Decadal Changes in the Interannual Variability of Heat Waves in East Asia Caused by Atmospheric Teleconnection Changes

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ABSTRACT

The heat wave in East Asia is examined by using empirical orthogonal function analysis to isolate dominant heat-wave patterns in the ground-based temperature observations over the Korean Peninsula and China and related large-scale atmospheric circulations obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis 1 during 1973–2012. This study focuses particularly on the interannual variability of heat waves and its decadal change. The analysis identifies two major atmospheric teleconnection patterns playing an important role in developing typical heat-wave patterns in East Asia—the Scandinavian (SCAND) and the circumglobal teleconnection (CGT) patterns, which exhibit a significant decadal change in the interannual variability in the mid-1990s. Before the mid-1990s, heat-wave occurrence was closely related to the CGT pattern, whereas the SCAND pattern is more crucial to explain heat-wave variability in the recent period. The stationary wave model experiments suggest an intensification of the SCAND pattern in the recent period driven by an increase in land–atmosphere interaction over Eurasia and decadal change in the dominant heat-wave patterns in East Asia.

1. Introduction

The heat wave is an extreme heat event. The heat wave in 2003 in Europe caused approximately 35 000 deaths (Larsen 2003), and in Russia a heat wave in 2010 claimed approximately 55 000 lives (Barriopedro et al. 2011). In East Asia, a record-breaking heat wave and drought occurred, with total deaths of more than 3000 in the Korean Peninsula in 1994 (Kysely and Kim 2009). China also experienced fatal heat-wave events in 1998

(Tan et al. 2007), 2003 (Huang et al. 2010), and 2013 (Sun et al. 2014). These extreme heat waves have shown an increase in intensity and frequency that is due to global warming (Hansen and Sato 2012; Trenberth and Fasullo 2012; Meehl and Tebaldi 2004).

Understanding the fundamental mechanisms of and the circumstances for the development of major heat waves is important to improve prediction skills and provide early warnings to the public. Heat waves can develop due to any local or regional process. For example, a region of strong atmospheric subsidence tends to increase the surface temperature through enhanced radiation under a clear sky (Takane et al. 2014). The foehn wind can be significant over the downslope region of a mountainous area (Takane and Kusaka 2011). Recently,

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urbanization and increased man-made surfaces tend to decrease surface albedo and play an important role in developing heat waves in major cities (Ma et al. 2014).

Previous studies also suggested the significant role of large-scale atmospheric circulation. For example, Park and Schubert (1997) suggested that the upper-tropospheric anticyclone over the Tibetan Plateau was associated with the 1994 heat wave in South Korea. Another study suggested that heat waves are affected by tropical forcing—for example, through the Pacific–Japan (PJ) pattern (Nitta 1987; Lee and Lee 2016) and the expansion of the North Pacific subtropical high (Park and Schubert 1997). Liu et al. (2019) also examined the relationship between the west Pacific (or North Pacific) subtropical high (WPSH) variability and the number of heat-wave days in East China. According to previous studies, major extreme heat-wave events seem to be closely related to persistent upper-level anticyclonic anomalies. For example, the European heat wave in 2003 was due to persistent atmospheric circulation anomalies during summer with dry soil moisture on a continental scale (Fischer et al. 2007). The other case is the Russian heat wave in 2010, which was mainly affected by the anomalous blocking events over western Russia. Moreover, the Russian heat wave was accompanied by extreme flood events in Pakistan. These simultaneous extreme events seem to be affected by large-scale atmospheric circulation along a Rossby wave train (Lau and Kim 2012). This indicates that understanding the atmospheric teleconnection associated with heat wave is necessary to explain extreme heat-wave mechanisms.

The atmospheric teleconnection patterns have been well recognized in previous literature, particularly during winter (Branstator 2002; Thompson and Wallace 1998; Wallace and Gutzler 1981; Barnston and Livezey 1987). Recently, the teleconnection pattern in summer has also been considered important concerning midlatitude weather and climate variability. In particular, the teleconnection patterns originating from the North Atlantic Ocean and Europe show a clear signal of propagation to East Asia (Schubert et al. 2011). Deng et al. (2019) also pointed out the important role of the North Atlantic Oscillation and the North Atlantic–Eurasian teleconnection (AEA) for the interannual variability of heat waves over China. While the aforementioned studies addressed the teleconnections associated with extratropical climate variability, other studies suggested the patterns developed due to tropical origins. For example, Ding and Wang (2005) suggested the circumglobal teleconnection (CGT) pattern associated with the Indian summer monsoon convection anomalies and El Niño–Southern Oscillation (ENSO). The Pacific–East Asia teleconnection suggested by Wang et al. (2000) also linked the East

Asian summer monsoon variability with the ENSO teleconnection.

