Impact of local atmospheric circulation and sea surface temperature of the East Sea (Sea of Japan) on heat waves over the Korean Peninsula

Jieun Wie¹ · Byung-Kwon Moon¹ · Yu-Kyung Hyun² · Johan Lee²

Received: 12 November 2020 / Accepted: 27 January 2021 / Published online: 11 February 2021
© The Author(s) 2021

Abstract

South Korea has frequently suffered from heat waves, which are mainly attributable to anomalously prolonged high-pressure systems. There have been many studies regarding the role of large-scale circulation in the Korean Peninsula heatwaves, but the contribution of local-scale circulation and sea surface temperature has not been analyzed. This study investigates the impact of local circulation and sea surface temperature (SST) of the East Sea (Sea of Japan) on the surface temperature variations of the Korean Peninsula. Based on empirical orthogonal function (EOF) analysis of the detrended daily surface temperature anomalies from July to August, 1991–2020, high-temperature days were classified into three categories: high pressure (HP), easterly wind (EW), and both high pressure and easterly wind (HPEW). On EW days, the mean surface temperatures in the western part of the peninsula are 1.75 °C higher than those on the eastern part of the windward side, indicating foehn wind warming on the leeward side. Under the synergistic effects of foehn wind warming and high-pressure anomalies, the surface temperature is the highest on HPEW days. Regression analysis also shows that, when the SST of the East Sea increased by 1 °C, the surface temperatures in the western region on HPEW and EW days increased by 0.36 °C and 0.22 °C, respectively. In contrast, the SST effect in the western region is negligible on HP days owing to the lack of foehn wind warming. Sensitivity experiments using the high-resolution Weather Research and Forecasting (WRF) model also showed that foehn wind warming becomes stronger on EW and HPEW days with warmer East Sea SST. Our results suggest that local circulation and SST are important factors in high-temperature events in the Korean Peninsula.

Keywords Heat wave · Korean Peninsula · Foehn wind warming · Sea surface temperature · The East Sea (Sea of Japan)

1 Introduction

A heat wave is a type of climate disaster characterized by extremely high temperatures, causing harmful effects such as poor human health, increased mortality, reduced agricultural production, and disruptions to power supply (McGregor et al. 2015; Kysely and Kim 2009; Son et al. 2012; Kim et al. 2016). The duration and intensity of heat waves in the Korean Peninsula continue to increase in an environment of global warming, and are expected to further intensify in the future (Stocker et al. 2013; Shin et al. 2018; Min et al. 2020; Kim et al. 2018; Lee et al. 2014; NIMR 2011).

Extended high pressure over the Korean Peninsula is considered to be the large-scale atmospheric condition responsible for heat waves in the Korean Peninsula (Yeo et al. 2019; Kim et al. 2018; Lee et al. 2020a; Kim et al. 2019, 2020). Yeo et al. (2019) analyzed long-term heat wave cases from 1979 to

✉ Byung-Kwon Moon
moonbk@jbnu.ac.kr

Jieun Wie
jenn@jbnu.ac.kr

Yu-Kyung Hyun
yukyung.hyun@gmail.com

Johan Lee
johan.j.lee@gmail.com

¹ Division of Science Education and Institute of Fusion Science, Jeonbuk National University, Jeonju 54896, Korea

² Operational Systems Development Department, National Institute of Meteorological Sciences, Seogwipo 63568, Korea

2017, and identified two types of heat waves caused by high pressure: a zonal wave type with high pressure originating in Europe and reaching East Asia after passing through Eurasia, and a meridional type with high pressure induced in East Asia due to convective activities in the western Pacific subtropical region. The development of high pressure results in persisting clear weather, suppressed atmospheric mixing with weak winds, and adiabatic heating induced by the downward flow, all leading to an increase in surface temperature. Heat waves in the Korean Peninsula can also be linked to high-temperature atmospheric advection, as reported by Yeh et al. (2018), who observed that the heat wave in 2016 was caused by an influx of hot air into the Korean Peninsula due to an increase in geopotential height over the Kamchatka Peninsula.

When high pressure persists over the Korean Peninsula for a long period and creates a favorable environment for a long-lasting heat wave, the sea surface temperature in the nearby ocean may increase; this phenomenon is referred to as a marine heat wave if the temperature is abnormally high (Lee et al. 2020b; Frölicher and Laufkötter 2018). The increased ocean temperature, especially in the upper ocean, promotes ocean stratification and suppresses vertical circulation, causing the upper ocean to act as a location for heat storage and as a heat source. As seen in the heat wave period of 2016, in the case of hot summer weather with a dominant easterly wind, the changing surface temperature is affected by the sea surface temperature in the East Sea/Sea of Japan. The Korean Meteorological Administration (KMA) Climate Information Portal reported that the temperature in the East Sea/Sea of Japan increased by 0.7–2.09 °C at various observation points over the 50 years from 1968 to 2017 (KMA 2020). Both the land surface temperature and the surface temperature of the oceans surrounding the Korean Peninsula increase simultaneously in the global warming scenario, which will likely intensify heat waves over the peninsula. According to the National Institute of Meteorological Sciences (NIMR 2011), the future climate change scenario, RCP8.5, indicates that the rate of increase in sea surface temperature of the East Sea/Sea of Japan will be higher than that of other oceans around the world and the temperature will be 4.5–7.0 °C higher in 2070–2100 compared to 1971–2000.

