Dynamic mechanisms of summer Korean heat waves simulated in a long-term unforced Community Climate System Model version 3

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Abstract
We investigate the natural variability of summer Korean heat waves through a long-term (500 year) unforced simulation using the Community Climate System Model version 3. A total of 82 extreme heat wave frequency (HWF) years are identified with positive barotropic geopotential height (GPH) anomalies over the Korean Peninsula. These anomalies represent the most important atmospheric pattern that causes Korean heat waves via adiabatic warming by anomalous subsidence. From a composite analysis of the extreme Korean HWF years, the silk road pattern (SRP) and central Pacific (CP) sea surface temperature (SST) anomalies are selected as the driving factors of extreme Korean heat waves. The positive SRP is a west–east upper-level Rossby wave train from the North Atlantic to East Asia under which positive barotropic GPH anomalies develop over the Korean Peninsula, thereby producing extreme heat waves. The positive SRP is a west–east upper-level Rossby wave train from the North Atlantic to East Asia under which positive barotropic GPH anomalies develop over the Korean Peninsula, thereby producing extreme heat waves. Cold CP SST anomalies induce cyclonic circulation and enhance convection over the subtropical western North Pacific through wind–evaporation–SST feedback, thereby acting as a source of the Pacific–Japan teleconnection pattern. They also cause positive barotropic GPH anomalies over the Korean Peninsula and intensify surface warming.

KEYWORDS
Community Climate System Model version 3, heat waves, natural variability, Pacific–Japan teleconnection pattern, silk road pattern

1 | INTRODUCTION

Heat waves are attracting considerable attention because they pose serious dangers to human life, the economy, and society. South Korea experienced record-breaking heat waves in the summer of 2018. Consequently, 4,526 individuals required medical care, and 48 fatalities occurred (Korea Meteorological Administration (KMA), 2019).

Previous studies examined the relationship between climate variability and Korean heat waves. Lee and Lee (2016) determined that the inter-annual variation of Korean heat waves is modulated by the Pacific–Japan (PJ) teleconnection pattern (Nitta, 1987), a northward propagating Rossby wave train resulting from the enhancement of convective anomalies over the South China Sea. The teleconnection pattern, along with
southerly wind anomalies, induces positive geopotential height (GPH) anomalies over the Korean Peninsula, leading to heat waves in South Korea. Recently, Yeh et al. (2018) investigated the physical mechanism of the extreme heat waves produced over South Korea in August 2016. The study showed that increased GPH over the Kamchatka Peninsula led to atmospheric blocking in the downstream region of the Korean Peninsula that produced anomalously high GPH and persistent positive surface temperature anomalies in Mongolia. The associated northerly winds caused warm advection from Mongolia that resulted in extreme heat waves in Korea during August 2016. Moreover, Kim et al. (2019) analyzed the impacts of thermodynamic forcing over the Tibetan Plateau and Indian subcontinent on the Korean heat waves. They found that diabatic heating over the Indian subcontinent yielded high-pressure anomalies over the Korean Peninsula, causing heat waves via a circumglobal teleconnection (CGT) pattern (Ding and Wang, 2005). Furthermore, sensible heating over the Tibetan Plateau and diabatic heating over northeastern Pakistan and northwestern India modulated significant high-pressure anomalies and Korean heat waves. A study by Yeo et al. (2019) investigated the modulation of most Korean heat waves by two types of waves: zonal and meridional (similar to those suggested by Ding et al., 2011). Similarly, Zhu et al. (2019) showed that extreme high-temperature events in eastern China are modulated by Eurasian and meridional waves. Yeo et al. (2019) characterized zonal waves as large-scale atmospheric waves that move across the Eurasian continent, whereas meridional waves are related to convective anomalies over the subtropical western North Pacific (SubWNP). Both types of waves develop positive GPH anomalies over the Korean Peninsula.

