1981–2009, and 2010–18. The black dot denotes the 70% confidence level. In Fig. 6a, HPT during 1981–2018 increased at most stations except for a few stations in western South Korea, but the increasing trend was statistically significant at the 70% confidence level at 50% of the stations. During 1981–2009, HPT at nearly all stations showed a decreasing trend, while it increased considerably in most parts of South Korea during 2010–18.

Figure 7 indicates the interannual variations in the frequency of HPT based on four categories. During 1981–2010, 53 days of HPT occurred at the levels of caution, extreme caution, and danger. However, between the periods of 1981–2009 (53 days) and 2010–18 (57 days), the frequency of HPT at four levels has increased by approximately 4 days. In 2013, 61 days of HPT with human health risks occurred. This indicates that South Korea frequently suffers from heat stress in summer. The frequency of caution and extreme caution days decreased, but the frequency of danger days increased. In particular, the frequency of danger days exhibited a significant increase in recent years, similar to the trend of HPT. This result suggests that the increasing trends in the combined effect of

high temperature and humidity have posed substantial health risks to human health in South Korea in recent years.

b. Changes in large-scale circulation associated with increasing HPT between 1981–2009 and 2010–18

The variability in HPT is linked to large-scale atmospheric circulation patterns. To analyze the cause of the rapid increase in HPT in South Korea since the late 2000s, we performed a composite analysis. Figure 8a shows the composite difference in the 500-hPa geopotential height anomaly between 1981–2009 and 2010–18. The stippling in the figure indicates statistically significant results at the 95% confidence level with the Student's t test. The contour lines denote the location of the WNPSH, which is at the 5880-gpm isopleth (He et al. 2015; Yoon et al. 2018), during 1981–2009 (solid line) and 2010–18 (dashed line), respectively. Figure 8a shows the positive anomalies of the 500-hPa geopotential height over the western North Pacific (WNP) and South Korea. The geopotential height at 200 hPa in Fig. 8b was similar to that at 500 hPa. This result indicates that the WNPSH has enhanced and expanded westward since the late 2000s, increasing the temperatures in the region that extends from northern China to Japan (Luo and Lau 2017; Yoon et al. 2018; Liu et al. 2019).

The upper-level tropospheric jet is one of the major factors affecting the summer climate system (Chen et al. 2016; Wang and Zuo 2016). As shown in Fig. 8c (the difference in the 200-hPa zonal wind), the upper-level tropospheric jet shifted northward from the climatological position (40°N). Note that the zonal wind was negative between 20° and 30°N, suggesting a weakened upper-level tropospheric jet stream in association with the changes in large-scale atmospheric circulation patterns since the late 2000s. In general, the upper-level tropospheric jet stream leads to the convergence of air, which can increase the upward motion and subsequently induce more precipitation, and vice versa (Wei et al. 2019; Choi et al. 2019). Thus, the decreased precipitation from the middle of China to southern Japan and South Korea in Fig. 8d can be explained by a weakened upper-level tropospheric jet stream. According to Tao and Wei (2006) and Enomoto et al. (2003), the movement of the WNPSH is also related to the Eurasian Rossby wave train along the upper-level tropospheric jet stream, which is associated with energy propagation. Therefore, an anomalous anticyclone appears in the upper-level troposphere by the positive geopotential height of 500 and 200 hPa over South Korea. It lead to the negative anomalies of meridional winds at 200 hPa (Figs. 8a,c).

Figure 8e shows the meridional vertical circulation averaged over 125°–130°E, where South Korea is located, during 1981–2009 and 2010–18. The strengthened convective activities over 20°–30°N and at 30°–38°N were the opposite of each other. This pattern supports the strengthened WNPSH and northward upper-level tropospheric jet. From 1981 to 2009, an anomalous downward motion developed around South Korea at all vertical levels of the troposphere. Strong vertical convection is necessary to transport the moisture; therefore, it may have induced anomalous divergence of air over South Korea and anomalous convergence over the lower latitudes in the upper level, accompanied by the strengthened WNPSH and

TABLE 2. Average and standard deviation for maximum (Tmax), HPT, and minimum relative humidity in South Korea from 1981 to 2010.

No.	Name	Lat (°N)	Lon (°E)	Height (m)	Tmax (°C)		HPT (°C)		RH (%)	
					Mean	Std dev	Mean	Std dev	Mean	Std dev
90	Sokcho	38.25	128.57	5.6	26.50	1.45	28.33	2.32	69.02	4.15
101	Chuncheon	37.9	127.73	2	29.43	0.96	32.10	1.75	57.93	4.28
105	Gangneung	37.75	128.9	5.3	28.03	1.64	30.02	2.44	61.14	4.18
108	Seoul	37.57	126.97	3.2	29.13	1.03	31.63	1.70	58.82	3.46
112	Incheon	37.48	126.63	3.3	28.27	1.15	30.79	2.04	63.42	3.72
114	Wonju	37.33	127.95	1.4	29.67	1.02	32.28	1.77	56.49	4.52
119	Suwon	37.27	126.98	2.7	29.28	1.03	32.25	1.73	60.43	4.42
129	Seosan	36.77	126.47	4	28.97	1.00	32.01	1.59	62.99	4.70
130	Ulsan	36.98	129.42	4.2	26.78	1.44	28.81	2.37	69.06	4.57
131	Cheongju	36.63	127.43	1.5	30.16	1.19	32.92	2.02	55.33	3.84
135	Chupungnyeong	36.22	128	0.7	28.67	1.47	31.01	2.13	60.39	4.99
138	Pohang	36.03	129.4	2.4	29.04	1.72	31.90	2.62	61.94	4.69
143	Daegu	35.88	128.62	−0.5	30.65	1.61	33.38	2.39	53.82	5.38
146	Jeonju	35.82	127.15	4.2	30.61	1.19	33.82	1.86	55.96	3.54
152	Ulsan	35.55	129.32	2.3	29.46	1.54	32.49	2.42	60.34	5.09
156	Gwangju	35.17	126.88	3	30.16	1.24	33.79	1.97	60.01	4.19
159	Busan	35.1	129.03	4.7	28.34	1.31	31.86	2.63	68.46	3.83
165	Mokpo	34.78	126.38	4.5	29.19	1.24	32.69	2.06	64.30	5.13
168	Yeosu	34.73	127.73	4.2	27.96	1.18	30.81	2.17	67.29	3.89
170	Wando	34.4	126.7	5.6	28.37	1.34	31.98	2.53	69.14	3.96
201	Ganghwa	37.7	126.45	3.2	28.24	0.89	30.71	1.80	63.03	5.23
211	Inje	38.05	128.17	2	28.40	1.08	30.60	1.86	59.92	4.79
212	Hongcheon	37.68	127.88	1.6	29.86	1.14	32.07	1.70	54.04	3.76
221	Jecheon	37.15	128.18	0.2	28.81	1.08	30.72	1.79	56.39	5.78
226	Boeun	36.48	127.73	−1.7	28.99	1.21	31.33	2.17	57.80	6.72
232	Cheonan	36.78	127.12	2.9	29.74	1.23	33.01	2.09	59.50	6.16
235	Boryeong	36.33	126.6	4.4	29.07	1.01	32.64	1.92	64.76	3.63
236	Buyeo	36.27	126.92	1.6	30.18	1.18	34.04	2.08	60.68	5.49
238	Geumsan	36.1	127.47	0.8	29.85	1.25	32.85	1.99	57.84	5.71
243	Buan	35.72	126.7	3.8	29.91	1.10	34.55	2.68	64.61	5.94
245	Jeongeup	35.57	126.88	3.1	30.64	1.23	33.96	1.88	56.25	3.65
260	Jangheung	34.68	126.92	3.6	29.51	1.35	33.08	2.24	62.72	4.04
261	Haenam	34.55	126.57	4.8	29.46	1.08	33.41	1.98	64.54	4.76
262	Goheung	34.6	127.27	3.2	29.57	1.38	33.31	2.88	62.15	7.11
272	Yeongju	36.87	128.52	−0.5	29.08	1.27	31.13	1.77	56.55	4.54
273	Mungyeong	36.62	128.15	0.1	28.97	1.51	31.44	2.20	59.67	6.69
277	Yeongdeok	36.53	129.42	2.8	28.46	1.75	30.82	2.77	61.10	5.69
278	Uiseong	36.35	128.68	−1.4	30.30	1.48	32.79	2.39	53.39	4.97
279	Gumi	36.12	128.32	−0.6	30.09	1.43	32.62	2.14	54.78	3.94
281	Yeongcheon	35.97	128.95	−1.3	29.89	1.70	32.16	2.33	54.38	4.33
284	Geochang	35.67	127.92	0.9	29.57	1.38	32.53	2.07	59.32	5.08
285	Hapcheon	35.57	128.17	−0.4	30.33	1.50	33.20	2.10	55.63	5.01
288	Miryang	35.48	128.75	0.1	30.44	1.41	33.80	2.75	57.00	7.04
289	Sancheong	35.42	127.88	1.3	29.92	1.33	33.05	2.32	58.37	3.91
295	Namhae	34.78	127.87	2.6	29.66	1.40	33.42	2.60	62.49	5.47

northward upper-level tropospheric jet. These results are consistent with those of several previous studies, which suggested that the enhancement of WNPSH and convective activities are important factors leading to heat waves in South Korea (Lee et al. 2020; Xu et al. 2019). Thus, as displayed in Fig. 8d, an enhanced outgoing longwave radiation anomaly appeared around South Korea, while a decreased outgoing longwave radiation anomaly with convective activity appeared in the South China Sea in recent decades.

This result reveals that the changes in the outgoing longwave radiation field over South Korea were caused by the descending motion in the airflows that are related to the northward upper-level tropospheric jet.