The number of heat-wave days in East Asia is also closely linked with the interannual variability of East Asian monsoon. Early cessation of the summer monsoon is in general followed by prolonged drought conditions and extended hot days. Therefore, the teleconnection patterns known to have profound impacts on East Asian summer monsoon variability are worthy of a more in-depth investigation to understand the dynamical mechanisms of heat waves in East Asia. Lin (2014) identified four teleconnection patterns that are related to monsoon precipitation in East Asia, including the Polar–Eurasia, Scandinavia (SCAND), east Atlantic–western Russia, and CGT patterns. However, it is argued that the mechanisms for the heat wave in East Asia should be examined separately from the monsoon precipitation period, typically from late May to early July, because heat wave usually occurs in peak summer (July–August). Not every pattern in the above seems to be linked with the heat waves developing in peak summer, and only a few studies examine heat-wave mechanisms separately from summer monsoon. Therefore, this study focuses on the dominant teleconnection patterns responsible for East Asian heat waves in peak summer.

Atmospheric teleconnection patterns associated with the heat waves may have not only interannual but also pronounced decadal variability, although relatively little attention was paid to the latter. There exist a couple of pronounced sources of decadal variability such as the Pacific decadal oscillation (PDO; Mantua et al. 1997) and the Atlantic multidecadal oscillation (AMO; Schlesinger and Ramankutty 1994) that presumably affect the decadal changes in the interannual variability of heat waves. Also, expedited global warming in the recent decades due to elevated greenhouse gas forcing should have a profound impact on the heat-wave development, although previous studies had difficulty in separating anthropogenic signal from the natural variability due to insufficient data and limited analysis period.

A handful of studies examined the decadal variability of heat waves in East Asia. The long-term variability of the heat wave in East Asia is related to the sea surface temperature (SST) variability over the North Atlantic Ocean, according to Xia et al. (2016). They separated heat-wave strength and duration in Shanghai into the nonlinear secular trend and climatic multidecadal variability component for the period 1873–2013. The climatic multidecadal variability identified in that study is similar to the variability of the AMO, indicating its significant role for the long-term variation of the heat waves. On the other hand, numerous studies have suggested that the climate variability in East Asia has

shown a regime shift in the mid-1990s (Yang and Yuan 2014; Kang et al. 2014), which could affect the decadal change in the interannual variability of heat waves.

Recently, Liu et al. (2019) also investigated the decadal change in the heat-wave days in East China based on the long-term analysis for 1959–2016. In their study, the interannual variation of heat-wave days shows a strong positive correlation with the WPSH intensity during the positive PDO phase. They attributed it to the more westward extension by stronger WPSH in El Niño decaying summer. Interestingly, they also indicated that the relationship depends on the PDO phase and it disappears in the negative PDO phase. Considering the summer PDO index that has been negative since the mid-1990s on the decadal time scale, there should be another mechanism other than ENSO that may explain the interannual variability of heat waves in East Asia in recent years.

In this study, the long-term variability and interannual variability of heat-wave pattern are examined for East Asia over 40 years (1973–2012) and the relationship between heat waves and large-scale atmospheric circulations are studied. Particularly, the primary atmospheric circulation patterns that modulate the interannual variability of the heat wave is compared for the “early period” (1973–93) and the “recent period” (1994–2012). This study further investigates the important mechanisms that drive the atmospheric circulation changes between the early and the recent periods, with a specific focus on examining recent changes in land surface conditions and their impacts on large-scale atmospheric teleconnection patterns. The results might answer the unaddressed question of what mechanisms are responsible for the interannual variability of heat waves in East Asia at the weakening of the ENSO influences in the recent period suggested by Liu et al. (2019).

This paper consists of the following sections. Section 2 introduces the data and method used in this study, and section 3 shows the spatial and temporal variability of the heat wave in East Asia with the decadal change in interannual variability. Section 3 also discusses the possible mechanisms for the decadal change using data analysis and simple numerical model experiments. Last, a summary is presented in section 4.

2. Data and method

a. Data

In this study, three observation-based datasets are combined for the daily maximum temperature over East Asia. The maximum temperature over China is obtained from 0.25 gridded daily meteorological variable infiltration

capacity forcing dataset (Zhang et al. 2014). This gridded dataset is interpolated from 756 ground monitoring stations of the Chinese Meteorological Administration (CMA). The temporal coverage is from January 1952 to December 2012. The daily maximum temperature over the Korean Peninsula is also obtained from the ground station with an Automated Surface Observing System of the Korean Meteorological Administration (KMA). For matching the periods, 61 stations in South Korea and 13 stations in North Korea are selected. This dataset covers data from 1973 to the present.