The characteristics of heat waves have dramatically changed over the past few decades; global warming cannot be excluded as a possible cause (IPCC, 2014). Additionally, large-scale climate variability has contributed to these changes. However, because the observation data includes the effects of both natural variability and anthropogenic forcing, it is difficult to determine which factor causes heat waves to arise. Therefore, in this study, we analyze the role of natural variability on Korean heat waves using a long-term simulation model with a fixed CO2 concentration, which is described in more detail in Data S1, Supporting Information. We conduct an unforced CCSM3 simulation over 600 years with a 355 ppmv fixed CO2 concentration, which represents CO2 level in the 1990s, to investigate the natural variability of Korean heat waves. We analyze daily maximum surface temperature (Tmax), GPH, wind, and sea surface temperatures (SST) from the simulated data over the last 500 years (model year range of 101–600).

2.2 | Observed and reanalysis datasets

This study utilizes the hourly-observed temperature dataset from 1982 to 2018 at 45 KMA stations. To investigate the large-scale climate variability associated with Korean heat waves, we use the daily Tmax and GPH data from the National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis version 1 with 2.5° longitude × 2.5° latitude horizontal resolution (Kalnay et al., 1996).

2.3 | Heat wave frequency index

The KMA defines the heat wave frequency (HWF) index as the number of days (more than two consecutive) per year with a daily Tmax during June–August (JJA) higher than the 33°C threshold (e.g., Lee and Lee, 2016). The threshold corresponds to the 90th percentile of the observed daily Tmax during the 1981–2010 climatological period (Yeh et al., 2018).

However, the simulated daily Tmax is produced as a grid format; therefore, we cannot directly apply the observed threshold to our simulation. Although the observed and reanalysis datasets have substantially different thresholds (Data S2), we identify the high correlation of HWF indices between them (Figure S1; r = .89).

Based on these results, we compute the 90th percentile threshold of the simulated daily Tmax during JJA for a representative area of the Korean Peninsula (i.e., 34°–38°N, 125°–130°E) over 500 years to be 26.53°C. The simulated HWF index is then obtained as the number of days per year with a simulated daily Tmax during JJA higher than 26.53°C (Figure S2).

3 | RESULTS

3.1 | Characteristics of the Korean heat waves

A one standard deviation threshold for the simulated HWF index is used to select 82 years with extreme
Korean HWF to understand the characteristics of the Korean heat waves in the simulation model.

Figure 1a,b shows composite maps of the 200 and 850-hPa GPH anomalies for the selected extreme Korean HWF years used in the simulation. The positive GPH anomalies at 200 and 850 hPa over the Korean Peninsula are evident and indicate a barotropic structure which can be related to extreme Korean HWF years. The barotropic GPH anomalies are produced through adiabatic heating caused by anomalous downward motion (Figure S3). High Tmax and low-precipitation anomalies induced by barotropic structures appear concurrently in the East Asian region including the Korean Peninsula (Figure 1c, d).

An upper-level west–east wavelike pattern in the mid-latitude Northern Hemisphere is another feature of the simulated Korean heat waves (Figure 1a). This wavelike pattern, known as the Silk Road pattern (SRP), propagates from the North Atlantic (NA) to East Asia along the westerly jet (Lu et al., 2002; Enomoto et al., 2003) and is considered the Eurasian component of the CGT pattern (Ding and Wang, 2005; Hong et al., 2018). In both the observed and reanalysis datasets, the heat waves show barotropic structures and wavelike patterns (Figure S4). These results indicate that the simulation model reflects the observed features of Korean heat waves.

In contrast, the composite map of GPH anomalies at 850 hPa shows a slight difference between the simulation and the observed/reanalysis dataset. Significant negative convective anomalies are located in SubWNP (Figure S4b) in the observed/reanalysis dataset, whereas no significant signal is apparent over the SubWNP in our simulation (Figure 1b). This is because the convective anomalies over the SubWNP are intimately related to the negative CP SST anomalies in our simulation, which will be discussed in section 3.4.