We further explored the differences in the SST during both periods because SST can directly and robustly affect the atmospheric circulation through air–sea interactions (Deser et al. 2004; Zhou and Wu 2015; Wei et al. 2019). The positive SST anomalies in Fig. 8f occur in most parts of the North Pacific and

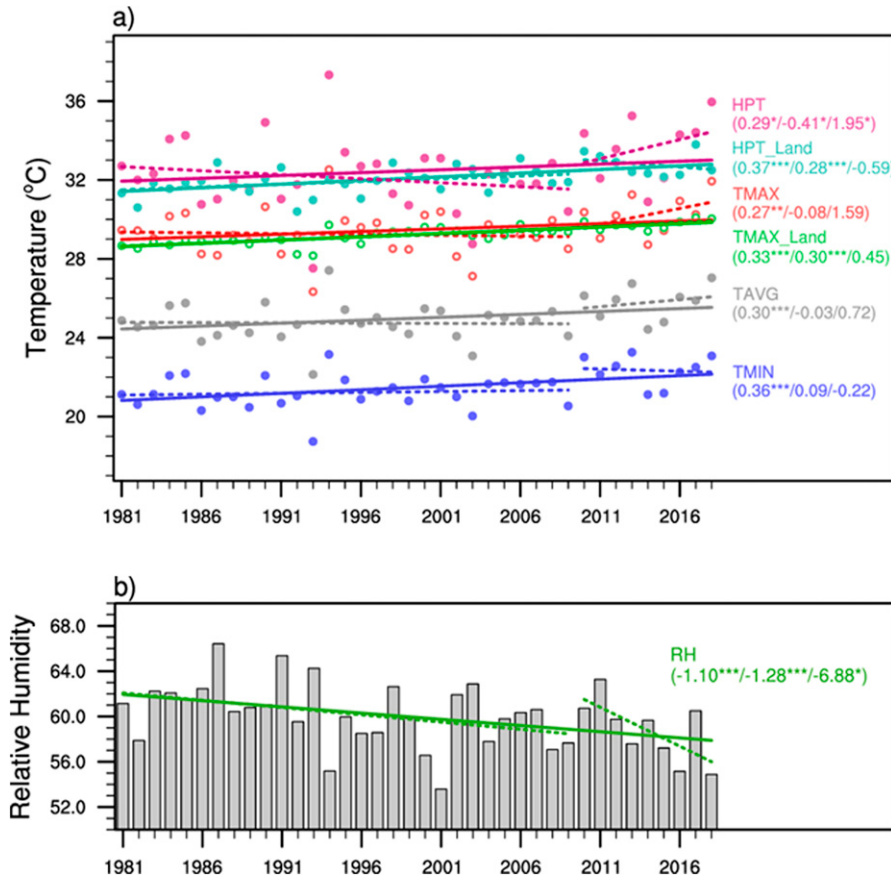


FIG. 4. Long-term variability of (a) the minimum, mean, and maximum temperature; HPT in South Korea; and the averaged maximum temperature and HPT over the land region within a latitudinal band (30° – 40° N) similar to South Korea, and (b) minimum relative humidity (%) averaged for 45 stations in South Korea. The solid and dashed lines indicate the linear trends for different periods. One, two, and three asterisks denote statistically significant results at the 70%, 85%, and 90% confidence levels, respectively.

the Maritime Continent with at least 95% confidence. This result suggests that the variability of SST corresponds well with the changes in the middle- and upper-level geopotential heights during 1981–2009 and 2010–18 (Figs. 8a,b). The SST variability

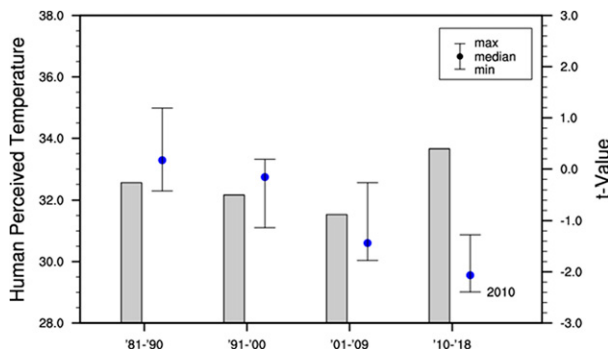


FIG. 5. Decadal average of HPT averaged for 45 stations in South Korea and the t value of statistical changepoint analysis. The bars denote the HPT. Error bars indicate the minimum, median, and maximum t value for the decades. The minimum t value during the period 1981–2018 is in 2010.

also plays an important role in strengthening and maintaining the WNPSH, and the WNPSH variability is related to the SST in the Pacific (Xiang et al. 2013; Choi and Kim 2019). The positive SST over the Maritime Continent and the tropics can modulate the WNPSH variability by its association with the anomalous Hadley circulation (Sui et al. 2007; Wu and Zhou 2008). In other words, the SST over the WNP has changed since the late 2000s relative to that in 1981–2009, which may strengthen the thermal forcing effect over the WNPSH, resulting in an extreme HPT over South Korea.

Therefore, we detected significant differences in large-scale atmospheric circulation patterns such as the northward upper-level subtropical jet, strengthened downward motion, anomalous anticyclones around South Korea, and increased SST over the northern Pacific, between 2010–18 and 1981–2009. These differences are related to the enhancement and westward expansion of WNPSH and are responsible for increasing HPTs over South Korea since the late 2000s.

c. Relationship between the position of WNPSH and extreme HPT days

In section 3b, we showed that the atmospheric circulation patterns that are related to the increasing HPTs are associated

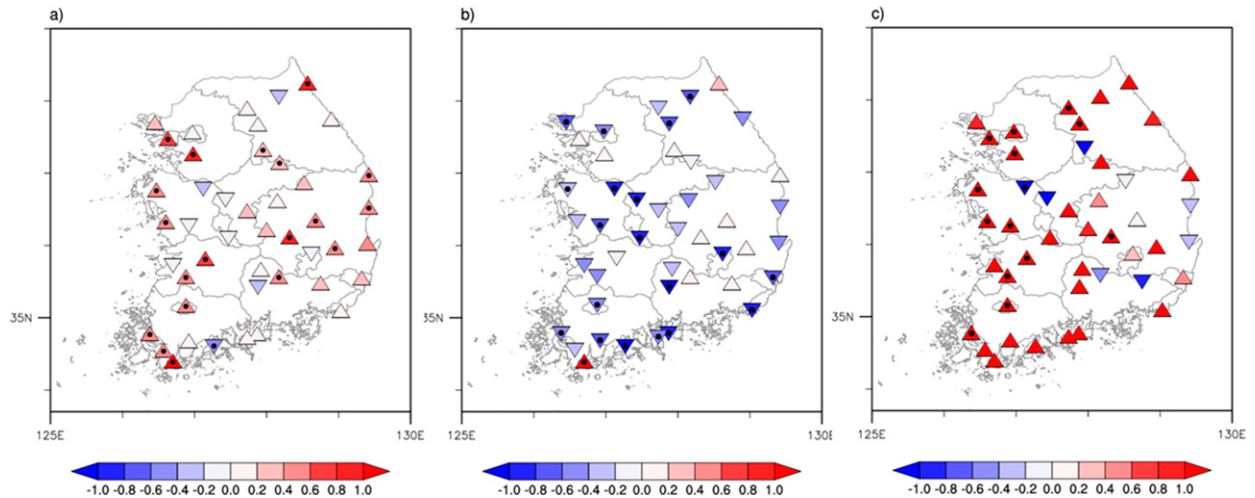


FIG. 6. Spatial distribution of the trends of HPT during 1981–2018, (b) 1981–2009, and (c) 2010–2018. The black dots denote statistically significant results at a 70% confidence level. The orientation of the triangles gives the direction of the trend, and the color of the triangle gives the magnitude of the trend.

with the northward and westward expansion of the WNPSH since the late 2000s. The WNPSH plays an important role in the weather patterns that affect the changes in temperature and precipitation over East Asia (Yang et al. 2003; Zhou and Yu 2005; Zhou et al. 2009; Guan et al. 2019). The WNPSH also exhibits both meridional and zonal movement from sub-seasonal to interannual time scales (Ren et al. 2013; Yang et al. 2017; Wang et al. 2019). Therefore, the position of the WNPSH may affect the variability of the HPT over South Korea. In this section, we analyze the relationship between the meridional and zonal movement of the WNPSH and extreme HPT days in South Korea. The extreme HPT days was defined as when extreme HPT occurs with extreme caution,

danger and extreme danger, that is, where the value of HPT exceeds 32°C .

The WNPSH is usually measured using the geopotential height over WNP (Chung et al. 2011; Chen et al. 2019; He et al. 2015; Yoon et al. 2018; M. Li et al. 2019) and some previous studies have revealed a need for caution to interpret the decadal change of WNPSH because the geopotential height increase with global warming according to the hypsometric equation (He et al. 2018; Hu et al. 2018). Thus eddy geopotential height (Huang et al. 2015; Wu and Wang 2015; He et al. 2018) or streamfunction (Li et al. 2012) have been proposed to consider precipitation and wind field. Therefore, we also compared the position of WNPSH using the eddy geopotential height and geopotential height. It was found that

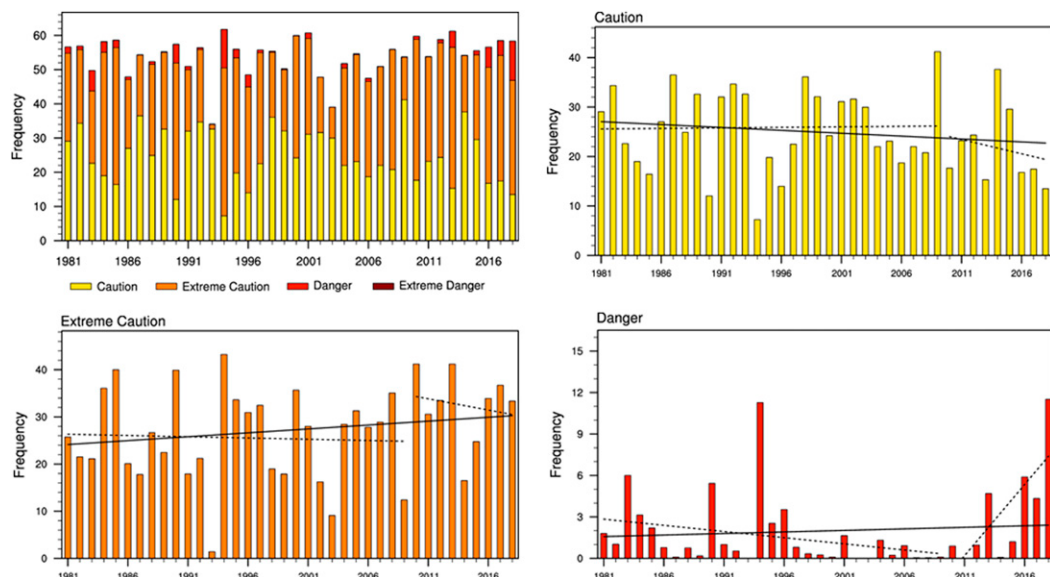


FIG. 7. Interannual frequency variability of HPT on the basis of four categories: caution, extreme caution, danger, and extreme danger. The solid and dashed lines indicate the linear trends for different periods.