The geography of the Korean Peninsula features mountain ranges stretching south–north, on the east (Fig. 1). This geographical feature of the Korean Peninsula causes foehn warming, depending on the wind direction, therefore increasing local temperatures on the leeward side. The intensity of a heat wave becomes even stronger when combined with the foehn wind warming (Ma et al. 2014; Yoon et al. 2018; Takane et al. 2017; Chen and Lu 2015). Yoon et al. (2018) analyzed the foehn wind warming in the southeastern part of the Korean Peninsula on heat wave days in 2015 through a Weather Research and Forecasting (WRF) experiment, and reported that the effect predominated at night with an increase

Fig. 1 Elevation distribution (m) of the Korean Peninsula. Red dots are the ASOS observation points. The combined (ALL), western (WR), and eastern (ER) regions are marked in green, red, and blue boxes, respectively

in surface temperature on the leeward side. If easterly wind occurs during a heat wave, the harmful effects of the increased temperature will be more pronounced in the densely populated mid-western part of the peninsula.

The aforementioned studies demonstrate that research on heat waves in the Korean Peninsula has mainly addressed the causes and large-scale atmospheric conditions of heat waves and the role of global warming in intensification of heat waves in the future. Model studies have not been conducted on the advection effect on heat waves as pointed out by Yeh et al. (2018). In particular, no studies have been conducted on the relevance of sea surface temperature in the East Sea/Sea of Japan along the path of advection. No research has been conducted on the heat wave characteristics modified by the local atmospheric circulation and sea surface temperature of the East Sea/Sea of Japan in the Korean Peninsula. Although the foehn effect in the Korean Peninsula has been studied by Yoon et al. (2018), the scope of the study was limited to a very narrow area in the southeastern part of the peninsula over a 1-year period in 2015. Therefore, an analysis of a wider area over a longer period is necessary. In this study, the regional heat wave characteristics in the Korean Peninsula are analyzed in relation to the synoptic and local-scale circulations, in an environment where a heat wave already exists.

The characteristics of regional temperature fluctuations and the corresponding atmospheric conditions in the Korean Peninsula during the summer heat wave periods from 1991

to 2020 were identified in the study. The heat wave processes induced by high pressure and advection were investigated, and the days when these processes appeared either simultaneously or independently were analyzed to understand the correlations of the atmospheric conditions and surface air temperature distribution to the foehn effect during each period. Moreover, assumptions were made regarding the relationship between the sea surface temperature of the East Sea/Sea of Japan and the surface air temperature in the Korean Peninsula, which were verified through high-resolution modeling experiments.

2 Data and methods

2.1 Observation data

In this study, temperature observation data from the Automated Surface Observation System (ASOS) from 1991 to 2020 were used, provided from the Climate Information Portal of the Korea Meteorological Administration (KMA) National Climate Data Center. Seventy-five sites were selected for continuous observation during the analysis periods (Fig. 1). Considering the data quality available due to changes in the observation site locations and replacement of equipment over time, we selected the last 30 years as the longest possible analysis period with the best available data set. Observation points in the vicinity of one other were provided identical point numbers and assumed to represent the same area. The Korean Peninsula is affected by the East Asian summer monsoon, characterized by localized and strong precipitation that typically begins in mid-June and continues through to mid-July. Temperatures are generally lower if precipitation persists throughout the summer, or solar radiation is blocked from reaching the ground by high cloud coverage such as from typhoons, as in the case of 2011 and 2020. To exclude these periods, only days with a positive value of temperature anomaly were analyzed after removing long-term trends and calculating daily anomalies. The total number of days for calculating the daily average surface temperature data in July and August during 1991–2020 was 1860. However, we selected an analysis period that excludes missing data and days with daily anomalies of less than 0, which resulted in a total of 956 days, or 51.40% of the total number of days.

The Korean Peninsula is a mountainous region with mountain ranges concentrated on the eastern side, and is surrounded by oceans in the east, south, and west. Figure 1 shows the distribution of elevation above sea level, provided by the United States Geological Survey (USGS). In this study, the area spanning latitudes 36–38° N was divided along the mountain ranges into the Eastern Region (ER) at longitudes 128.5–129.5° E and the Western Region (WR) at longitudes 126–128° E, for separate analysis. For the analysis of the

overall central area of the Korean Peninsula, the area at longitudes 126–129.5° E was considered without the mountain range boundary, and referred to as “All-Region (ALL)”.

Atmospheric data with a $2.5^\circ \times 2.5^\circ$ resolution were used, including daily 850 hPa geopotential height, wind, and temperature, which was provided by the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis 2 (NCEP2) (Kanamitsu et al. 2002). Moreover, daily Optimum Interpolation Sea Surface Temperature (OISST) data with a $0.25^\circ \times 0.25^\circ$ resolution were used (Reynolds et al. 2007).

2.2 Model and experiments

The WRF model version 4.0 was used to analyze the impact of the changing sea surface temperature of the East Sea/Sea of Japan on summer temperatures in the Korean Peninsula (Skamarock et al. 2019). The model is based on Euler's method for fully compressible non-hydrostatic equations, cast in the form of flux conservation, using vertical mass coordinates. In the model, dry-air thermal mass, velocity, potential temperature, and geopotential height were used as prognostic variables, while the variables that were not conserved, such as temperature, pressure, and density, were diagnosed through the prognostic variables. The Arakawa-C grids were used in this model, while the schemes used in the model were as follows: WRF Single-Moment (WSM) 3-class simple ice scheme for microphysics (Hong et al. 2004), Dudhia scheme for short-wavelength radiation (Dudhia 1989), and rapid and accurate radiative transfer model (RRTM) scheme for long-wavelength radiation (Mlawer et al. 1997). Yonsei University (YSU) scheme for the Planetary Boundary Layer (PBL) (Hong et al. 2006) and the Kain–Fritsch scheme for cumulus parameterization (Kain 2004) were also used.

Three nested domains were used in this study. The largest domain had an 18-km resolution and 180×180 grid, covering East Asia (Fig. 2), and the second nested domain had a 6-km resolution and 180×180 grid, covering the Korean Peninsula and some marine areas. The third, a 180×180 grid with 2-km resolution, encompassing the central part of the Korean Peninsula.