### 3.2 | Potential factors affecting the Korean heat waves

As stated above, the Korean heat waves are closely associated with the SRP. The SRP fluctuates on an interannual time scale and has a barotropic structure with significant circulation anomalies reaching the lower troposphere, which can modulate East Asian climate variability (Wang and He, 2015) such as the East Asian summer monsoon rainfall (Huang et al., 2011). Hence, the SRP is chosen as the first potential factor affecting Korean heat waves. We perform an empirical orthogonal function analysis of the JJA mean meridional wind anomalies at 200 hPa over (20°–60°N, 0°–150°E); its leading mode in the simulation is defined as the SRP (Figure S5; Yasui and Watanabe, 2010). Additionally, the SRP index is obtained from the inter-annual time series of the first principal component.

To explore other potential factors affecting Korean heat waves, we perform a composite analysis of the SST anomalies for the extreme Korean HWF years in our

**FIGURE 1** Composite maps of JJA mean (a) 200 and (b) 850 hPa GPH (shaded; m) anomalies for the selected extreme Korean HWF years. (c, d) Same as (a) with the exception of Tmax (shaded; °C) and precipitation (shaded; mm·day⁻¹) anomalies, respectively. The contours represent statistically significant areas satisfying the 99% confidence level through Student’s *t* test.
simulation (Figure 2). The simulated extreme Korean HWF years are associated with remote SST variability and have strong signals in the central Pacific (CP), NA, and near the Korean Peninsula. Park and Schubert (1997) showed that mid-latitude SST anomalies are primarily a response to atmospheric forcing. Therefore, warm SST anomalies over the area adjacent to the Korean Peninsula can be considered a response to the barotropic structure-inducing Korean heat waves. Additionally, previous studies showed a relationship between mid-latitude teleconnections in the Northern Hemisphere and NA SST anomalies (and/or oscillations over the Atlantic; Choi et al., 2020; Lim and Seo, 2019). The SRP is one of the Northern Hemisphere mid-latitude teleconnections; therefore, we exclude the NA SST anomalies from potential factors affecting the Korean Peninsula to ensure the independence of each potential factor. To consider these points, we select CP SST anomalies as the second factor potentially affecting Korean heat waves. The CP index is defined as the CP SST anomaly averaged over the region \(5^\circ\text{C} - 15^\circ\text{C}, 160^\circ\text{W} - 150^\circ\text{E}\).

As Supporting Information, the selected two indices have no significant relationships over the total analysis period \((r = -0.08)\).

### 3.3 Dynamic mechanism of the SRP

Figure 3a,b shows regressed maps of the 200 and 850-hPa GPH anomalies versus the SPR index obtained from our simulation. Positive barotropic GPH anomalies appear over the Korean Peninsula. Furthermore, there is a very strong relationship between the simulated HWF and SRP indices \((r = 0.64, p < .001)\).

The simulated SPR is characterized by positive GPH anomalies over NA and northern Europe \((50^\circ - 70^\circ\text{N}, 0^\circ - 15^\circ\text{E})\), the Middle East \((30^\circ - 50^\circ\text{N}, 45^\circ - 75^\circ\text{E})\), and East Asia \((30^\circ - 50^\circ\text{N}, 100^\circ - 140^\circ\text{E})\) and by negative GPH anomalies over central and eastern Europe \((40^\circ - 60^\circ\text{N}, 15^\circ - 40^\circ\text{E})\) and Mongolia \((30^\circ - 50^\circ\text{N}, 75^\circ - 100^\circ\text{E})\;\text{Figure 3a)}).

To investigate the SPR propagation, we used a two-dimensional wave activity flux (WAF) and stream function \((\Psi)\), as suggested by Takaya and Nakamura (2001): where \(W\) is the WAF, \(p\) is the normalized pressure, \(U\) (\(V\)) is the zonal (meridional) basic flow, \(\lambda\) (\(\phi\)) is the longitude (latitude), and \(a\) is the radius of the earth.