The geopotential height, wind and surface heat flux data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1 data are used to examine atmospheric teleconnection patterns (Kalnay et al. 1996). The NCEP–NCAR Reanalysis 1 data have a horizontal resolution of 2.5° longitude/latitude global grids and 17 pressure levels. Relative to other datasets, this reanalysis dataset has a long coverage of more than 40 years. This study uses the NCEP–NCAR Reanalysis 1, because it is the only reanalysis that covers the period before 1979. Although it may have large uncertainty in the continental inland area where in situ observations are sparse and poorly assimilated, there is an overall agreement in the seasonal-mean climatology patterns of soil moisture and sensible and latent heat fluxes when compared with other global reanalyses for the overlapping period since 1979 (not shown).

SST is obtained from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) for related oceanic variation, which has a horizontal resolution of 1° (Rayner et al. 2003). Snow cover is estimated from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record for Northern Hemisphere Snow Cover Extent, version 1 (Robinson and Estillow 2012). It covers the monthly snow cover for the Northern Hemisphere from October 1966 to the present.

The AMO index is obtained from the NOAA/Earth System Research Laboratory Physical Science Division (Enfield et al. 2001). The AMO index is calculated from an area-weighted average over the North Atlantic (0°–70°N) by using the Kaplan SST dataset (https://www.esrl.noaa.gov/psd/data/gridded/data.kaplan_sst.html; Kaplan et al. 1998) with 5° × 5° latitude–longitude grids, which is subsequently detrended and smoothed over 121 months.

b. Method

In East Asia, the definition of a heat wave is different in each country and region. For example, KMA (the heat-wave definition is available at https://web.kma.go.kr/eng/weather/forecast/standard_warning_info.jsp) considers maximum temperature exceeding 33°C for two successive

days as a heat wave, and according to CMA (the heat-wave definition is available at http://www.cma.gov.cn/en2014/weather/Warnings/WarningSignals/201409/t20140919_261774.html) it is 35°C. In this study, heat-wave days (HWD) are defined as the total number of hot days on which the daily maximum temperature exceeds a threshold determined as the 90th percentile of the June–August daily maximum temperature distribution for 1973–2012. From this definition, consecutive hot days during one heat-wave event can contribute to increasing HWD so that the index reflects not only the frequency of heat waves but also their duration. By definition, there are approximately 6.7 HWDs for July–August in the climatological-mean sense. The absolute threshold of 29°C is applied in the region where the 90th-percentile value is below 29°C. This value of 29°C is adopted by Ye et al. (2014).

To separate the decadal signal and interannual variability, 8-yr low-pass-filter and high-pass-filter data are considered, respectively. The low-pass-filtered HWD is considered as the decadal variability of HWD, and the high-pass-filtered HWD (HF-HWD) is considered as the interannual variation of HWD. The period is also separated as “early” (1973–93) and “recent” (1994–2012) to investigate the decadal change in heat-wave variability.

Following Lee and Lee (2016), empirical orthogonal function (EOF) analysis is performed to obtain the dominant spatial patterns of heat-wave variability. Each corresponding principal component (PC) time series is used as the heat-wave index that represents the interannual variability of heat-wave days.

The wave activity flux (WAF) is used to show the spatial distribution of wave propagation. The WAF is calculated following Plumb’s (1985) method. The horizontal WAF is given as

$$F_x = \frac{p \cos \phi}{2a^2 \cos^2 \phi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \quad \text{and} \quad (1)$$

$$F_y = \frac{p \cos \phi}{2a^2 \cos \phi} \left(\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right). \quad (2)$$

The variables p , ψ' , ϕ , and λ represent pressure, streamfunction, latitude, and longitude, respectively. The constant a is the radius of Earth. Using WAF is an effective way to analyze wave propagation on a monthly to seasonal time scale (Lim 2015).

To investigate the decadal changes in the land–atmosphere interaction, the residual diabatic heating rate is calculated following Chan and Nigam (2009), which is given in vertical pressure p coordinates as

$$\overline{Q}(x, y, p, t) = \frac{\Delta T}{\Delta t} + \nabla \cdot \nabla T + \left(\frac{p}{p_0} \right)^{R/C_p} \overline{\omega} \frac{\partial \overline{\theta}}{\partial p} + \left(\frac{p}{p_0} \right)^{R/C_p} \left[\nabla \cdot \nabla' \theta' + \frac{\partial (\omega' \theta')}{\partial p} \right]. \quad (3)$$

The variable Q is the diabatic heating rate (K day^{-1}), T is the temperature, ∇ is the horizontal wind vector, ω is the vertical motion or pressure velocity (Pa s^{-1}), and the potential temperature is $\theta = T(p_0/p)^{R/C_p}$. The constants are $p_0 = 1000 \text{ hPa}$, $R = 287 \text{ J kg}^{-1} \text{ K}^{-1}$, and $C_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$. The overbar indicates the monthly mean, and the prime indicates the deviation of the 6-hourly data from the monthly mean.