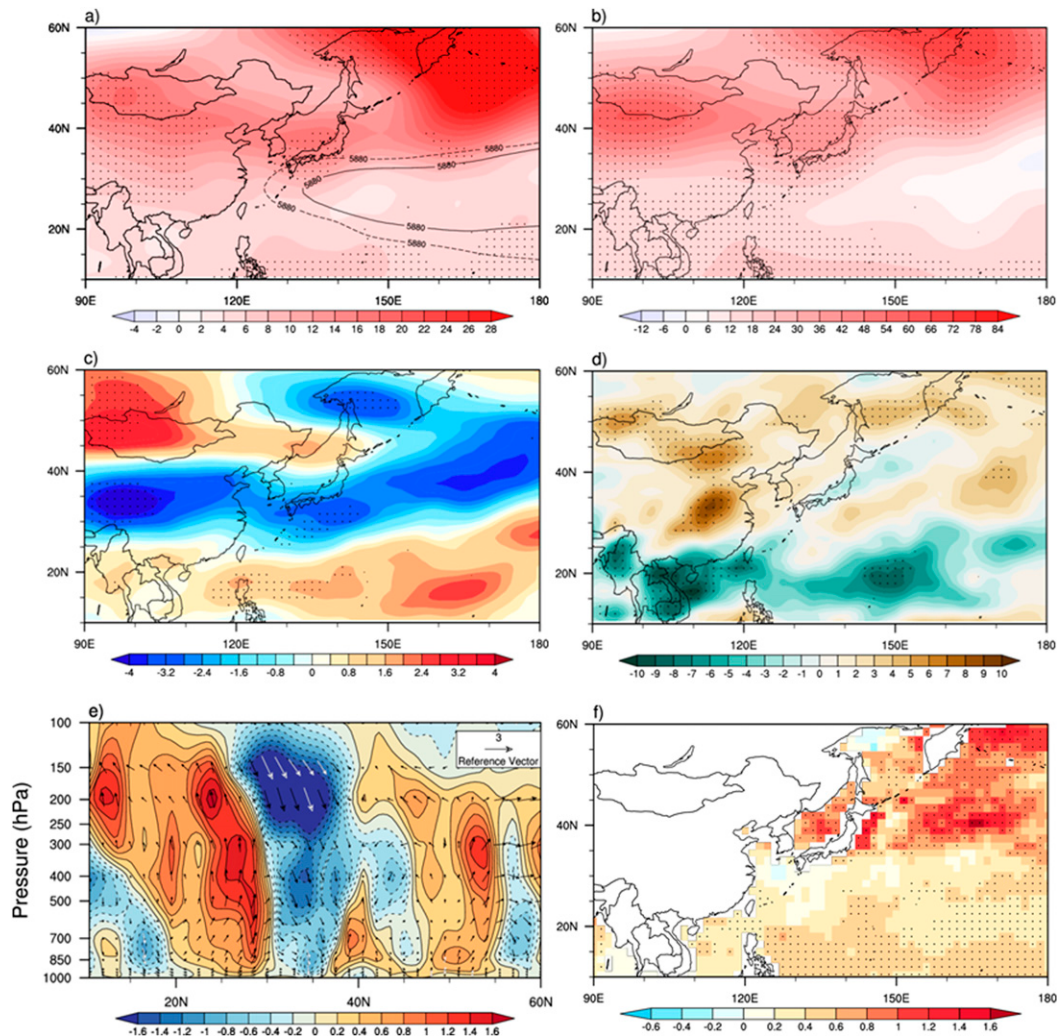


FIG. 8. Differences in large-scale atmospheric circulation patterns for (a) geopotential height at 500 hPa (shading, with 2-gpm interval), (b) geopotential height at 200 hPa (shading, with 6-gpm interval), (c) zonal wind at 200 hPa (shading, with 0.4 m s^{-1} interval), (d) outgoing longwave radiation (shading, with 1 W m^{-2} interval), (e) meridional vertical circulation (vectors; 10^{-3} m s^{-1}) and vertical velocity (shading; 10^{-3} m s^{-1}) averaged over 125° – 130°E , and (f) sea surface temperature (shading, with 0.2°C interval) between 2010–18 and 1981–2009. Stippling indicates statistical significance exceeding the 95% confidence level with Student's t test. The contour lines in (a) denote the location of the WNPSH during 1981–2009 (solid line) and 2010–18 (dashed line). In (e), positive values indicate upward motion and negative values represent downward motion.

eddy geopotential height was inconsistent with the change in circulation of wind and the East Asian rain belt, which is usually located on the northwest of WNPSH (not shown). Herein, we used the geopotential height to determine the western edge and intensity of WNPSH. Mathematically, the western ridge of the WNPSH defines the intersection between the zonal winds with zero and 5880-gpm isopleths (He et al. 2015; Yoon et al. 2018; M. Li et al. 2019) because there is wind reversion from easterly to westerly along the ridge line shown in Fig. 9. Climatologically, the western ridge of the WNPSH is located at approximately 29°N , 132°E . To investigate the relationship between the western ridge of the WNPSH and the extreme HPT days over South Korea, we divided the study

domain into four regions around the climatological position of the western ridge of the WNPSH: northeast (NE), northwest (NW), southwest (SW), and southeast (SE) (Fig. 9).

Figure 10 indicates the occurrence rate of the western ridge of the WNPSH in extreme HPT days during 1981–2009 (Fig. 10a) and 2010–18 (Fig. 10b). In 1981–2009, the western ridge of the WNPSH exhibited an occurrence rate of 25.4% in the SW and 38.1%, 13.3%, and 23.2% in the NW, SE, and NE, respectively. In 2010–18, the western ridge of the WNPSH was located in the SW, NW, SE, and NE with rates of occurrence of 34.9%, 39.2%, 11.8%, and 14%, respectively (Fig. 10). Figure 11 shows the normalized intensity of WNPSH following He et al. (2018), which was calculated as the sum of

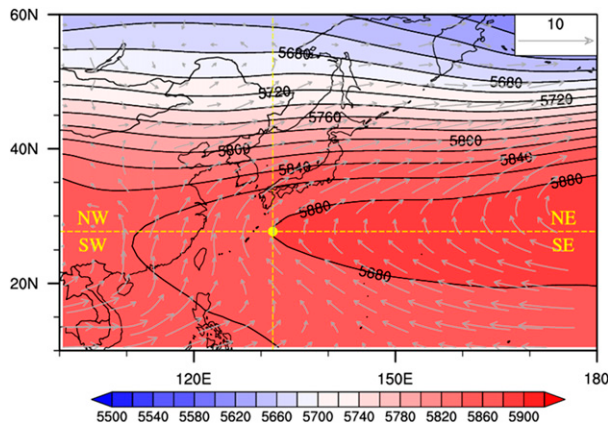


FIG. 9. Climatological position of the western ridge of WNPSH (yellow dot), geopotential height at 500 hPa (contours, with 20-gpm interval), and wind at 850 hPa (vectors; m s^{-1}) during 1981–2010.

geopotential height at 500 hPa minus 5870 gpm for all of the grid points with geopotential height greater than that of 5880 gpm over the region 110° – 180°E , 10° – 85°N . It illustrated that the WNPSH was intensified after 2010 even accounting for interannual variability. These results confirm the westward extension and intensification of the WNPSH since the late 2000s, as described in section 3b. Therefore, we focused on the analysis of the position of the western ridge of the WNPSH in the NW and SW regions during 1981–2018 to identify the common characteristics of extreme HPT days.

To examine the large-scale atmospheric circulation patterns associated with the movement of the western ridge of the WNPSH, we performed a composite analysis excluding trend to eliminate the effect of global warming. Figure 12 presents the temperature anomalies at 2 m above ground, geopotential height at 500 hPa, sea level pressure and zonal wind at 200 hPa, vertically integrated moisture flux and wind at 850 hPa, and SST when the ridge was located in the NW region relative to its climatological position during 1981–2010. An anomaly of temperature 2 m above ground (Fig. 12a) indicated that most

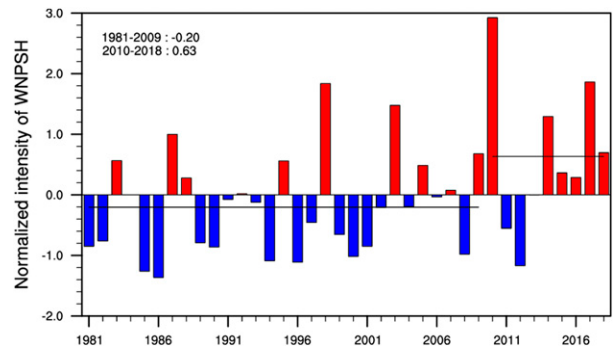


FIG. 11. Normalized intensity of WNPSH from 1981 to 2018. The two horizontal lines indicate the average of normalized intensity of WNPSH during 1981–2009 and 2010–18.