Figure 3c shows the composite map of 200 hPa WAF and the stream function in JJA for selected positive SRP phases, where the selection is a normalized SRP index larger than one standard deviation. The WAF is

**FIGURE 2** Composite map of JJA mean SST (shaded; °C) anomalies for the selected extreme Korean HWF years. The contours represent statistically significant areas satisfying the 99% confidence level through Student’s \(t\) test. The purple box indicates the CP index region.
generally directed eastward over NA and northern Europe with a positive stream function. Meanwhile, the direction of the WAF persists in the East Asian region with a positive stream function. The East Asia part of the SRP has a distinct barotropic structure with positive GPH anomalies (Figure 3d), which leads to extreme Korean heat waves.

The baroclinic GPH anomalies over the Middle East are closely related with the enhanced convective anomalies over the same region (figure not shown) and may be associated with the Indian summer monsoon that can play an important role in driving SRP (Ding and Wang, 2005; Yeo et al., 2019).

Quantitative results of the SRP on extreme Korean HWF years are investigated calculating the co-occurrence years between the extreme Korean HWF years and positive SRP phases. Consequently, approximately 55% (45/82) of the extreme Korean HWF years occurred during positive SRP phases (Table 1). Additionally, the mean extreme HWF (33.60 days) associated with positive SRP phases is 9% higher than that of the selected extreme Korean HWF years (30.78 days, Table 1).

### 3.4 Dynamic mechanism of the CP SST anomalies

We use composite difference analysis to investigate the dynamic mechanism of the CP SST anomalies for the extreme Korean HWF years in the simulation model.

![Composite maps](image)

**FIGURE 3** Regressed JJA mean (a) 200 and (b) 850 hPa GPH anomalies (shaded; m) against the SRP index. Composite map of (c) 200 hPa WAF (vector; m² s⁻¹) / stream function (shaded) and (d) vertical profile of GPH anomalies for the selected positive SRP phases. The GPH anomalies in (d) are meridional averages over (30°–50° N; purple box). The contours represent statistically significant areas satisfying the 99% confidence level through Student’s t test.

|               | +HWF | +HWF &+SRP | +HWF &−CP | +HWF &+SRP &−CP |
|---------------|------|------------|------------|----------------|
| # of years    | 82   | 45         | 23         | 15             |
| Mean HWF      | 30.78| 33.60      | 32.70      | 36.07          |

**Note:** The symbol “&” represents the co-occurrence year of indices; +HWF indicates the selected extreme Korean HWF years; +SRP represents positive SRP phases; −CP denotes negative CP phases.
We divide the CP index into positive and negative phases using standard deviation thresholds of 1.0 and −1.0, respectively. The selected positive and negative phases correspond to 103 and 93 years, respectively. Figure 4a,b shows the composite difference maps of the 200 and 850 hPa GPH and wind anomalies between the negative and positive CP phases. Zonally elongated positive barotropic GPH anomalies and anticyclonic circulation are clearly apparent over the Korean Peninsula. Additionally, negative barotropic GPH anomalies are located over the SubWNP (Figure 4a,b). The north-south dipolar barotropic structures correspond to the PJ teleconnection pattern. This pattern results from the anomalous convective anomalies over the SubWNP, which can act as the source of a northward-propagating Rossby wave train.

The negative CP phases are concurrent with the positive GPH anomalies and anticyclonic circulation over the northwestern part of the negative SST forcing (Figure 4b; Gill, 1980), which decreases trade winds. The weakening of trade winds increases the SST anomalies over the SubWNP because of reduced evaporation and entrainment surface cooling, causing low GPH and convective anomalies over the SubWNP. This series of processes, proposed by Wang et al. (2000), is well known in wind–evaporation–SST (WES) feedback.