The stationary wave model (SWM; Ting and Yu 1998; Lim 2015) is used in section 4 to simulate the atmospheric teleconnection pattern and test the hypothesis of upper-level teleconnection amplification in the recent period. The model is a fully nonlinear, baroclinic model with a dry dynamical core only. This spectral model has the rhomboidal 30 (R30) truncation (roughly equivalent to $2.25^\circ \times 3.75^\circ$ in latitude $\times$ longitude) in horizontal space, and 14 vertical levels in sigma coordinates. The model includes Rayleigh friction and Newtonian cooling terms for damping in the momentum and temperature equations. For further details of the model, see Ting and Yu (1998) and Lim (2015).

The stationary wave solutions are obtained by integrating the model with idealized forcing terms for diabatic heating and transient vorticity. To reproduce the observed SCAND-like pattern, this study uses a sine-squared $10^\circ \times 30^\circ$ latitude–longitude transient vorticity forcing pattern imposed over the North Atlantic with a vertical profile of maximum at 250 hPa. Additional diabatic heating pattern is imposed to the model in western Russia over $10^\circ \times 10^\circ$ latitude–longitude grids to represent the recent drying land surface conditions and increased sensible heat fluxes in the region. The idealized diabatic heating has a vertical profile with the maximum at the surface and gradually damped in the vertical, mimicking the diabatic heating profile obtained from the reanalysis.

3. Results

a. Spatial and temporal variability of heat waves in East Asia

The surface elevation over East Asia is shown in Fig. 1a. East Asia includes the Tibetan Plateau, where the elevation is higher than 4000 m. The rest of the region has a lower elevation of less than 1500 m. Figure 1b shows the climatology of daily maximum temperature during peak summer for 1973–2012. South Korea (SK),

FIG. 1. (a) Surface elevation of the analysis domain, (b) climatological-mean (1973–2012) daily maximum temperature in peak summer (July–August), (c) trend of HWD, (d) difference of IAV (standard deviation) between the early (1973–93) and the recent (1994–2012) periods, and (e) the standardized time series of the domain-averaged HWD over all data points. The linear trend in HWD is removed at each data point before calculation of (d).

Southeast China (SEC), and Northwest China (NWC) have relatively hot summers in East Asia. Elevated or high latitude regions such as Tibetan Plateau where the climatological-mean daily maximum temperature is below

25°C show fewer HWD or no heat-wave events. With secular warming during the analysis period, HWD tends to occur more frequently, as Fig. 1c evidences that most parts of East Asia have a positive trend. It is noticeable

that the upward trend of the heat wave is more dominant over the region with hot summers (SK, SEC, and NWC). The HWD index is calculated as the average of all HWDs over the entire analysis domain and then the resulting time series are normalized by subtracting mean and dividing by standard deviation. (Fig. 1e). The HWD index clearly shows a strong upward trend of HWD across East Asia. Apart from the upward trend of HWD, the interannual variability (IAV) of HWD has become stronger in the recent period. Figure 1d shows the difference in the IAV of HWD between the early and recent periods. In particular, the SK and SEC regions show a significantly larger IAV in the recent period. This increase of IAV is also confirmed in the time series of the HWD index (Fig. 1e). This decadal difference should be considered with the known climate regime shift in the mid-1990s (i.e., Yang and Yuan 2014; Kang et al. 2014).

The low-frequency variability of HWD is extracted by using an 8-yr low-pass filter. The leading EOF of the low-pass-filtered HWD (LF-HWD) is shown in Fig. 2. EOF 1 of LF-HWD has a variance of 56.7%, which seems to be the trend of HWD. The PC time series (PCs) shows a monotonic increase in this analysis, which seems to indicate the signal of global warming. In addition, the PC time series resembles the time series of the AMO index, with a similar phase change in the mid-1990s. Because of the short analysis period of observation data, it is challenging to reasonably separate the global warming effect from the multidecadal variation of HWD. The possible impact of AMO on the heat wave in East Asia is discussed by Xia et al. (2016). They suggested that during the positive phase of the AMO, the anomalous southerly winds with warm temperatures are driven in eastern China. However, the regressed SST pattern on LF-PC1 (Fig. 2c) resembles more the linear trend of SST rather than the AMO SST pattern (not shown), although the latter two patterns are hardly distinguished.

Although the EOF2 accounts for 19.3% of the total variance (not shown), this study does not attempt to interpret this mode as the analysis period of 40 years is short to extract a reliable signal of the low-frequency variability longer than 8 years.

The leading EOF modes for high-frequency (<8 yr) variability of HWD (HF-HWD) are shown in Fig. 3. From the high-pass filter, PCs clearly represent the interannual variability of heat waves. The first mode shows a north–south dipole pattern (N–S pattern), with variability maxima north of 30°N and in southern China. It is noticeable that the variability of PC1 becomes significantly stronger in the recent period. The variability of the second mode shows a maximum in central China and South Korea (the region between 20° and 30°N ; C–C pattern). Unlike the case of PC1, there is no signal of

variability change in PC2. The third mode accounts for less than 10% and is not investigated further in this study.