of the positive temperature anomalies occurred in South Korea and extended farther into the west and north of the country. The geopotential height anomaly at 500 hPa was positive, with its center over South Korea, while a negative geopotential height anomaly was observed over the South China Sea (Fig. 12b). This meridional wave pattern with cyclone–anticyclone anomalies from south to north along the East Asian coast resembles the Rossby wave and is known as the Pacific–Japan pattern, associated with extreme temperatures over East Asia (Xu et al. 2019). Moreover, the sea level pressure anomaly was positive (Fig. 12c) around South Korea and Japan and negative over the South China Sea. These features with anomalous anticyclonic circulation at the upper and lower levels over South Korea may be attributable to the downward motion and tend to increase the temperature at the upper and lower levels through adiabatic atmospheric warming caused by subsidence and enhanced solar radiation. These structures are similar to large-scale atmospheric circulation patterns associated with heat waves over South Korea (Lee and Lee 2016; Lee et al. 2016). The composite of the zonal wind anomaly at 200 hPa (Fig. 12d) is characterized by weakened westerly winds in South Korea, indicating a northward shift of the upper-level tropospheric jet. In general, upper-level divergence (convergence) is associated with upward (downward) vertical motion. The weakened westerly

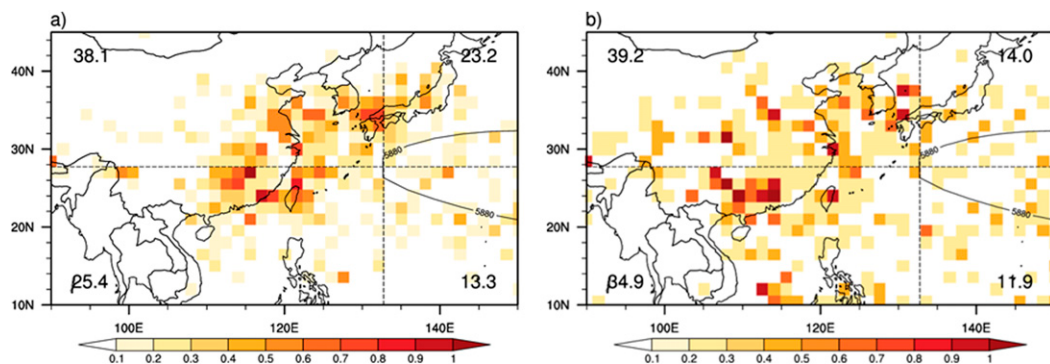


FIG. 10. Occurrence rate of the western ridge of WNPSH for extreme HPT days during (a) 1981–2009 and (b) 2010–18. The values in the respective corners indicate the occurrence rate of the western ridge of WNPSH in the northwest (NW), southwest (SW), northeast (NE), and southeast (SE).

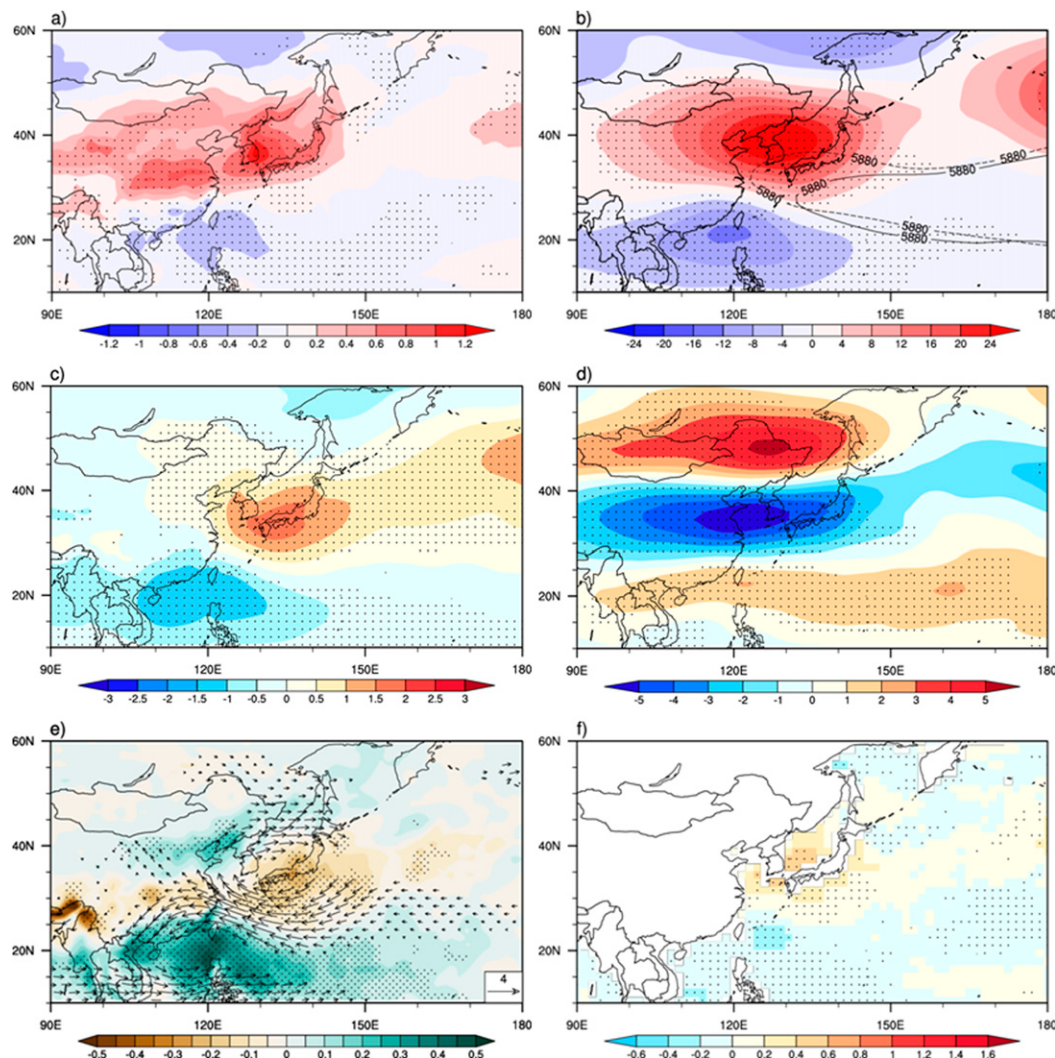


FIG. 12. Composite anomaly map of (a) temperature 2 m above ground (shading, with 0.2°C interval), (b) geopotential height at 500 hPa (shading, with 4-gpm interval), (c) sea level pressure (shading, with 0.5-hPa interval), (d) zonal wind at 200 hPa (shading, with 1 m s⁻¹ interval), (e) vertical integrated moisture (shading, with 10⁴ kg m⁻² s⁻¹ interval) and wind at 850 hPa (vectors; m s⁻¹), and (f) sea surface temperature (shading, with 0.2°C interval) when the western ridge is located in the northwest region relative to its climatological position in 1981–2018. The stippling indicates statistical significance exceeding the 95% confidence level with Student's *t* test.

upper-level tropospheric jet leading convergence at upper levels along the middle of China and South Korea decreases (for divergence) the vertical integral of moisture (Fig. 12e) (Lin 2013; Xie et al. 2015).

Another composite analysis was also performed for the atmospheric variables when the ridge was located in the SW region relative to its climatological position for 1981–2010. In this case, the western edge of the WNPSH shifted southwestward and reached the coastal regions of eastern China. Thus, the 500-hPa geopotential height anomaly centered over the South China Sea and South Korea was affected by the western edge of this anomalous anticyclone, accompanied by westerly winds (Figs. 13b,e). The vertical integral of the moisture anomaly when the western edge of WNPSH was located in the

SW region showed negative anomalies over most parts of the South China Sea and South Korea near 110°–150°E and 10°–40°N (Fig. 13e). This means that convective activities were strongly suppressed over the South China Sea, but their intensity over South Korea was weak in comparison with the position of the western edge of the WNPSH in the NW. The SST anomaly was characterized by a positive anomaly in the South China Sea in contrast to a negative SST anomaly when the western edge of the WNPSH is located in the NW region (Fig. 13f).

To compare the position of the western edge of the WNPSH between extreme HPT days and extreme maximum temperature days, we applied the occurrence rate of the western ridge of WNPSH to the extreme maximum temperature days (Fig. 14).