The model consists of 32 vertical layers from the surface up to 50 hPa. The NCEP GDAS/FNL 0.25-degree global tropospheric analyses and forecast grids, from July 15 to August 15, 2018, were used for initial and boundary fields (NCEP 2015). The daily average OISST data with a resolution of $0.25^\circ \times 0.25^\circ$ during the same periods were used for the control (CTL) experiment. Since the model was focused on the fluctuations in sea surface temperature of the East Sea/Sea of Japan, the corresponding marine area between 35 and 45° N and 128–135° E was taken as the basis and the sea surface temperature of the area was raised by 0.5 °C and 1.0 °C. These experiments were named “SST + 0.5” and “SST + 1.0”, respectively.

Fig. 2 Model domain for the 18-km resolution 180×180 grid (outline), 6-km resolution 180×180 grid (d02), and 2-km resolution 180×180 grid (d03)

The duration of the model was 32 days, from July 15 to August 15, 2018, of which the first 2 days (48 h) were considered spin-up hours, while the span from July 17 to August 15, 2018 was the analysis period. Initial and boundary fields with 6-hour intervals, and sea surface temperatures with 1-day interval were applied in the model. The results of the model were calculated at 1-h interval, and averaged on a daily basis or over the analysis period, depending on the analysis method.

3 Results and discussion

3.1 Heat wave characteristics in the Korean Peninsula, 1991–2020

To confirm the heat wave characteristics of the Korean Peninsula, Empirical Orthogonal Function (EOF) analysis was conducted using ASOS surface temperature data (Fig. 3). The daily average temperature data for the July–August period from 1991 to 2020 were used, which were calculated by converting the daily data to daily anomalies, and eliminating trends. Temperature data with positive values were selected to analyze high-temperature cases in summer.

The EOF analysis result indicates that the first mode accounts for 46.4% of the total summer temperature variations, and that the temperature increases across the entire Korean Peninsula. The second mode accounts for 18.1% of the total

summer temperature variations, with increases and decreases concentrating in the western and eastern regions of South Korea. Principal component (PC) time series data were not available for the years 1993, 1999, 2003, 2015, and 2019, implying that there were many days when temperatures were lower than usual.

If an identical analysis as that depicted in Fig. 3 was conducted for all days in July and August during the 30-year timespan without any particular criteria, the total number of analyzed days would be 1832 since only the missing data were excluded. The variations of the first and second modes were 72.4% and 8.1%, respectively; this indicated that the first mode had a significant impact on the surface temperature variation of the Korean Peninsula during summers (Fig. S1). In addition, the same analysis was only conducted for days where standard deviation values of detrended surface temperature anomalies exceeded 1 sigma (Fig. S2); however, to analyze only those values that exceed 1 sigma, the same method was used as that employed to define and select the general days among the heatwave days. The number of analyzed days was 593 in this method. In Fig. S2, the variations for the first and second mode were 36.2% and 22.1%, respectively; the variability of the first mode decreased, while the variability of the second mode increased when compared with those in Fig. S1. As we moved toward cases with higher temperature, the spatial pattern for the surface temperature did not change; however, the variability of the second mode increased. The

Fig. 3 Spatial pattern of **a** the first EOF mode (EOF 1) and **b** the second (EOF 2) for the surface temperature anomalies in the Korean Peninsula from July 1 to August 31 during 1991–2020, and **c** the corresponding PCs. The red and blue lines in (c) indicate PC1 and PC2, respectively.

analyzed days in this study adapt to those with the detrended surface temperature anomalies of over 0. The spatial pattern and the degree of variability assimilate those of Fig. S2, while the number of available days for analysis expanded to 956, representing a 161% increase as compared to the days analyzed in Fig. S2. Because this study uses PC1 and PC2 to reclassify heatwave situations into three types, a substantial number of days are required for analysis to ensure the reliability of the study results. Furthermore, this study discusses the number of heatwave days and the increased heatwave intensity with regard to the easterly wind effect, which occurs in succession during the heatwave that arises after the sea surface temperature increases in the East Sea/Sea of Japan. Thus, it is believed that a variety of days that experience high temperatures as well as heatwaves should be included. Therefore, the analysis period selected in this study is considered to substantially reflect the heatwave days.

Regression analysis was performed on the 850 hPa temperature, geopotential height, wind, and sea surface temperature using two PC time series, to verify the atmospheric variations in relation to the variations in surface temperature pattern in summer (Fig. 4). In the first mode, the 850 hPa temperature increased across the broad area of the East Sea/Sea of Japan at the center. The 850 hPa geopotential height showed high pressures in the area between latitudes 30 and 40° N with the Korean Peninsula and southern Japan at the center. The Korean Peninsula was close to the center of high pressure, hence exhibiting low wind speeds. The sea surface temperature increased in the Japanese coast, East Sea/Sea of Japan, and the Yellow Sea. The combination of temperature, pressure, and sea surface temperature demonstrated in the first

mode is a typical high pressure heat wave pattern observed in the Korean Peninsula.

In the second mode, there appears to be a gradation of the 850 hPa temperature across the Korean Peninsula, with a high value for temperature in the north and a low value for temperature in the south. The pressure distribution also shows high pressure in the north and low pressure in the south, causing a strong easterly wind over the Korean Peninsula. The sea surface temperature was high in the East Sea/Sea of Japan and the Yellow Sea. The second mode replicated an environment under the influence of the strong easterly wind caused by the south–north pressure distribution, where the east–west temperature pattern at the ground level was influenced by the wind. The Korean Peninsula is high in altitude in the east due to the Taebaek Mountain Range and low in altitude in the west (Fig. 1). As the easterly wind passes over the mountain range, the temperature in the western region may increase due to the foehn wind warming. While the 850 hPa pressure distribution in the second mode resulted in a south–north 850 hPa temperature pattern (Fig. 4b), the surface temperature showed an east–west pattern given the Korean peninsula's topography and strong easterly wind (Fig. 3b).