Figures 4a and 4b show the 200-hPa geopotential height patterns regressed on the PC1 and PC2 shown in Figs. 3b and 3d, respectively. The regressed pattern on PC1 shows the Rossby wave train from the Mediterranean Sea and the Scandinavian Peninsula to East Asia along Russia. The downstream area of the regressed teleconnection pattern over East Asia (Fig. 5a) shows a pattern very similar to the N–S dipole pattern, consistent with that of heat-wave variability (Fig. 3a). This cross-continent teleconnection pattern over Eurasia resembles the SCAND teleconnection pattern suggested by Bueh and Nakamura (2007). The SCAND is originally introduced as the Eurasia-1 pattern (EU1; Barnston and Livezey 1987; Wallace and Gutzler 1981) and noted as a boreal winter teleconnection pattern in the Northern Hemisphere. On the other hand, the Climate Prediction Center (CPC) of NOAA uses the monthly SCAND index, derived from the monthly SCAND loading vectors obtained from the rotated EOF (REOF) analysis to the 500-hPa geopotential height anomalies. For comparison, the original SCAND pattern at 200-hPa level and the associated index are provided in Figs. 5a and 5b, respectively, following the original definition of Barnston and Livezey (1987) except the loading vectors are obtained from the REOF analysis to the July–August mean 500-hPa geopotential height anomalies for 1973–2012. This pattern appears as the 10th EOF mode accounting for 5.2% of the total variance. This pattern resembles much of the SCAND-like pattern presented in Fig. 4a.

In Fig. 4b, a significant signal can be seen over East Asia, which is similar to the C–C pattern of heat-wave variability (Fig. 3c). The large-scale upper-level circulation pattern shows the zonal wavenumber-5 structure centered over western Europe, northwestern India, East Asia, the North Pacific Ocean, and northwestern United States. This wave pattern is similar to the CGT pattern identified by Ding and Wang (2005). This study also compares the pattern in Fig. 4b with the original CGT pattern presented in Fig. 5c. The CGT pattern is obtained from the regression of the 200-hPa geopotential height anomalies onto the CGT index, which is the areal average of 200-hPa geopotential height anomalies over northwest India (35° – 40°N , 60° – 70°E) following the method suggested by Ding and Wang (2005). This pattern matches well with the CGT-like pattern associated with the heat wave in East Asia in Fig. 4b.

The correlation coefficients between PCs and the two large-scale teleconnection indices (i.e., SCAND and CGT) are shown in Fig. 6. As indicated in Fig. 4, the N–S pattern of the heat wave is correlated to the SCAND pattern with a coefficient of 0.69 and the C–C pattern of

FIG. 2. (a) Leading EOF pattern of low-frequency variability of HWD using an 8-yr low-pass filter, (b) the corresponding PC time series (solid), and (c) the regressed SST patterns on the PC time series. Also shown in (b) is the AMO index (dashed). The dotted area in (c) indicates statistical significance at the 95% confidence level.

FIG. 3. (a),(c) Two leading EOF patterns of high-frequency variability of HWD using an 8-yr high-pass filter, and (b),(d) the corresponding PC time series.

the heat wave is correlated to the CGT with a coefficient of 0.59. Both the correlation coefficients are significant at 95% confidence level. This suggests that the two leading patterns of heat-wave variability can be identified as SCAND and CGT, respectively.

It is also noted that the PC time series of N-S pattern shows strong correlation (coefficient $r = -0.56$) with the WPSH index defined as the areal average of the 700-hPa streamfunction anomalies over 25° – 35° N and 110° – 130° E by Liu et al. (2019). Considering the weak correlation ($r = -0.15$) between the SCAND and the WPSH indices for 1973–2012, the heat-wave variability with the N-S pattern may not be entirely associated with the SCAND teleconnection. Being consistent with the results from Liu et al. (2019), the high correlation of the N-S pattern with the WPSH index suggests the importance of other mechanisms related to the WPSH variability such as the northwest Pacific convection and the ENSO variability. On the other hand, the C-C pattern does not show a significant correlation with the WPSH index ($r = 0.16$) at 95% confidence level.

b. Decadal change of interannual variability of heat waves

As shown in Fig. 6, the N-S pattern of the heat wave (EOF 1 in high frequency) shows a dramatic difference

between the early and recent periods. In the early period, the SCAND pattern cannot be observed in any heat-wave patterns. However, PC1 in the recent period shows a very high correlation coefficient of 0.82 with SCAND. This change in the relationship with SCAND is consistent with the change in the variability of HF-PC 1 (Fig. 3b).

Figure 7 shows two leading EOF patterns in each period. In the early period, the C-C pattern can be seen in the first mode. The second mode shows a negative signal over the NWC and a positive signal over the northern part of the Korean Peninsula. In this study, this pattern is not classified because of the lack of clarity of the atmospheric circulation pattern. In the recent period, two classified patterns are clearly observed. The first mode is the N-S pattern and the second mode is the C-C pattern.