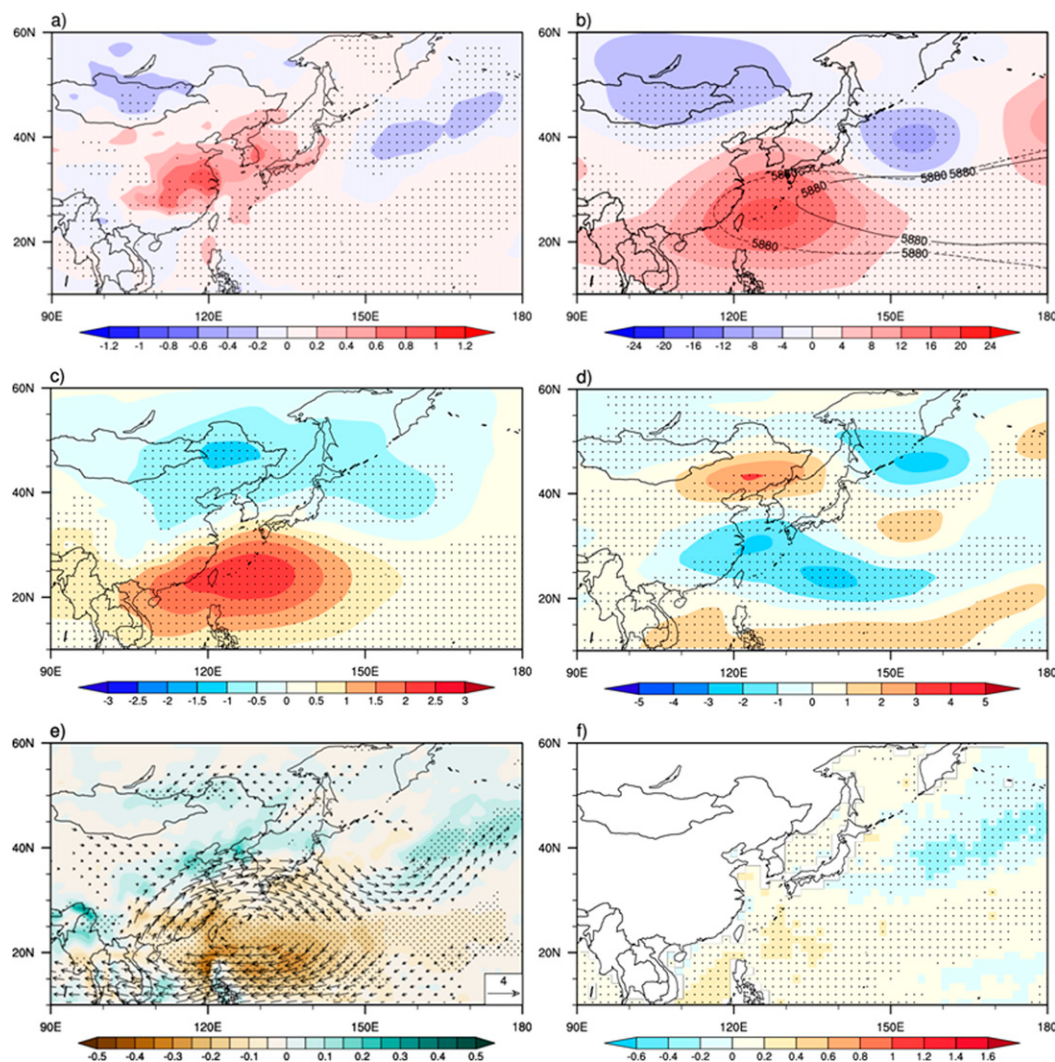


FIG. 13. As in Fig. 12, but when the western ridge is located in the southwest region relative to its climatological position in 1981–2018.

The extreme maximum temperature days were defined as above 32°C in the maximum temperature only. Unlike extreme HPT days, the western edge of the WNPSH was located in the NW region approximately 50% of the time when the extreme maximum temperature days occurred. They could be explained considering that the typical large-scale features associated with the extreme maximum temperature days over South Korea are characterized by the dominant anticyclone circulation centered on South Korea and the Pacific–Japan pattern (Lee and Lee 2016; Xu et al. 2019). Furthermore, to understand the difference in atmospheric circulation of extreme HPT and extreme maximum temperature days, we presented the composite differences between extreme HPT and extreme temperature days (Fig. 15). In the sea level pressure field during an extreme HPT day, an anomalous low is located over South Korea and an anomalous high is located over the south of Japan. The vertical integral of the moisture showed positive anomalies over South Korea. It is

clear that extreme HPT days are associated with enhanced anticyclonic circulation over the south of Japan and increased moisture over South Korea, relative to the situation with extreme maximum temperature. These results indicate that the extreme HPT days can be caused by an increase in relative humidity. The frequency of extreme HPT days considering the combined effect between temperature and relative humidity was higher compared to the frequency when only temperature was considered (Fig. 14b). This implies that extreme days can be underestimated when only temperature not considering humidity to quantify heat hazard and heat risk assessment.

Table 3 and Fig. 16 indicate the observational average of HPT, maximum temperature, relative humidity, and the number of stations when the extreme HPT occurred over South Korea according to the position of the ridge of the WNPSH. When the ridge of WNPSH was in the NW region, approximately 37% of the stations in South Korea had an HPT

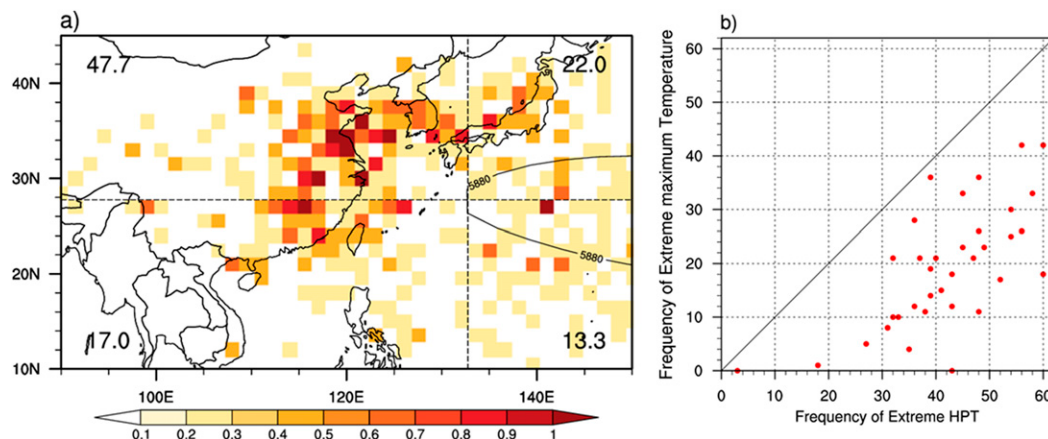


FIG. 14. (a) Occurrence rate of the western ridge of WNPISH for extreme maximum temperature days during 1981–2009 and (b) the frequency of extreme maximum temperature and HPT days. The values in (a) in the respective corners indicate the occurrence rate of the western ridge of WNPISH in the NW, SW, NE, and SE.

of at least 34.06°C . This indicates a relatively higher average HPT and maximum temperature and relatively lower relative humidity when compared with the position of the western edge of the WNPISH in the SW (Figs. 16e,f). The higher maximum temperature and relatively lower relative humidity likely contribute to the occurrence of the extreme HPT when the western edge of the WNPISH is located in the NW.

There is a relatively lower temperature and higher relative humidity when the western edge of the WNPISH is located in the SW region. Approximately 32% of the stations in South Korea experienced extreme HPT days. The average HPT was 32.81°C when the western edge of the WNPISH was located in the SW. The average maximum temperature and relative humidity were 29.59°C and 60.64%, respectively. These results suggest that the occurrence of extreme HPT over South Korea was due to the lower maximum temperature and higher relative humidity due to the wind circulation pattern, bringing warm and moist air from the West (Yellow) Sea of South Korea along the ridge line of the WNPISH.

These results suggest that the position of the western edge of the WNPISH plays an important role in the variability of HPT in terms of intensity and spatial distribution. When the western edge of the WNPISH is located in the NW, a positive geopotential height anomaly at 500 hPa is centered over South Korea, which is associated with high temperature and low relative humidity. Otherwise, the southwestern extension of the WNPISH modifies the wind circulation pattern and brings warm and moist air from the West Sea along the ridge line of the WNPISH (Hong et al. 2018; M. Li et al. 2019; Ha et al. 2020; Yoon et al. 2020). Eventually, this leads to extreme HPT associated with high relative humidity and temperature in South Korea.

4. Summary and conclusions

In this study, we analyzed the temporal and spatial trends and changepoints in HPT in South Korea to investigate the potential impact of the combination of temperature and relative humidity

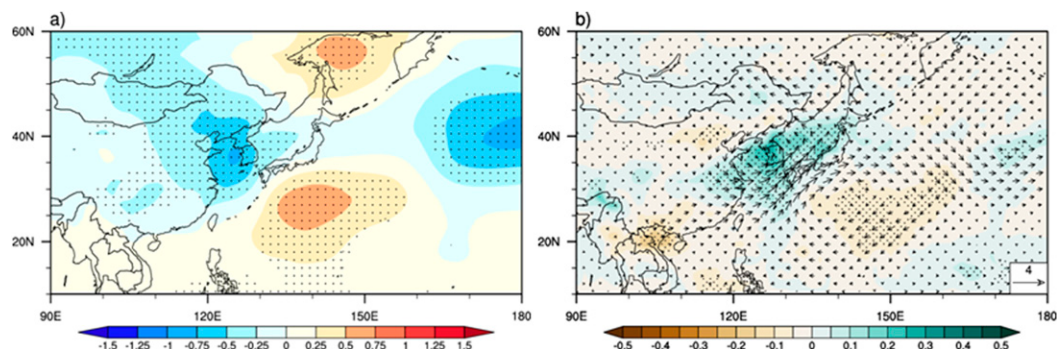


FIG. 15. Difference map of (a) sea level pressure (shading, with 0.5-hPa interval) and (b) vertical integrated moisture (shading, with $10^4 \text{ kg m}^{-2} \text{ s}^{-1}$ interval) and wind at 850 hPa (vectors; m s^{-1}) between extreme HPT and extreme maximum temperature days. The stippling indicates statistical significance exceeding 95% confidence level with Student's t test.

TABLE 3. The observational average of HPT (°C), maximum temperature (°C), relative humidity (%), and the rate of stations (%) when extreme HPT occurs with extreme caution, danger, and extreme danger (HPT > 32°C) in South Korea according to the position of the ridge of WNPSH in 1981–2018 and in 2010–18 (in parentheses).

Position of western edge of WNPSH	Rate of stations (%)	HPT (°C)	Tmax (°C)	RH (%)
NW	37.18 (38.31)	34.06 (34.93)	30.51 (31.13)	58.16 (57.02)
SW	31.71 (34.13)	32.81 (33.97)	29.59 (30.27)	60.64(59.91)

on the human body in the summers of the years between 1981 and 2018. Our results showed clear interdecadal variations and a statistically significant increasing trend for temperature and HPT at the 70% confidence level. The trend of HPT is stronger than that of the minimum, mean, and maximum temperatures during 1981–2018. These results are in good agreement with those of recent studies; HPT increased faster than the air temperature (Li et al. 2018; Russo et al. 2017; Luo and Lau 2019). There was an abrupt change in temperature at the 95% confidence level between 1981–2009 and 2010–18. This detection point is likely related to the changes in large-scale atmospheric

circulation patterns. In the interannual frequency variability of HPT, the category for danger has been established since the late 2000s. This result suggests that human health risks of the combined effects of high temperature and humidity have increased in South Korea since the late 2000s.