The variations in surface air temperature over the entire Korean Peninsula and across the east–west direction were confirmed through the surface temperature variation mode. The temperature variation across the entire peninsula appeared to be related to high pressure, while the east–west variation pattern was influenced by the easterly wind. This demonstrates the heat wave mechanism reported in previous studies, that involves high pressure over the Korean Peninsula combined with the advection of warm air. The period with

Fig. 4 Regressed distribution of **a, b** temperature (shaded) at 850 hPa, **c, d** geopotential height (shaded) and horizontal wind (vector) at 850 hPa, and **e, f** sea surface temperature on the (left panel) first and (right panel)

second PCs. The black dots indicate statistical significance at the 90% confidence level. All the variables and PC time-series utilized in the analysis are represented at the daily time-scale

dominant high pressure is referred to as “high pressure (HP)”, the period with a dominant easterly wind as “easterly wind (EW)”, and the period affected by both high pressure and easterly wind as “high pressure and easterly wind (HPEW)”. The HP period is defined as the time when PC1 is greater than 1 and PC2 is between -1 and 1 , the EW period is when PC2 is greater than 1 and PC1 is between -1 and 1 , and the HPEW period is when both PC1 and PC2 have values of 1 or more (Table 1).

Table 1 Definitions of HPEW, HP, and EW		
Name	Description	Criteria for PCs
HPEW	High pressure and easterly wind	$1 < PC1, 1 < PC2$
HP	High pressure	$1 < PC1, -1 < PC2 < 1$
EW	Easterly wind	$-1 < PC1 < 1, 1 < PC2$

The composite maps of the 850 hPa temperature, geopotential height, wind, and sea surface temperature for each of the periods are provided in Fig. 5. High pressure is prevalent in the southwestern part of the Korean Peninsula during HP, in the Japanese Islands during HPEW, and in the northeastern part of the Korean Peninsula during EW. Low pressure is prevalent in the East China Sea during both HPEW and EW, subjecting the Korean Peninsula to the influence of a southeasterly wind during HPEW and to an easterly wind during EW, depending on the interaction with the high pressure system. During HPEW and HP, the high pressure is skewed to the eastern region of the Korean Peninsula, and the air temperature and sea surface temperature appear to be high around the East Sea/Sea of Japan. On the other hand, high temperatures are seen in the western region of the peninsula and the Yellow Sea during EW. The HPEW period showed the highest 850 hPa temperature, indicating that the surface temperature is also likely the highest during this period.

The number of days in the HPEW, HP, and EW periods during the major heat wave years, namely 1994, 2016, and 2018, were counted, and are shown in Table 2. These major heat waves have relatively more days chosen for the analysis since there are more heat wave days in these years compared

Table 2 Number of days of HPEW, HP, and EW for major heat wave years and for entire period of study

Name	1994	2016	2018	1991–2020
HPEW	3	0	3	8
HP	7	0	8	26
EW	3	5	6	53

to other years. The total number of days in HPEW, HP, and EW was the highest in 1994 and 2018, exhibiting the longest heat waves. Particularly, the number of HP and EW days was higher in 2018 than in 1994. In 2016, EW days were dominant with no HPEW or HP days. The total number of EW days over the entire period from 1991 to 2020 was about twice as high as that of HP days.

3.2 Heat waves and foehn wind warming in the Korean Peninsula

Considering the characteristics of overall surface air temperature variations in the Korean Peninsula as well as in the east–

Fig. 5 Composite distribution of the 850 hPa air temperature ($^{\circ}\text{C}$, contour, left panel), geopotential height (m, contour, center panel) and wind (m s^{-1} , vector), and sea surface temperature ($^{\circ}\text{C}$, contour, right panel) for the **a–c** HPEW, **d–f** HP, and **g–i** EW days

west direction, larger temperature variations were seen in the east–west direction relative to the mountain ranges stretching in the south–north direction. Therefore, at latitudes 36–38° N, the area at longitudes 126–129.5° E was defined as “ALL,” the area at longitudes 126–128° E as “Western Region (WR),” and the area at longitudes 128.5–129.5° E as “Eastern Region (ER),” as shown in Fig. 1, and the surface temperature histograms for the three regions were analyzed for each period. As shown in Fig. 6, HPEW has the highest average surface temperature, and HP has a higher average temperature than EW in ALL. Similar trends are seen in the WR and ER, with the average temperature difference between the two periods being the greatest at 2.8 °C in the ER. During the HP period, the surface temperature is higher in the ER than in the WR, as shown in Fig. 5, likely because the wind speed is low and the center of the high pressure is skewed to the east. On the other hand, the average temperature in the WR is higher than in the ER during the HPEW and EW periods, unlike the 850 hPa temperature pattern in Fig. 5. The average temperature difference between the WR and ER during the HPEW and EW

periods is 1.05 °C and 1.75 °C, respectively. The foehn warming possibly being the cause for the increased temperatures.

The slight difference between the surface temperature distribution and the 850 hPa temperature distribution during HPEW and EW is likely the result of the local circulation caused by the easterly wind and the topography of the Korean Peninsula. The distribution of surface temperature anomalies at the observation stations was confirmed for each period using the altitude and longitude information of the stations (Fig. 7). The station at longitude 129° E and approximately 750 m in elevation is in Taebaek, which has the highest altitude among all the stations. The station located at 131° E is in Ulleungdo Island in the middle of the East Sea/Sea of Japan and is further away from the peninsula. With the exception of Taebaek and Ulleungdo, the distribution of the stations follows the shape of the mountain range in Fig. 1, with the highest point at longitude 128.4° E, and the eastern slope being steeper than the western slope.