The corresponding upper-level atmospheric circulation and WAF in the early period are shown in Fig. 8. The first mode shows the CGT pattern similar to the result in Fig. 4b, with a statistically significant correlation with the CGT index ($r = 0.52$, Fig. 6). The pattern shows a strong signal of wave propagation over the Korean Peninsula and further eastward propagation to the North Pacific, North America, and western Europe.

FIG. 4. Regressed 200-hPa geopotential height (m) on (a) PC1 and (b) PC2 obtained from high-frequency variability of HWD. The dotted area indicates statistical significance at the 95% confidence level.

The strong WAF over East Asia sustains the stationary wave with a steady upper-level anticyclonic circulation that can lead to heat-wave events in that region. Although the wave propagation over the Middle East is weaker than the others, the waves propagate well circumglobally. The circulation pattern associated with the second mode is not clear, as two teleconnection patterns can be observed from the North Atlantic Ocean and west Pacific Ocean. The wave propagation from the tropics could be related to PJ (Nitta 1987). The correlation coefficient between PC2 in the early period and the PJ index is 0.6. On the other hand, the Rossby wave starts over the North Atlantic Ocean and it propagates along Eurasia with contributing to the heat wave in East Asia (Fig. 8b).

The corresponding teleconnection in the recent period is presented in Fig. 9. The teleconnection pattern in the recent period tends to be similar to SCAND (Fig. 9a) and CGT (Fig. 9b), with high correlation coefficients of 0.82 and 0.68, respectively (Fig. 6). In particular, the SCAND pattern clearly shows the strong Rossby wave propagation from the North Atlantic Ocean to East Asia via western Russia. The strong WAF in northern Eurasia seems to extend to the downstream region over East Asia, forming the upper-level structure that may drive the N-S dipole pattern of the heat wave.

As mentioned in the previous section, the SCAND has a statistically insignificant connection with the WPSH

variability for the entire analysis period of 1973–2012. However, it is noted that the correlation between the two indices has increased in the recent period ($r = -0.41$). As shown in Fig. 9a, the SCAND pattern shows significant variability in southern China where the WPSH variability is maximized. This suggests that enhanced teleconnection by SCAND is more frequently impacting on the WPSH variability, thereby increasing heat-wave variability in southern China.

The second mode, similar to CGT, also shows a track of wave propagation that passes East Asia. The CGT pattern related to the C-C pattern of heat wave indicates that the signal is concentrated in Europe in the recent period, while a strong signal can be observed over the Pacific in the early period.

c. Mechanisms for the decadal change of heat-wave variability

The question remains as to why the decadal change occurs in the interannual variation of the heat wave, as shown by the significant relationship to the SCAND teleconnection pattern in the recent period. This study hypothesizes that the land–atmosphere interaction is considered as one of the major drivers in strengthening the SCAND variability. Numerous studies are emphasizing the important role of land–atmosphere interaction in enhancing upper-level stationary waves (Matsumura et al. 2010; Matsumura and Yamazaki 2012; Seo et al. 2019;

FIG. 5. (a) The SCAND teleconnection pattern obtained by the regression of the 200-hPa geopotential height anomalies (m) on (b) the SCAND index, and the CGT (c) pattern and (d) index. The dotted area in (a) and (c) indicates statistical significance at the 95% confidence level. The SCAND index in (b) is defined as the PC time series associated with the 10th REOF mode for the analysis period of 1973–2012. The CGT index in (d) is defined as the areal average of 200-hPa geopotential height anomalies over the northwest of India (35° – 40° N, 60° – 70° E). See the text for details.

Lau et al. 2018). For example, Seo et al. (2019) showed that the upper-level stationary wave pattern associated with the European heat wave in 2003 was better simulated by realistic soil moisture initialization in the global coupled climate model forecasts.

Figure 10 shows the climatological-mean land surface conditions for soil moisture, sensible, and latent heat fluxes (Figs. 10a,c,e) and their decadal changes (Figs. 10b,d,f). In the time-mean state, central and northern Europe show relatively wet soil moisture condition as compared with southern Europe, northern Africa, and the Middle East (Fig. 10a). Soil moisture becomes drier in most of the continent in the recent period, particularly in eastern Europe and Russia (Fig. 10b). Given the incoming net radiative flux, deficient soil moisture would limit the surface evaporation and prefer the sensible heat flux to the atmosphere (Koster et al. 2011). This response is well captured by the changes in the sensible and latent heat fluxes. The sensible heat flux tends to increase in most of the land (Fig. 10d), particularly over the regions where the soil moisture becomes drier in the recent period, whereas the latent heat flux tends to decrease in opposite to the response of sensible heat flux (Fig. 10f). This suggests that the recent drying land surface condition may provide a more favorable condition for the enhanced sensible heat flux at surface.