To determine the causes of the rapidly increasing trend of HPT over South Korea in recent years, we investigated the large-scale atmospheric circulations between two periods. We identified significant differences in large-scale atmospheric circulation patterns including a northward upper-level subtropical jet, strengthened downward motion, anomalous anticyclones, and increased SST

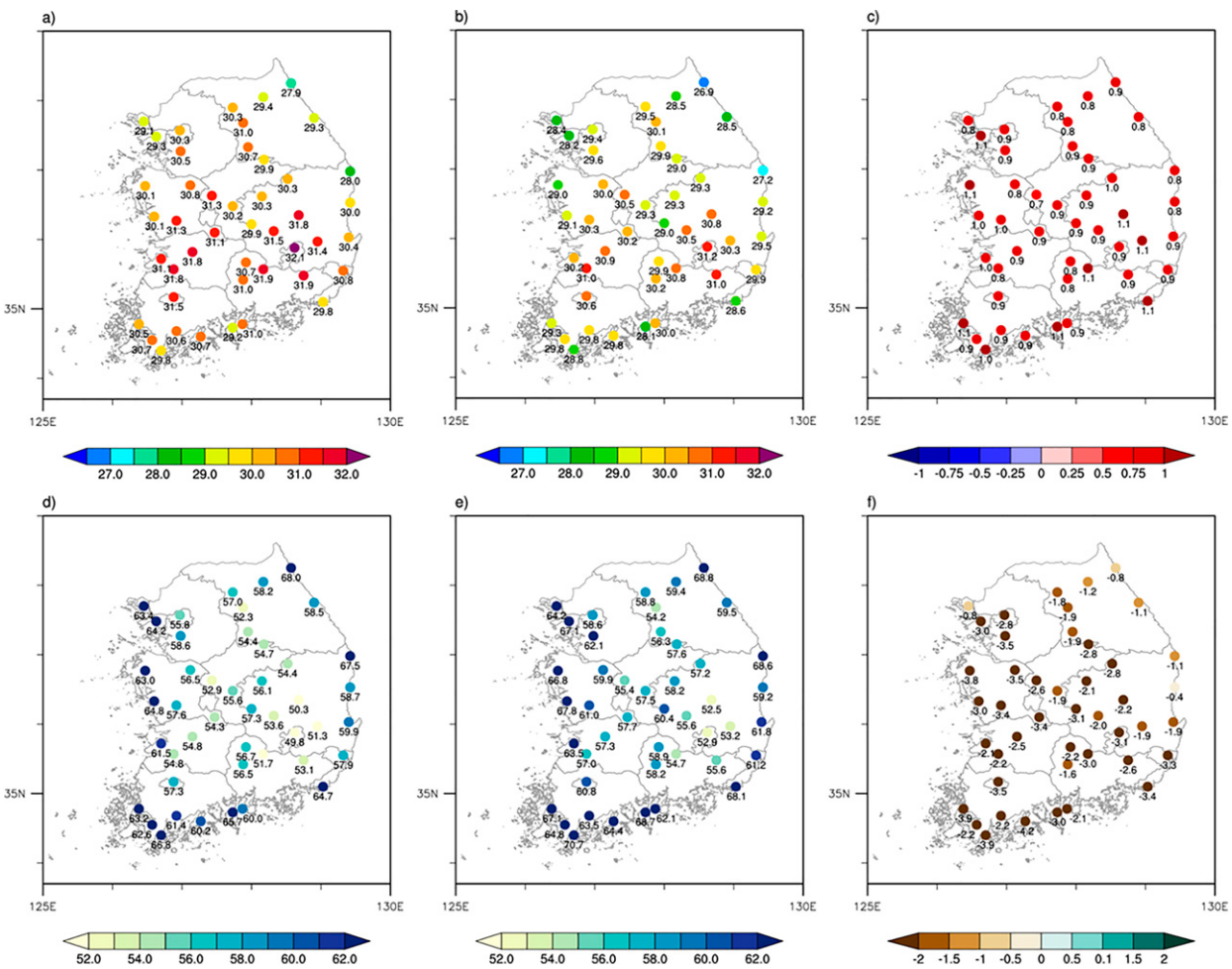


FIG. 16. Composite maps of (a),(b) daily maximum temperature (°) and (d),(e) daily minimum relative humidity (%) when the western ridge is located in the (left) NW or (center) SW region relative to its climatological position in 1981–2018. Also shown are (c) the difference between (a) and (b) and (f) the difference between (d) and (e).

over the northern Pacific, which are related to the enhancement and westward expansion of the WNPSH between 1981–2009 and 2010–18. These results suggest that the northward and westward expansion of the WNPSH is associated with the increasing HPT in South Korea since the late 2000s.

This study focused on the relationship between the position of the western edge of the WNPSH and the extreme HPT days in South Korea. When the western edge of the WNPSH was located in the northwest, a positive geopotential height anomaly at 500 hPa is centered over South Korea, which is associated with high temperature and low relative humidity. The southwestern extension of the WNPSH modifies the wind circulation pattern and brings warm and moist air from the South China Sea along the ridge line of the WNPSH. This leads to extreme HPTs in South Korea, particularly in the southern part of the country. The results of this study imply that the position of the western edge of the WNPSH plays an important role in the variability of HPT over South Korea. Although this study focused on the variability of HPT in South Korea and relationship between the position of WNPSH and the variability, WNPSH is one of the key factors modulating summer monsoon system on East Asia including Japan and China. Therefore, we concluded that monitoring and predicting the location of the WNPSH and understanding what mechanisms and factors cause the movement of WNPSH under global warming is necessary for predicting and coping with the extreme temperature events.

While the relationship between the position of the western edge of the WNPSH and extreme HPT days in South Korea is addressed in this study, the causes of the westward extension and intensification of the WPSH since the late 2000s are not discussed. Further research is needed based on a more quantitative and detailed analysis of the observations and climate models to simulate the WNPSH.

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REFERENCES

- Black, M. T., and D. J. Karoly, 2016: Southern Australia's warmest October on record: The role of ENSO and climate change [in "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **97**, S118–S121, <https://doi.org/10.1175/BAMS-D-16-0124.1>.
- Buzan, J. R., K. Oleson, and M. Huber, 2014: Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5. *Geosci. Model Dev. Discuss.*, **7**, 5197–5248, <https://doi.org/10.5194/gmdd-7-5197-2014>.
- Chen, R., Z. Wen, R. Lu, and C. Wang, 2019: Causes of the extreme hot midsummer in central and South China during 2017: Role of the western tropical Pacific warming. *Adv. Atmos. Sci.*, **36**, 465–478, <https://doi.org/10.1007/s00376-018-8177-4>.
- Chen, W., and Coauthors, 2016: Variation in summer surface air temperature over Northeast Asia and its associated circulation anomalies. *Adv. Atmos. Sci.*, **33** (1), 1–9, <https://doi.org/10.1007/s00376-015-5056-0>.
- Choi, J.-W., H.-D. Kim, and B. Wang, 2019: Interdecadal variation of Changma (Korean summer monsoon rainy season) retreat date in Korea. *Int. J. Climatol.*, **40**, 1348–1360, <https://doi.org/10.1002/joc.6272>.
- Choi, W., and K. Kim, 2019: Summertime variability of the western North Pacific subtropical high and its synoptic influences on the East Asian weather. *Sci. Rep.*, **9**, 7865, <https://doi.org/10.1038/s41598-019-44414-w>.
- Chung, P.-H., C.-H. Sui, and T. Li, 2011: Interannual relationships between the tropical sea surface temperature and summertime subtropical anticyclone over the western North Pacific. *J. Geophys. Res.*, **116**, D13111, <https://doi.org/10.1029/2010JD015554>.
- Coffel, E. D., R. M. Horton, and A. de Sherbinin, 2018: Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environ. Res. Lett.*, **13**, 014001, <https://doi.org/10.1088/1748-9326/aaa00e>.
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.
- Deser, C., G. Magnusdottir, R. Saravanan, and A. S. Phillips, 2004: The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: Direct and indirect components of the response. *J. Climate*, **17**, 877–889, [https://doi.org/10.1175/1520-0442\(2004\)017<0877:TEONAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0877:TEONAS>2.0.CO;2).
- Ding, T., Y. Yuan, J. Zhang, and H. Gao, 2019: 2018: The hottest summer in China and possible causes. *J. Meteor. Res.*, **33**, 577–592, <https://doi.org/10.1007/s13351-019-8178-y>.
- Dole, R., and Coauthors, 2011: Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.*, **38**, L06702, <https://doi.org/10.1029/2010GL046582>.
- Enomoto, T., B. J. Hoskins, and Y. Matsuda, 2003: The formation mechanism of the Bonin high in August. *Quart. J. Roy. Meteor. Soc.*, **129**, 157–178, <https://doi.org/10.1256/qj.01.211>.
- Fischer, E. M., and R. Knutti, 2013: Robust projections of combined humidity and temperature extremes. *Nat. Climate Change*, **3**, 126–130, <https://doi.org/10.1038/nclimate1682>.
- , K. W. Oleson, and D. M. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change. *Geophys. Res. Lett.*, **39**, L03705, <https://doi.org/10.1029/2011GL050576>.
- Freychet, N., S. Tett, J. Wang, and G. Hegerl, 2017: Summer heat waves over eastern China: Dynamical processes and trend attribution. *Environ. Res. Lett.*, **12**, 024015, <https://doi.org/10.1088/1748-9326/aa5ba3>.
- Ghatak, D., B. Zaitchik, C. Hain, and M. Anderson, 2017: The role of local heating in the 2015 Indian heat wave. *Sci. Rep.*, **7**, 7707, <https://doi.org/10.1038/s41598-017-07956-5>.
- Grotjahn, R., and G. Faure, 2008: Composite predictor maps of extraordinary weather events in the Sacramento, California, region. *Wea. Forecasting*, **23**, 313–335, <https://doi.org/10.1175/2007WAF2006055.1>.
- Guan, W. N., H. B. Hu, X. J. Ren, and X.-Q. Yang, 2019: Subseasonal zonal variability of the western Pacific subtropical high in summer: Climate impacts and underlying mechanisms. *Climate Dyn.*, **53**, 3325–3344, <https://doi.org/10.1007/s00382-019-04705-4>.