Fig. 6 Histograms of surface temperature at each 0.3 °C interval for **a–c** HPEW, **d–f** HP, and **g–i** EW days in ALL (left panel), the WR (center panel), and the ER (right panel). Mean temperatures for each site and period are shown in the upper left of each graph

Fig. 7 Composite temperature anomaly distributions (°C) at each observation site with longitude and elevation in latitudes from 36 to 38°N for **a** HPEW, **b** HP, and **c** EW days

During the HP period, when the wind effect is small, the temperature increases around latitude 129° E as well as in Ulleungdo and Taebaek. During the HPEW and EW periods, under the influence of easterly winds, the temperature increases significantly on the leeward western slope, especially at longitude 127° E at a low elevation of 200 m. This foehn warming, in which the temperature increases due to wind and topography, causes the WR to be warmer than the ER. Also, if wind and high pressure are prevalent at the same time, the WR is expected to experience even more extreme temperatures.

The easterly wind comes from the East Sea/Sea of Japan during the EW period, given the relative position of the land

and oceans around the Korean Peninsula. Therefore, if the East Sea/Sea of Japan stores a large amount of energy, more heat will be delivered to the Korean Peninsula, and the rate of temperature increase will be greater. Figure 8 shows the scatter diagrams and regression lines of the average detrended sea surface temperature anomalies in the East Sea/Sea of Japan area (36–38° N, 129–135° E) and average surface air temperature in ALL, the WR, and the ER. Most show a positive correlation except the ER during HP. The p value in the upper right corner of each diagram indicates that ALL and the WR during HPEW, and all three regions during EW, show a statistically significant correlation of more than 95%. During the HP period, ALL and the WR do not show a statistically significant correlation, albeit being positive. During HPEW and EW, for every 1 °C increase in sea surface temperature, the temperature in ALL increases by 0.23 °C and 0.18 °C, and the temperature in the WR increases by 0.36 °C and 0.22 °C, respectively.

The different rates of increase in temperature during HPEW and EW in the WR are due to the different number of days and weather conditions associated with each period. While the correlation between the sea surface temperature in the East Sea/Sea of Japan and surface temperature in the WR during HP is not significant, the sea surface temperature may still increase under the influence of high pressure and low wind speed, eventually affecting the surface air temperature if the easterly wind continues to occur. Therefore, additional model experiments are required under the same atmospheric conditions while varying the sea surface temperature, to confirm the effect of the surface temperature of the East Sea/Sea of Japan on the temperature rise in the Korean Peninsula. This experiment will also verify whether the increase in the surface temperature of the East Sea/Sea of Japan will intensify the foehn effect.

3.3 Increases in surface temperature of the East Sea (Sea of Japan) and surface air temperature of the WR in the Korean Peninsula

The effect of the surface temperature of the East Sea/Sea of Japan on the surface air temperature of the Korean Peninsula is likely related to the wind direction, wind speed, and sea surface temperature. To understand the scale of this effect, WRF modeling was performed for 2018 when there was an extended heat wave in the Korean Peninsula. The year 2018 set the record for the longest heat wave period, highest temperature, and the highest average number of tropical nights in recorded weather history. The modeling was performed for the period between July 15 and August 15, and the sea surface temperature was assigned for the same period. The modeling experiment consisted of the control scenario, CTL, and the SST + 0.5 and SST + 1.0 scenarios where the surface temperature of the East Sea/Sea of Japan was increased by 0.5 °C and

Fig. 8 Scatter diagram (red dots) and regression lines (black lines) of detrended sea surface temperature anomalies averaged for the East Sea/Sea of Japan region (36–38 °N, 129–135 °E) and ASOS 1.5-m air temperature anomalies averaged for ALL (left panel), the WR (center

panel), and the ER (right panel); averaged for **a–c** HPEW days, **d–f** HP days, and **g–i** EW days. Slope values (K/K) and *p* values of the regression line for each region and case are shown in the upper right of each graph

1.0 °C, respectively. The first 48 h were considered as a spin-up period, and the analysis was conducted from July 17 to August 15.

In the WRF experiment, the areas with higher temperatures in the Korean Peninsula during the analysis period were the Seoul metropolitan area at 37.5° N and 127° E, and the southern part of the peninsula (Fig. 9). A northeasterly 10-m wind is observed during this period across the Korean Peninsula. The

surface temperature increases around the central area of the Korean Peninsula when the sea surface temperature is increased by 0.5 °C and 1.0 °C. Since the average wind direction during the period is easterly, the increased sea surface temperature of the East Sea/Sea of Japan causes the temperature in the western and southern areas of the peninsula to rise. Considering region-wise, the average surface air temperature of ALL during the analysis period is 14.12 °C, which

Fig. 9 **a** Mean distribution of 2-m temperature ($^{\circ}\text{C}$, contour) and 10-m wind (m s^{-1} , vector) for the period of July 17 to August 15, 2018 in the WRF model. Difference distributions of 2-m temperature between **b** SST + 0.5 and CTL, and **c** between SST + 1.0 and CTL

increases by 0.02°C and 0.18°C when the sea surface temperature is increased by 0.5°C and 1.0°C , respectively; in the WR, the average surface air temperature is 14.41°C , which increases by 0.01°C and 0.16°C when the sea surface temperature is increased by 0.5°C and 1.0°C , respectively.