This study further tests the hypothesis if the enhanced land–atmosphere interaction and low-level heating could amplify the preexisting atmospheric teleconnection pattern. Figure 11 compares the vertically averaged diabatic heating pattern in the past and recent periods. In the recent period, the diabatic heating becomes stronger in western Russia due to decreased soil moisture and the

FIG. 6. Correlation coefficient between each HWD index (PC1 and PC2 obtained from the EOF analysis to the high-frequency variability of HWD) and the teleconnection indices (SCAND and CGT). Solid-filled bars show that the correlation is statistically significant at the 95% confidence level, which is over 0.31, 0.43, and 0.46 for the periods of 1973–2012, 1973–93, and 1994–2012, respectively. Hatched bars are not statistically significant.

FIG. 7. Two leading EOF patterns of high-frequency variability of HWD using an 8-yr high-pass filter for the (a),(b) early (1979–93) and (c),(d) recent (1994–2012) periods.

enhanced sensible heat flux in the region (Fig. 11b). The vertical profile also shows the maximum values in the lower atmosphere, suggesting an increased heat flux from the surface (not shown). Note that the diabatic heating also becomes stronger in the North Atlantic, due to the increased upper-level diabatic heating at the positive AMO phase.

According to the change in the diabatic heating pattern between the early and the recent periods, simple numerical experiments were carried out using SWM and the results are given in Fig. 12. Figure 12a is the SCAND-like pattern reproduced by SWM, which is generated by upper-level vorticity transient forcing at 45°N, 15°W (green contour in Fig. 12a). This pattern is similar to the SCAND shown in Fig. 5a. The development of the Eurasian teleconnection pattern excited by the source in the North Atlantic variability is supported well by previous studies (Sun et al. 2015; Hao et al. 2016).

In the next, diabatic heating forcing is imposed on the model at 60°N, 50°E, where the low-level diabatic heating is enhanced over western Russia in the recent period (Fig. 11c). This region is also featured by enhanced land–atmosphere coupling with the decrease of

soil moisture (Fig. 10b) and the increase of sensible heat flux (Fig. 10d). The result shows the response in the upper-level circulation anomalies, with an anomalous anticyclonic circulation in the east of the forcing location and a cyclonic circulation in the west (Fig. 12b). When these two upper-level circulation anomalies are superposed (Fig. 12c), it shows the overall amplification of the SCAND pattern. This pattern is very similar to the SCAND-like pattern associated with the N–S heat-wave pattern in the recent period (Fig. 9a).

The result of this simple baroclinic model experiment is to a large extent consistent with those from previous numerical experiments with more sophisticated models. Matsumura et al. (2010) conducted numerical experiments with increased and reduced snow cover, respectively, over Eurasia in spring. The land surface becomes warmer and drier in the following summer in the reduced-snow-cover experiment, which leads to the development of large-scale stationary waves propagating eastward with enhanced upper-level winds and WAF along the pathway. The staging of upper-level stationary waves due to enhanced land–atmosphere interaction is also confirmed by the observation and the reanalysis in Matsumura and Yamazaki (2012).

FIG. 8. Regressed 200-hPa geopotential height (shaded; m) and wave activity flux (vectors; $\text{m}^2 \text{s}^{-2}$) on (a) PC1 and (b) PC2 obtained from high-frequency variability of HWD in the early period (1973–93). The regression was performed for the high-pass-filtered geopotential height and wave activity flux. The dotted area indicates statistical significance at the 95% confidence level.

The amplification of the SCAND pattern is also evident from the data. This study further examines whether there was any significant change in the Scandinavian pattern in the recent period by conducting REOF analysis on the reanalysis data. The NCEP CPC has defined the various teleconnection patterns on the basis of the REOF analysis to the 500-hPa geopotential height fields. Following this method, Fig. S1 in the online supplemental material shows the 10 leading patterns and associated time series for the entire period (1973–2012).

The SCAND pattern appears as the 10th mode accounting for 5.2% of the total variance. The associated time series in Fig. S1 exhibits increased year-to-year variability since the mid-1990s, agreeing with the amplitude increase in the PC time series in Fig. 3b. The standard deviation of the time series has increased from 0.8 for 1973–93 to 1.2 for 1994–2012, being amplified by 50%. When the REOF analysis was applied to the separated period, the SCAND pattern does not show up within the 10 leading modes for the analysis period of 1973–93, but

FIG. 9. As in Fig. 8, but for the recent period (1994–2012).

FIG. 10. (a) Climatological-mean (1973–2012) state of surface (0–10 cm) volumetric soil moisture ($\times 100 \text{ m}^3 \text{ m}^{-3}$), and (b) the difference between the early and the recent period (1994–2012 minus 1973–93) during July and August. (c) The sensible heat flux (W m^{-2}) and (d) its difference, and (e) the latent heat flux (W m^{-2}) and (f) its difference. The data are obtained from the NCEP–NCAR Reanalysis 1, and the dotted area indicates statistical significance at the 95% confidence level.

it becomes the fifth mode accounting for 9.1% of the total variance. These results support the idea that the SCAND pattern exhibits a significant decadal change in the peak summer in the Northern Hemisphere.