- Ha, K.-J., J.-H. Yeo, Y.-W. Seo, E.-S. Chung, J.-Y. Moon, X. Feng, Y.-W. Lee, and C.-H. Ho, 2020: What caused the extraordinarily hot 2018 summer in Korea? *J. Meteor. Soc. Japan*, **98**, 153–167, <https://doi.org/10.2151/jmsj.2020-009>.
- He, C., T. Zhou, A. Lin, B. Wu, D. Gu, C. Li, and B. Zheng, 2015: Enhanced or weakened western North Pacific subtropical high under global warming? *Sci. Rep.*, **5**, 16771, <https://doi.org/10.1038/srep16771>.
- , A. Lin, D. Gu, C. Li, B. Zheng, B. Wu, and T. Zhou, 2018: Using eddy geopotential height to measure the western North Pacific subtropical high in a warming climate. *Theor. Appl. Climatol.*, **131**, 681–691, <https://doi.org/10.1007/s00704-016-2001-9>.
- Hong, J. S., S. W. Yeh, and K. H. Seo, 2018: Diagnosing physical mechanisms leading to pure heat waves versus pure tropical nights over the Korean Peninsula. *J. Geophys. Res. Atmos.*, **123**, 7149–7160, <https://doi.org/10.1029/2018JD028360>.
- Hope, P., G. Wang, E.-P. Lim, H. H. Hendon, and J. M. Arblaster, 2016: What caused the record-breaking heat across Australia in October 2015? *Bull. Amer. Meteor. Soc.*, **97**, S122–S126, <https://doi.org/10.1175/BAMS-D-16-0141.1>.
- Hu, X., M. Cai, S. Yang, and Z. Wu, 2018: Delineation of thermodynamic and dynamic responses to sea surface temperature forcing associated with El Niño. *Climate Dyn.*, **51**, 4329–4344, <https://doi.org/10.1007/s00382-017-3711-0>.
- Huang, Y. Y., H. J. Wang, K. Fan, and Y. Q. Gao, 2015: The western Pacific subtropical high after the 1970s: Westward or eastward shift? *Climate Dyn.*, **44**, 2035–2047, <https://doi.org/10.1007/s00382-014-2194-5>.
- Im, E.-S., I. W. Jung, and D. H. Bae, 2011: The temporal and spatial structures of recent and future trends in extreme indices over Korea from a regional climate projection. *Int. J. Climatol.*, **31**, 72–86, <https://doi.org/10.1002/joc.2063>.
- , J. S. Pal, and E. A. B. Eltahir, 2017: Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci. Adv.*, **3**, e1603322, <https://doi.org/10.1126/sciadv.1603322>.
- , N.-X. Thanh, Y.-H. Kim, and J.-B. Ahn, 2019: 2018 summer extreme temperatures in South Korea and their intensification under 3°C global warming. *Environ. Res. Lett.*, **14**, 094020, <https://doi.org/10.1088/1748-9326/ab3b8f>.
- IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 1–29.
- ISO, 1989: Hot environments—Estimation of the heat stress on working man, based on the WBGT index. International Organization for Standardization Doc. 7243, 9 pp., <https://www.iso.org/standard/13895.html>.
- Jung, I. W., D. H. Bae, and G. Kim, 2011: Recent trends of mean and extreme precipitation in Korea. *Int. J. Climatol.*, **31**, 359–370, <https://doi.org/10.1002/joc.2068>.
- Kendall, M. G., 1975: *Rank Correlation Methods*. Charles Griffin, 272 pp.
- King, A. D., G. J. van Oldenborgh, D. J. Karoly, S. C. Lewis, and H. Cullen, 2015: Attribution of the record high central England temperature of 2014 to anthropogenic influences. *Environ. Res. Lett.*, **10**, 054002, <https://doi.org/10.1088/1748-9326/10/5/054002>.
- KMA, 2016: Annual report 2016. Korea Meteorological Administration Rep., 45 pp., https://www.kma.go.kr/download_01/Annual_Report_2016.pdf.
- , 2020: Climate information portal. Korea Meteorological Administration, accessed 1 April 2020, <https://data.kma.go.kr/stcs/grnd/grndTaList.do?pgmNo=70>.
- Lee, H.-J., W.-S. Lee, and J. Yoo, 2016: Assessment of medium-range ensemble forecasts of heat waves. *Atmos. Sci. Lett.*, **17**, 19–25, <https://doi.org/10.1002/asl.593>.
- , J. A. Chun, and H. W. Lee, 2020: Probabilistic heat wave forecast based on a large-scale circulation pattern using the TIGGE data. *Wea. Forecasting*, **35**, 367–377, <https://doi.org/10.1175/WAF-D-19-0188.1>.
- Lee, S.-M., and S.-K. Min, 2018: Heat stress changes over East Asia under 1.5° and 2.0°C global warming targets. *J. Climate*, **31**, 2819–2831, <https://doi.org/10.1175/JCLI-D-17-0449.1>.
- Lee, W.-S., and M.-I. Lee, 2016: Interannual variability of heat waves in South Korea and their connection with large-scale atmospheric circulation patterns. *Int. J. Climatol.*, **36**, 4815–4830, <https://doi.org/10.1002/joc.4671>.
- Li, J., Y. D. Chen, T. Y. Gan, and N.-C. Lau, 2018: Elevated increases in human-perceived temperature under climate warming. *Nat. Climate Change*, **8**, 43–47, <https://doi.org/10.1038/s41558-017-0036-2>.
- Li, M., Y. Yao, D. Luo, and L. Zhong, 2019: The linkage of the large-scale circulation pattern to a long-lived heatwave over mideastern China in 2018. *Atmosphere*, **10**, 89, <https://doi.org/10.3390/atmos10020089>.
- Li, W., L. Li, M. Ting, and Y. Liu, 2012: Intensification of Northern Hemisphere subtropical highs in a warming climate. *Nat. Geosci.*, **5**, 830–834, <https://doi.org/10.1038/ngeo1590>.
- , T. Zou, L. Li, Y. Deng, V. T. Sun, Q. Zhang, J. B. Layton, and S. Setoguchi, 2019: Impacts of the North Atlantic subtropical high on interannual variation of summertime heat stress over the conterminous United States. *Climate Dyn.*, **53**, 3345–3359, <https://doi.org/10.1007/s00382-019-04708-1>.
- Lin, Z. D., 2013: Impacts of two types of northward jumps of the East Asian upper-tropospheric jet stream in midsummer on rainfall in eastern China. *Adv. Atmos. Sci.*, **30**, 1224–1234, <https://doi.org/10.1007/s00376-012-2105-9>.
- Liu, B., C. Zhu, J. Su, S. Ma, and K. Xu, 2019: Record-breaking northward shift of the western North Pacific subtropical high in July 2018. *J. Meteor. Soc. Japan*, **97**, 913–925, <https://doi.org/10.2151/jmsj.2019-047>.
- Loikith, P. C., and A. J. Broccoli, 2015: Comparison between observed and model-simulated atmospheric circulation patterns associated with extreme temperature days over North America using CMIP5 historical simulations. *J. Climate*, **28**, 2063–2079, <https://doi.org/10.1175/JCLI-D-13-00544.1>.
- Lu, R., and R. Chen, 2016: A review of recent studies on extreme heat in China. *Atmos. Oceanic Sci. Lett.*, **9**, 114–121, <https://doi.org/10.1080/16742834.2016.1133071>.
- Luo, M., and N.-C. Lau, 2017: Heat waves in southern China: Synoptic behavior, long-term change, and urbanization effects. *J. Climate*, **30**, 703–720, <https://doi.org/10.1175/JCLI-D-16-0269.1>.
- , and —, 2019: Characteristics of summer heat stress in China during 1979–2014: Climatology and long-term trends. *Climate Dyn.*, **53**, 5375–5388, <https://doi.org/10.1007/s00382-019-04871-5>.
- , N. Lau, W. Zhang, Q. Zhang, and Z. Liu, 2020: Summer high temperature extremes over China linked to the Pacific meridional mode. *J. Climate*, **33**, 5905–5917, <https://doi.org/10.1175/JCLI-D-19-0425.1>.
- Mann, H. B., 1945: Nonparametric tests against trend. *Econometrica*, **13**, 245–259, <https://doi.org/10.2307/1907187>.