We conducted additional experiments by increasing the sea surface temperatures of the East Sea/Sea of Japan by 2.0°C , 3.0°C , and 4.0°C , and subsequently analyzing the surface temperature trendlines. Supplemental Fig. S3 shows the analysis of the average surface temperatures and their trendlines in the CTL, SST + 0.5, SST + 1.0, SST + 2.0, SST + 3.0, and SST + 4 experiments for ALL, the WR, and the ER, during the analysis period. As the sea surface temperature increases, the surface temperature of the Korean Peninsula increases linearly; the slopes of the trendlines of ALL, the WR, and the ER are 0.17, 0.14, and 0.22, respectively. The rate of change in the surface temperature induced from a 1°C in the sea surface temperature is 0.17°C for all areas of the Korean Peninsula; this result is similar to the average of ALL (0.18°C), as determined in the study. The result indicates that the surface temperature changes of SST + 0.5 and SST + 0.1 in Table 4 do not originate from the model errors, but from the changes in the sea surface temperature.

Using the PC time series in Fig. 3 and the classification in Table 1, the HPEW, HP, and EW days during the analysis period are categorized as case 1, case 2, and case 3 (Table 3). In case 1, the PC1 and PC2 values are similar. In case 2, PC2 is near zero while PC1 is 1.43. Case 3 is opposite to case 2, with PC1 almost zero and PC2 high.

The daily average temperature and wind distribution for each period are provided in Fig. 10. Case 1 shows an easterly wind and high temperatures in the western and southern regions. The reason for the decrease in the 10-m wind is assumed to be friction. Case 2 shows high temperatures across

a broader area than case 1. While southeasterly winds are dominant in the southwestern region of the Korean Peninsula, the peninsula is also under the influence of low-speed winds since the speed of wind from the East Sea/Sea of Japan area is very low. Case 3 has the lowest temperature compared to the other cases; however, there are localized areas with high temperatures, such as the Seoul metropolitan area and the southeastern coast of the Korean Peninsula. This case exhibits an environment that is affected by northwesterly winds.

The impact of the increased surface temperature of the East Sea/Sea of Japan on the surface temperature of the Korean Peninsula is analyzed under the atmospheric conditions of each case. The center panel in Fig. 10 is the difference in 2-m temperature distributions between SST + 0.5 and CTL, and in the right panel, between SST + 1.0 and CTL. The variation in the 10-m wind speed with the changing sea surface temperature was minimal, and therefore, is not presented here. In case 1, with easterly winds, the temperature increases around the western region, while the entire Korean Peninsula is affected when the sea surface temperature is increased by 1.0°C . In case 2, with minimal effect of winds, the temperature variation is very small compared to case 1, indicating that the changing sea surface temperature of the East Sea/Sea of Japan does not have a significant influence on the surface temperature of the

Table 3 Descriptions of cases considered in this study

	Period (KST)	PC1	PC2	Description
Case 1	Aug 3, 2018	1.26	1.28	HPEW
Case 2	Jul 23, 2018	1.43	0.04	HP
Case 3	Jul 29, 2018	-0.02	1.89	EW

Fig. 10 a Mean distributions of 2-m temperature (°C, contour) and 10-m wind (m s^{-1} , vector) in a Case 1, d Case 2, and g Case 3 in WRF model. Difference distributions of 2-m temperature between b, e, h SST + 0.5

and CTL, and c, f, i between SST + 1.0 and CTL in case 1 (upper panel), case 2 (middle panel), and case 3 (lower panel).

peninsula. In case 3, high temperatures appear around the central region at latitude 37°N with an increase of 0.5 °C in sea surface temperature, and the temperature increases significantly throughout the Korean Peninsula with an increase of 1.0 °C in sea surface temperature.

As shown in Fig. 10, the increase in sea surface temperature affects the entire Korean Peninsula, while an increase in temperature specifically in the western region (leeward side) is only seen in the SST + 0.5 experiment of case 1. To quantify this difference, the average surface temperatures of ALL and the WR are listed in Table 4. The average surface temperature in the CTL experiment is higher in the WR than in ALL, in all three cases. In the SST + 0.5 experiment, no significant changes are seen, except for case 1. While there are areas where the surface air temperature increases, in case 3 (Fig. 10 h), the scale of the temperature increase is small when averaged over the entire region. In case 1, the temperature in the WR is higher than in ALL by 0.02 °C, as shown in Fig. 10b. With sea surface temperature increase of 1.0 °C, the temperature increases by 0.63 °C and 0.74 °C in case 1 and case 3 relative to CTL. However, the differences between ALL and the WR are minimal, and case 3 shows that the increase in temperature in the eastern region is significant based on the higher temperature observed in ALL compared to the WR. Since the increase in surface temperature in the Korean Peninsula occurs regardless of the region, the increase in sea surface temperature does not contribute to the strengthening of the foehn effect but serves as a source of heat. However, combined with the foehn wind warming, the temperature increase in the WR is greater.

As seen in Table 4, the SST + 1.0 experiment in case 3 demonstrated the largest impact on the surface temperature of the Korean Peninsula. The differences in the 2-m temperature, and the vertical distribution of potential temperature at latitude 37°N were identified at 6 h, 4 h, and 2 h before 00KST on July 29, 2018 (July 28, 2018 1500UTC), and falls under case 3. The peninsula was under the influence of a northeast wind before 6 h, and the surface air temperature difference in the interior region had a positive value. The potential temperature increases up to an elevation of about 1500 m above the East Sea/Sea of Japan, and this increase extends to the top of the

mountain ranges in the eastern region of the peninsula. The potential temperature is also high in the western region, where high temperatures appear. Before 4 h, the potential temperature remains high above the East Sea/Sea of Japan, and also increases in the western region beyond the mountain ranges. Before 2 h, the western region shows the highest surface temperature as well as higher potential temperature in the entire Korean Peninsula (Fig. 11).