The PJ teleconnection pattern induced by CP SST anomalies is confirmed by the composite difference maps

![Composite difference maps of JJA mean (a) 200 and (b) 850 hPa GPH (shaded; m) and wind vector anomalies between negative and positive CP phases. (c–e) Same as (a) with the exception of OLR (shaded; W m−2), omega (shaded; 10−2 Pa s−1), and SST (shaded; °C) anomalies, respectively. The omega anomalies are averaged over 115°–140°E. Contours and vectors represent statistically significant areas satisfying the 99% confidence level through Student’s t test](image)
of outgoing longwave radiation (OLR) and vertical motion. The cold CP phases generate strong negative OLR anomalies over the SubWNP (Figure 4c), which drive a PJ teleconnection pattern source with significant upward motion (Figure 4d). The wave train propagates to higher latitudes and produces positive OLR anomalies in the mid-latitudes, including the Korean Peninsula (Figure 4c), with downward motion (Figure 4d). Consequently, the positive OLR anomalies and downward vertical motion produce adiabatic warming and lower precipitation over the Korean Peninsula, thus increasing the heat wave frequency.

The composite difference in SST anomalies between negative and positive CP phases is shown in Figure 4e. We confirm the presence of a tripolar SST pattern with alternating signals from near the Tropics to the mid-latitudes, with positive values over the Philippine Sea, negative values over the East China Sea, and positive values in the vicinity of the Korean Peninsula. This pattern is intimately associated with the PJ teleconnection (Lee and Lee, 2016).

We investigate the co-occurrence years between extreme Korean HWF years and negative CP phases for the quantitative analysis. Approximately 28% (23/82) of the extreme HWF years in Korea occur during negative CP phases (Table 1). Thus, the mean HWF of extreme heat waves (32.70 days) is 6% higher than that of selected extreme Korean HWF years (30.78 days, Table 1). The HWF index is also significantly correlated with the CP index ($r = -0.19$, $p < 0.001$).

4 | SUMMARY AND DISCUSSION

This study investigates the two dynamic mechanisms of Korean heat waves using an unforced 500-year CCSM3 simulation with a fixed CO$_2$ concentration of 355 ppmv. Eighty-two years are selected as extreme Korean HWF years using a standard deviation threshold of 1.0. Positive barotropic GPH anomalies over the Korean Peninsula commonly appeared in the extreme Korean HWF years in our simulation and in previous studies based on observation data (e.g., Kim et al., 2019). This atmospheric pattern results in persistent subsidence and adiabatic warming with increased atmospheric stability, which can cause severe Korean heat waves.

SRP and CP SST anomalies are identified as factors modulating extreme Korean HWF years with a composite analysis (Figures 1a and 2). The positive SRP phases show a west–east Rossby wave train starting in NA and moving to East Asia (Figure 3). Consequently, anticyclonic circulation and positive GPH anomalies increase the frequency of Korean heat waves.

The negative CP SST anomalies produce negative GPH anomalies and cyclonic circulation over the Sub-WNP through WES feedback, which plays a crucial role in the propagation of the Rossby wave to higher latitudes. Wave propagation is accompanied by vertical motion and convective anomalies along the wave path. Consequently, positive GPH anomalies with downward motion and adiabatic heating lead to Korean heat waves (Figure 4).

Notably, under the effects of positive SRP and negative CP SST anomalies (36.07 days), the HWF is significantly higher than in any of the extreme HWF years (30.78 days, Table 1).

Our results show that the Korean heat waves in our simulation are more influenced by the SRP than by CP SST anomalies. In contrast, Yeo et al. (2019) showed that the formation Korean heat waves in the observation/reanalysis dataset are more spurred by M-waves similar to the PJ teleconnection pattern than by Z-waves, which are analogous to the SRP. Z-waves and M-waves were the dominant modes modulating Korean heat waves before and after 1995, respectively (fig. 4 in their study). Additionally, East Asia is severely affected by heat waves and associated mechanisms that are amplified by climate variability including ENSO (Luo and Lau, 2019) and the Arctic anomaly (Wu and Francis, 2019). Because Korea belongs to East Asia, the features of heat waves in Korea can be changed by climate variability, which will be the subject of further studies using a long-term simulation model.

Anthropogenic forcings are crucial factors that modulate heat waves and change the intensity, frequency, and duration of Korean heat waves. However, the roles of atmospheric and oceanic variability on heat waves over Korea were not analyzed for a warmer climate. This topic is very important and will be examined in our future research using an additional long-term model simulation forced by increasing the CO$_2$ concentration.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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