- Matthews, T. K., R. L. Wilby, and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. *Proc. Natl. Acad. Sci. USA*, **114**, 3861–3866, <https://doi.org/10.1073/pnas.1617526114>.
- Meehl, G. A., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994–997, <https://doi.org/10.1126/science.1098704>.
- NWS, 2020: Heat safety. National Weather Service, accessed 1 April 2020, <https://www.weather.gov/grb/heat>.
- Oliver, E. C. J., and Coauthors, 2018: Longer and more frequent marine heatwaves over the past century. *Nat. Commun.*, **9**, 1324, <https://doi.org/10.1038/s41467-018-03732-9>.
- Pall, P., T. Aina, D. A. Stone, P. A. Stott, T. Nozawa, A. G. J. Hilberts, D. Lohmann, and M. R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470**, 382–385, <https://doi.org/10.1038/nature09762>.
- Perkins, S. E., and P. B. Gibson, 2015: Increased risk of the 2014 Australian May heatwave due to anthropogenic activity [in “Explaining Extremes of 2014 from a Climate Perspective”]. *Bull. Amer. Meteor. Soc.*, **96**, S154–S157, <https://doi.org/10.1175/BAMS-D-15-00074.1>.
- Peters, W., and Coauthors, 2010: Seven years of recent European net terrestrial carbon dioxide exchange constrained by atmospheric observations. *Global Change Biol.*, **16**, 1317–1337, <https://doi.org/10.1111/j.1365-2486.2009.02078.x>.
- Ratnam, J. V., S. K. Behera, S. B. Ratna, M. Rajeevan, and T. Yamagata, 2016: Anatomy of Indian heat waves. *Sci. Rep.*, **6**, 24395, <https://doi.org/10.1038/srep24395>.
- Ren, X., X.-Q. Yang, and X. Sun, 2013: Zonal oscillation of western Pacific subtropical high and subseasonal SST variations during Yangtze persistent heavy rainfall events. *J. Climate*, **26**, 8929–8946, <https://doi.org/10.1175/JCLI-D-12-00861.1>.
- Reynolds, R., T. Smith, C. Liu, B. Chelton, K. Casey, and M. Schlax, 2007: Daily high-resolution-blended analyses for sea surface temperature. *J. Climate*, **20**, 5473–5496, <https://doi.org/10.1175/2007JCLI1824.1>.
- Russo, S., J. Sillmann, and A. Sterl, 2017: Humid heat waves at different warming levels. *Sci. Rep.*, **7**, 7477, <https://doi.org/10.1038/s41598-017-07536-7>.
- Schiermeier, Q., 2011: Increased flood risk linked to global warming. *Nature*, **470**, 316, <https://doi.org/10.1038/470316a>.
- Sherwood, S. C., 2018: How important is humidity in heat stress? *J. Geophys. Res. Atmos.*, **123**, 11 808–11 811, <https://doi.org/10.1029/2018JD028969>.
- , and M. Huber, 2010: An adaptability limit to climate change due to heat stress. *Proc. Natl. Acad. Sci. USA*, **107**, 9552–9555, <https://doi.org/10.1073/pnas.0913352107>.
- Steadman, R. G., 1979: The assessment of sultriness. Part I: A temperature–humidity index based on human physiology and clothing science. *J. Appl. Meteor.*, **18**, 861–873, [https://doi.org/10.1175/1520-0450\(1979\)018<0861:TAOSPI>2.0.CO;2](https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2).
- Su, Q., and B. Dong, 2019: Recent decadal changes in heat waves over China: Drivers and mechanisms. *J. Climate*, **32**, 4215–4234, <https://doi.org/10.1175/JCLI-D-18-0479.1>.
- Sui, C. H., P. H. Chung, and T. Li, 2007: Interannual and interdecadal variability of the summertime western North Pacific subtropical high. *Geophys. Res. Lett.*, **34**, L11701, <https://doi.org/10.1029/2006GL029204>.
- Sun, Q., C. Miao, M. Hanel, A. G. L. Borthwick, Q. Duan, D. Ji, and H. Li, 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environ. Int.*, **128**, 125–136, <https://doi.org/10.1016/j.envint.2019.04.025>.
- Tao, S.-Y., and J. Wei, 2006: The westward, northward advance of the subtropical high over the west Pacific in summer (in Chinese). *J. Appl. Meteor. Sci.*, **17**, 513–525.
- Tomczyk, A. M., and M. Owczarek, 2020: Occurrence of strong and very strong heat stress in Poland and its circulation conditions. *Theor. Appl. Climatol.*, **139**, 893–905, <https://doi.org/10.1007/s00704-019-02998-3>.
- Trewin, B., and H. Vermont, 2010: Changes in the frequency of record temperatures in Australia, 1957–2009. *Aust. Meteor. Oceanogr. J.*, **60**, 113–119, <https://doi.org/10.22499/2.6002.003>.
- Uhe, P., F. Otto, K. Haustein, G. van Oldenborgh, A. King, D. Wallom, M. Allen, and H. Cullen, 2016: Comparison of methods: Attributing the 2014 record European temperatures to human influences. *Geophys. Res. Lett.*, **43**, 8685–8693, <https://doi.org/10.1002/2016GL069568>.
- van der Wiel, K., and Coauthors, 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrol. Earth Syst. Sci.*, **21**, 897–921, <https://doi.org/10.5194/hess-21-897-2017>.
- Wang, P., J. Tang, X. Sun, S. Wang, J. Wu, X. Dong, and J. Fang, 2017: Heat waves in China: Definitions, leading patterns, and connections to large-scale atmospheric circulation and SSTs. *J. Geophys. Res. Atmos.*, **122**, 10 679–10 699, <https://doi.org/10.1002/2017JD027180>.
- Wang, S. X., and H. C. Zuo, 2016: Effect of the East Asian westerly jet’s intensity on summer rainfall in the Yangtze River valley and its mechanism. *J. Climate*, **29**, 2395–2406, <https://doi.org/10.1175/JCLI-D-15-0259.1>.
- Wang, T., Z. Zhong, Y. Sun, and J. Wang, 2019: Impacts of tropical cyclones on the meridional movement of the western Pacific subtropical high. *Atmos. Sci. Lett.*, **20**, e893, <https://doi.org/10.1002/asl.893>.
- Wei, W., W. Li, Y. Deng, and S. Yang, 2019: Intraseasonal variation of the summer rainfall over the southeastern United States. *Climate Dyn.*, **53**, 1185, <https://doi.org/10.1007/s00382-018-4415-9>.
- WHO, 2014: *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. World Health Organization, 115 pp., <https://apps.who.int/iris/handle/10665/134014>.
- Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences*. Academic Press, 464 pp.
- Willett, K. M., and S. Sherwood, 2012: Exceedance of heat index thresholds for 15 regions under a warming climate using the wet-bulb globe temperature. *Int. J. Climatol.*, **32**, 161–177, <https://doi.org/10.1002/joc.2257>.
- WMO, 2013: The global climate 2001–2010: A decade of climate extremes. World Meteorological Organization Rep. 1103, 119 pp.
- , 2020: Information and public health advice: Heat and health. Accessed 1 April 2020, <https://www.who.int/globalchange/publications/heat-and-health/en/>.
- Wu, B., and T. J. Zhou, 2008: Oceanic origin of the interannual and interdecadal variability of the summertime western Pacific subtropical high. *Geophys. Res. Lett.*, **35**, L13701, <https://doi.org/10.1029/2008GL034584>.
- Wu, L., and C. Wang, 2015: Has the western Pacific subtropical high extended westward since the late 1970s? *J. Climate*, **28**, 5406–5413, <https://doi.org/10.1175/JCLI-D-14-00618.1>.
- Xia, J., K. Tu, Z. Yan, and Y. Qi, 2016: The super-heat wave in eastern China during July–August 2013: A perspective of climate change. *Int. J. Climatol.*, **36**, 1291–1298, <https://doi.org/10.1002/joc.4424>.

- Xiang, B., B. Wang, W. Yu, and S. Xu, 2013: How can anomalous western North Pacific subtropical high intensify in late summer? *Geophys. Res. Lett.*, **40**, 2349–2354, <https://doi.org/10.1002/grl.50431>.
- Xie, Z., Y. Du, and S. Yang, 2015: Zonal extension and retraction of the subtropical westerly jet stream and evolution of precipitation over East Asia and the western Pacific. *J. Climate*, **28**, 6783–6798, <https://doi.org/10.1175/JCLI-D-14-00649.1>.
- Xu, K., R. Lu, B. Kim, J. Park, J. Mao, J. Byon, R. Chen, and E. Kim, 2019: Large-scale circulation anomalies associated with extreme heat in South Korea and southern-central Japan. *J. Climate*, **32**, 2747–2759, <https://doi.org/10.1175/JCLI-D-18-0485.1>.
- Yang, H., and S. Q. Sun, 2003: Longitudinal displacement of the subtropical high in the western Pacific in summer and its influence. *Adv. Atmos. Sci.*, **20** (6), 921–933, <https://doi.org/10.1007/BF02915515>.
- Yang, R., Z. Xie, and J. Cao, 2017: A dynamic index for the westward ridge point variability of the western Pacific subtropical high during summer. *J. Climate*, **30**, 3325–3341, <https://doi.org/10.1175/JCLI-D-16-0434.1>.
- Yeh, S., Y. Won, J. Hong, K. Lee, M. Kwon, K. Seo, and Y. Ham, 2018: The record-breaking heat wave in 2016 over South Korea and its physical mechanism. *Mon. Wea. Rev.*, **146**, 1463–1474, <https://doi.org/10.1175/MWR-D-17-0205.1>.
- Yeo, S.-R., S.-W. Yeh, Y. Won, H. Jo, and W. Kim, 2017: Distinct mechanisms of Korean surface temperature variability during early and late summer. *J. Geophys. Res. Atmos.*, **122**, 6137–6151, <https://doi.org/10.1002/2017JD026458>.
- Yoon, D., D.-H. Cha, G. Lee, C. Park, M.-I. Lee, and K.-H. Min, 2018: Impacts of synoptic and local factors on heat wave events over southeastern region of Korea in 2015. *J. Geophys. Res. Atmos.*, **123**, 12 081–12 096, <https://doi.org/10.1029/2018JD029247>.
- , and Coauthors, 2020: Recent changes in heatwave characteristics over Korea. *Climate Dyn.*, **55**, 1685–1696, <https://doi.org/10.1007/s00382-020-05420-1>.
- Yoon, S.-J., I.-H. Oh, H.-Y. Seo, and E.-J. Kim, 2014: Measuring the burden of disease due to climate change and developing a forecast model in South Korea. *Public Health*, **128**, 725–733, <https://doi.org/10.1016/j.puhe.2014.06.008>.
- Zeng, Z., and Coauthors, 2019: A reversal in global terrestrial stilling and its implications for wind energy production. *Nat. Climate Change*, **9**, 979–985, <https://doi.org/10.1038/s41558-019-0622-6>.
- Zhou, L., and R. Wu, 2015: Interdecadal variability of winter precipitation in Northwest China and its association with the North Atlantic SST change. *Int. J. Climatol.*, **35**, 1172–1179, <https://doi.org/10.1002/joc.4047>.
- Zhou, T. J., and R. C. Yu, 2005: Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. *J. Geophys. Res.*, **110**, D08104, <https://doi.org/10.1029/2004JD005413>.
- , and Coauthors, 2009: Why the western Pacific subtropical high has extended westward since the late 1970s. *J. Climate*, **22**, 2199–2215, <https://doi.org/10.1175/2008JCLI2527.1>.