4 Summary and conclusions

This study confirmed that the advection of heat from the nearby oceans as well as the extended high atmospheric pressure over the peninsula are relevant factors in determining the characteristics of heat wave variations in the Korean Peninsula from 1991 to 2020. In the presence of an easterly wind, the surface air temperature was 1.05–1.75 °C higher in the WR than in the ER due to the foehn wind warming. Also, when the sea surface temperature of the East Sea/Sea of Japan, east of the Korean Peninsula, increased by 1 °C, the surface air temperature of the western region of the peninsula increased by 0.22–0.36 °C as per observed data, and by 0.63–0.74 °C as per the model data. Considering the higher frequency of EW days compared to HP and HPEW days, the advection of warm air was found to be strongly correlated to the high-temperature heat waves in the Korean Peninsula.

Typical heat waves caused by high pressure lead to an increase in surface and sea surface temperatures. The rate of increase of sea surface temperature is lower than that of land given the higher specific heat, light permeability, and vertical mixing of the ocean compared to the land surface. The role of the ocean in reducing the magnitude of the surface temperature variation in the adjacent areas, and the abnormal increase in ocean temperature during a marine heat wave as a result of the atmospheric conditions have been discussed. However, the results of this study indicate that in a heat wave environment associated with high pressure, a large amount of heat may remain in the ocean due to low wind speed. Also, the increase in sea surface temperature increases the temperature of the air over adjacent land as a result of the stratification of the ocean and suppression of vertical mixing. This condition, combined with an incoming wind warmed by the excess heat stored in the ocean, will extend or intensify heat waves in the Korean Peninsula.

According to the global warming scenario, sea surface temperature is expected to increase with surface air temperature, providing conditions favorable for heat waves in the future. According to the IPCC 5th report, East Asia is seeing a relatively rapid increase in sea surface temperatures compared to other coastal areas

Table 4 Daily mean temperature averaged in ALL and the WR in CTL and differences of surface temperature between SST + 0.5 and CTL and between SST + 1.0 and CTL (°C) in case 1, case 2, and case 3

	CTL		SST + 0.5 minus CTL		SST + 1.0 minus CTL	
	ALL	WR	ALL	WR	ALL	WR
Case 1	15.48	16.23	0.22	0.25	0.63	0.63
Case 2	16.32	16.75	−0.05	−0.09	0.09	0.04
Case 3	14.01	14.30	0.06	−0.04	0.74	0.63

Fig. 11 Distributions of 2-m temperature and 10-m wind at **a** 6 h, **d** 4 h, and **g** 2 h before July 29, 2018, 00KST in SST + 1.0 (left panel). Difference distributions of the temperature between SST + 1.0 and CTL at **b** 6 h, **e** 4 h, and **h** 2 h before July 29, 2018, 00KST (middle panel).

Difference distributions of the potential temperature at latitude 37° N between SST + 1.0 and CTL at **c** 6 h, **f** 4 h, and **i** 2 h before July 29, 2018 00KST

(Stocker et al. 2013), implying that the Korean Peninsula could also be subjected to stronger heat

waves. The results of this study suggest that the effects of the surrounding oceans should also be considered as

critical factors in understanding heat waves and temperature changes in the Korean Peninsula.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00704-021-03546-8>.

Author contribution All authors have contributed to the conceptualization of the study. JW and BKM wrote the original draft and prepared the figures. All authors took part in revising the manuscript.

Funding This work was funded by the Korea Meteorological Administration Research and Development Program under Grant KMI2020-01212.

Data availability The KMA's ASOS data, NCEP-DOE reanalysis 2, NOAA OI SST, and NCEP GDAS/FNL datasets are freely available on the web sites (<https://data.kma.go.kr/emmn/main.do>, <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>, <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>, and <https://rda.ucar.edu/datasets/ds083.3>, respectively). The WRF model source code can be download from the internet (<https://www.mmm.ucar.edu/weather-research-and-forecasting-model>).

Code availability Model results are available from the corresponding author upon request.