Figure 13 shows the SCAND patterns from the 10 leading REOF modes of the 500-hPa geopotential height fields for the entire (1973–2012) and the recent (1994–2012) period. The correlation of the PC time series of the two (not shown) is over 0.87 for 1994–2012, indicating that SCAND is robust both in the entire and the recent analysis periods. It is noted that the SCAND pattern is more strongly projected in East Asia in the recent period.

Comparing to the downstream of the SCAND pattern, it shows a much stronger WAF in the recent period (Fig. 13b). As mentioned, the SCAND pattern in the recent period is more connected with the WPSH variability in southern China. Overall strengthening of the SCAND pattern in the reanalysis data is also consistent with the SWM experiment results shown in Fig. 12.

4. Summary

This study analyzes the large-scale spatial pattern of the heat wave in East Asia and corresponding large-scale

FIG. 11. Vertically averaged diabatic heating (K day^{-1}) for the 1000–100-hPa level in July–August during the (a) early (1973–93) and (b) recent (1994–2012) periods. Also shown is (c) the difference of (b) minus (a).

atmospheric circulations. On a decadal time scale, the heat-wave frequency shows a strong upward trend, presumably due to global warming, although the analysis period is too short to clearly separate the signal of AMO from the global warming trend.

On an interannual time scale, there are two dominant spatial patterns in the East Asian heat wave. The first heat-wave pattern is the north–south dipole pattern along

30°N (N–S pattern), closely related to the SCAND teleconnection pattern, and the second pattern shows a zonally elongated pattern centered along 30°N (C–C pattern) that corresponds to the CGT pattern. These large-scale teleconnection patterns cause cyclonic and anticyclonic circulations along the wave propagation path, with the anticyclonic circulation linked to the solar radiation increases and the dominant downward atmospheric

FIG. 12. (a) The SCAND-like teleconnection pattern in the 200-hPa streamfunction anomalies ($\times 10^6 \text{ m}^2 \text{ s}^{-1}$) simulated by SWM forced by the idealized transient vorticity forcing over the Atlantic Ocean (green contours). (b) The stationary wave response in the 200-hPa streamfunction anomalies by SWM forced by the idealized diabatic heating (green contours) over western Russia. (c) The sum of (a) and (b), which represents the amplification of the SCAND-like teleconnection pattern by diabatic heating in western Russia.

motion and the cyclonic circulation linked to the solar radiation decreases and the dominant upward atmospheric motion.

The interannual variation in the heat wave in East Asia also shows a substantial change on the decadal time scale. In the early period (1973–93), the C-C pattern of the heat wave is most dominant, impacted by the CGT teleconnection pattern. However, the N-S pattern becomes most dominant in the recent period (1994–2012), followed by the C-C pattern of the heat wave. The associated large-scale atmospheric circulation patterns well match the SCAND and CGT patterns, respectively.

This study further investigates what is responsible for the decadal change in the atmospheric teleconnection patterns, particularly in SCAND in the recent period. It is hypothesized that changing land surface conditions

may enhance the land–atmosphere coupling and strengthen the SCAND teleconnection pattern. Comparing with the early period, soil moisture becomes drier in most of the land regions, particularly in eastern Europe and western Russia, providing a more favorable condition for sensible heat flux as the dominant heat transfer mechanism to the atmosphere. The simple SWM experiment results support this hypothesis that the enhanced land–atmosphere interaction and low-level heating could amplify the preexisting atmospheric teleconnection pattern.

The amplification of the SCAND pattern is also evident from the reanalysis data. The SCAND teleconnection pattern is identified as the 5th mode accounting for 9.1% of the total summer variability in the 500-hPa geopotential height fields in the recent period, whereas it is not included in the leading modes in the early

FIG. 13. (a) The SCAND pattern (shaded) and the associated WAF vector (arrows) shown in the 10th mode from 10 leading REOFs in the whole period (1973–2012). (b) The SCAND pattern and the WAF shown in the 5th mode in the recent period (1994–2012). The number to the upper right in (a) and (b) indicates the percentage variance from the total.

period. These results support the idea that the SCAND pattern exhibits a significant decadal change in the peak of summer and impacts more on East Asian heat-wave variability.

This study implies that the interannual variation in heat waves shows a significant difference in the two periods. In particular, the intensified role of SCAND in the East Asian heat wave indicates that the atmospheric bridge from the North Atlantic Ocean and Eurasia to East Asia provides a new perspective to large-scale atmospheric circulations causing heat waves in East Asia. Further analysis of the heat-wave variability in association with the North Atlantic Ocean impact would be necessary to eventually improve the prediction of East Asian heat-wave activity.

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