Declarations

Conflict of Interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Chen R, Lu R (2015) Comparisons of the circulation anomalies associated with extreme heat in different regions of eastern China. *J Clim* 28: 5830–5844. <https://doi.org/10.1175/JCLI-D-14-00818.1>
- Dudhia J (1989) Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J Atmos Sci* 46:3077–3107. [https://doi.org/10.1175/1520-0469\(1989\)046<3077:NSOCOD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2)
- Frölicher TL, Laufkötter C (2018) Emerging risks from marine heat waves. *Nat Commun* 9:650. <https://doi.org/10.1038/s41467-018-03163-6>
- Hong SY, Dudhia J, Chen SH (2004) A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon Weather Rev* 132:103–120. [https://doi.org/10.1175/1520-0493\(2004\)132<0103:ARATIM>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2)
- Hong SY, Noh Y, Dudhia J (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon Weather Rev* 134:2318–2341. <https://doi.org/10.1175/MWR3199.1>
- Kain JS (2004) The Kain-Fritsch convective parameterization: an update. *J Appl Meteorol* 43:170–181. [https://doi.org/10.1175/1520-0450\(2004\)043<0170:TKCPAU>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2)
- Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo JJ, Fiorino M, Potter GL (2002) NCEP-DOE AMIP-II reanalysis (R-2). *Bull Am Meteorol Soc* 83:163–1643. <https://doi.org/10.1175/bams-83-11-1631>
- Kim DW, Deo RC, Chung JH, Lee JS (2016) Projection of heat wave mortality related to climate change in Korea. *Nat Hazards* 80:623–637. <https://doi.org/10.1007/s11069-015-1987-0>
- Kim YH, Min SK, Stone DA, Shigama H, Wolski P (2018) Multi-model event attribution of the summer 2013 heat wave in Korea. *Weather Clim Extrem* 20:33–44. <https://doi.org/10.1016/j.wace.2018.03.004>
- Kim MK, Oh JS, Park CK, Min SK, Boo KO, Kim JH (2019) Possible impact of the diabatic heating over the Indian subcontinent on heat waves in South Korea. *Int J Climatol* 39:1166–1180. <https://doi.org/10.1002/joc.5869>
- Kim HK, Moon BK, Kim MK, Kwon M (2020) Dynamic mechanisms of summer Korean heat waves simulated in a long-term unforced Community Climate System Model version 3. *Atmos Sci Lett* 21: e973. <https://doi.org/10.1002/asl.973>
- Korea Meteorological Administration (2020) Climate change monitoring information. KMA http://www.climate.go.kr/home/09_monitoring/marine/sst_change. Accessed 5 October 2020
- Kysely J, Kim J (2009) Mortality during heat waves in South Korea, 1991 to 2005: how exceptional was the 1994 heat wave. *Clim Res* 38: 105–116. <https://doi.org/10.3354/cr00775>
- Lee JW, Hong SY, Chang EC, Suh MS, Kang HS (2014) Assessment of future climate change over East Asia due to the RCP scenarios downscaled by GRIMs-RMP. *Clim Dyn* 42:733–747. <https://doi.org/10.1007/s00382-013-1841-6>
- Lee HD, Min K-H, Bae JH, Cha DH (2020a) Characteristics and comparison of 2016 and 2018 heat wave in Korea. *Atmos, Korean Meteorological Society* 30:1–15. <https://doi.org/10.14191/Atmos.2020.30.1.001>
- Lee S, Park M-S, Kwon M, Kim YH, Park Y-G (2020b) Two major modes of East Asian marine heatwaves. *Environ Res Lett* 15: 074008. <https://doi.org/10.1088/1748-9326/ab8527>
- Ma H, Shao H, Song J (2014) Modeling the relative roles of the foehn wind and urban expansion in the 2002 Beijing heat wave and possible mitigation by high reflective roofs. *Meteorog Atmos Phys* 123: 105–114. <https://doi.org/10.1007/s00703-013-0289-x>
- McGregor GR, Bassemoulin P, Ebi K, Menne B (Eds.) (2015) Heatwaves and health: guidance on warning-system development. World Meteorological Organization and World Health Organization. <http://dro.dur.ac.uk/28811/1/28811.pdf>
- Min SK, Kim YH, Lee SM, Sparrow S, Li S, Lott FC, Stott PA (2020) Quantifying human impact on the 2018 summer longest heat wave in South Korea. *Bull Am Meteorol Soc* 101:S103–S108. <https://doi.org/10.1175/BAMS-D-19-0151.1>
- Mlawer EJ, Taubman SJ, Brown PD, Iacono MJ, Clough SA (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J Geophys Res Atmos* 102(D14):16663–16682. <https://doi.org/10.1029/97jd00237>
- National Institute of Meteorological Research (NIMR) (2011) Climate change scenarios report 2011 for IPCC Assessment report 5 (AR5). NIMR, South Korea (in Korean) http://www.climate.go.kr/home/cc_data/scenario_report.pdf
- National Centers for Environmental Prediction (NCEP)/National Weather Service/NOAA/U.S. Department of Commerce (2015) updated daily. NCEP GDAS/FNL 0.25 Degree global tropospheric analyses and forecast grids. Research data archive at the National Center for Atmospheric Research, Computational and Information

- Systems Laboratory. <https://doi.org/10.5065/D65Q4T4Z> Accessed 12 September 2020.
- Reynolds RW, Smith TM, Liu C, Chelton DB, Casey KS, Schlax MG (2007) Daily high-resolution-blended analyses for sea surface temperature. *J Clim* 20:5473–5496. <https://doi.org/10.1175/2007JCLI1824.1>
- Shin J, Olson R, An SI (2018) Projected heat wave characteristics over the Korean Peninsula during the twenty-first century. *Asia-Pacific J Atmos Sci* 54:53–61. <https://doi.org/10.1007/s13143-017-0059-7>
- Skamarock WC, Klemp JB, Dudhia J, Gill DO, Liu Z, Berner J, Wang W, Powers JG, Duda MG, Barker DM, Huang X-Y (2019) A description of the advanced research WRF version 4. NCAR Tech. Note NCAR/TN-556 + STR, 145 pp. doi:<https://doi.org/10.5065/1dfh-6p97>
- Son JY, Lee JT, Brooke Anderson G, Bell ML (2012) The impact of heat waves on mortality in seven major cities in Korea. *Environ Health Perspect* 120:566–571. <https://doi.org/10.1289/ehp.1103759>
- Stocker TF et al (2013) Climate change 2013: the physical science basis. In Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). New York, NY: Cambridge University Press.
- Takane Y, Kondo H, Kusaka H, Katagi J, Nagafuchi O, Nakazawa K, Kaneyasu N, Miyakami Y (2017) Foehnlike wind with a traditional foehn effect plus dry-diabatic heating from the ground surface contributing to high temperatures at the end of a leeward area. *J Appl Meteorol Climatol* 56:2067–2079. <https://doi.org/10.1175/JAMC-D-16-0257.1>
- Yeh SW, Won YJ, Hong JS, Lee KJ, Kwon MH, Seo KH, Ham YG (2018) The record-breaking heat wave in 2016 over South Korea and its physical mechanism. *Mon Weather Rev* 146:1463–1474. <https://doi.org/10.1175/MWR-D-17-0205.1>
- Yeo SR, Yeh SW, Lee WS (2019) Two types of heat wave in Korea associated with atmospheric circulation pattern. *J Geophys Res Atmos* 124:7498–7511. <https://doi.org/10.1029/2018JD030170>
- Yoon D, Cha DH, Lee G, Park C, Lee MI, Min KH (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>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.