Influences of Boreal Summer Intraseasonal Oscillation on Heat Waves in Monsoon Asia

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ABSTRACT

By analyzing observation-based high-resolution surface air temperature (SAT) data over the Asian monsoon region (here called “monsoon Asia”) for 1981–2007, the modulation by boreal summer intraseasonal oscillation (BSISO) of heat wave (HW) occurrence is examined. Strong SAT variability and a high probability of HW occurrence on intraseasonal time scales are found consistently in the densely populated regions over central India (CI), the Yangtze River valley in China (YR), Japan (JP), and the Korean Peninsula (KP). The two distinct BSISO modes (30–60-day BSISO1 and 10–30-day BSISO2) show different contributions to HW occurrence in monsoon Asia. A significant increase in HW occurrence over CI (YR) is observed during phases 2–3 (8–1) of BSISO2 when the 10–30-day anticyclonic and descending anomaly induce enhanced upward thermal heating and sensible heat flux (warm advection) around the areas. On the other hand, the northeastward propagating BSISO1 is closely connected to the increased HW probability over JP and KP. During phases 7–8 of BSISO1, the 30–60-day subsidence along with the low-level anticyclonic anomaly moves into northeastern Asia, leading to enhanced diabatic (adiabatic) warming near surface in JP (KP). Analysis of a three-dimensional streamfunction tendency equation indicates that diabatic cooling induced by the BSISO-related suppressed convections is the main forcing term of anticyclonic anomaly although it is largely offset by the decreased static stability associated with adiabatic warming. The BSISO-related vorticity advection leads to an anticyclonic (cyclonic) tendency to the northwestern (south-eastern) part of the center of anticyclonic anomaly, favoring northwestward development of the BSISO anomalous circulations and thus providing a favorable condition for HW occurrence over the western Pacific–East Asia sector.

1. Introduction

Heat waves (HW) pose widespread risks as they not only affect public health and ecosystems directly but also damage infrastructure and other societal services. Several extreme HW events have occurred in various parts of the globe in recent years. For instance, a mega HW hit the European sector in 2003, leading to a European death toll of more than 70 000 (Robine et al. 2008). The 2003 European HW was followed by an even more intense and widespread HW across the European, Russian, North American, African, and Asian sectors in 2010 (Blunden et al. 2011). The 2010 HW caused about $500 billion of damage in the Northern Hemisphere. More recently, the China HW of
2013 and India HW of 2015 also led to dramatic impacts on human life, agriculture, and water resources in the densely populated areas of the Asian monsoon region (here called “monsoon Asia”). Owing to high vulnerability to heat extremes in populated regions, a useful forecast of HW beyond 10 days is of great value. Unfortunately, the extended-range or subseasonal forecasts for the next 2–4 weeks remain still challenging in the meteorological and climate communities (Shukla et al. 2010; Webster et al. 2010; Waliser 2011; Hoskins 2013).

The major source of predictability at the subseasonal and extended time range comes from the intraseasonal oscillation (ISO), especially the Madden–Julian oscillation (MJO) characterized by a planetary scale with periods of 30–60 days propagating eastward along the equator (Madden and Julian 1971). Since it is the leading periods of 30–60 days propagating eastward along the equator (Madden and Julian 1971). Since it is the leading mode of subseasonal variability in the tropical climate system, many studies have been devoted to understand how the ISO/MJO affects precipitation and temperature in different parts of the globe (e.g., Jones et al. 2004; Donald et al. 2006; Lin and Brunet 2009; Pai et al. 2011; Zhang et al. 2009; Jia et al. 2011; Alvarez et al. 2016; Matsueda and Takaya 2015; Chu et al. 2017). The anomalous circulation and convective signals associated with the equatorially trapped MJO exert a direct effect on the weather and climate over the tropics (Zhang 2005; Donald et al. 2006; Pai et al. 2011). Meanwhile, the MJO-related heating at the equator could modulate large-scale circulation anomalies and weather systems at the mid-latitudes through Rossby wave trains (Jones et al. 2004; Lin and Brunet 2009; Alvarez et al. 2016). Thus, the MJO has a crucial impact on extratropical rainfall and temperature forecasts at the subseasonal time scale (Jones et al. 2011; Matsueda and Takaya 2015).

The tropical ISO exhibits remarkable seasonal variations (Wang and Rui 1990; Madden and Julian 1994; Salby and Hendon 1994). The eastward-propagating MJO discussed above is most vigorous during boreal winter, whereas it tends to be weakened during boreal summer. The boreal summer intraseasonal oscillation (BSISO) reveals more complex propagating features as compared to the MJO. Prominent northward and northeastward propagations of the BSISO were frequently observed in South Asian monsoon regions (e.g., Yasunari 1980; Annamalai and Slingo 2001; Jiang et al. 2004). In addition to the northward/northeastward propagating signals, the BSISO also shows a northward/northwestward propagating feature over the East Asian monsoon areas and western North Pacific (Lau and Chan 1986; Hsu and Weng 2001; Yun et al. 2008; Chu et al. 2012; Lee et al. 2013). Through altering the large-scale circulation and moisture processes, BSISO activity is highly correlated to rainfall variability and flooding in the Asian monsoon regions (Webster et al. 1998; Mao and Wu 2006; Yang et al. 2010; Moon et al. 2013; Chen et al. 2015; Hsu et al. 2016; Lee et al. 2017). However, how and to what extent the BSISO may exert influences on temperature variability and extreme HW events in monsoon Asia has not been assessed in detail yet. In this study, we examine the association between the life cycle of BSISO and variability of summer HW in the Asian monsoon region. The BSISO-related physical processes responsible for the HW occurrence are also discussed. This work may provide a scientific and statistic basis for developing the extended-range forecast system of HW occurrence in populous Asian monsoon areas.

The remainder of this paper is organized as follows. Section 2 introduces the gauge-based and reanalysis datasets used in the analysis. The methods to define the HW and BSISO and the diagnostic equations to quantify the processes causing near-surface temperature changes are also described here. Section 3 reveals the modulation of SAT and HW by the different modes of BSISO in the Asian summer monsoon regions. The controlling mechanisms of increased HW occurrence in distinct BSISO phases are further discussed. How the anomalous flow patterns associated with BSISO phases are maintained and developed is diagnosed in section 4 based on a three-dimensional streamfunction tendency equation. Finally, the major findings of the study are summarized in section 5.

2. Data and methodology

a. Observation SAT data and definition of HW

To investigate the spatial variations of HW occurrence and their relationship with the BSISO, we utilize the gridded daily surface air temperature (SAT) dataset provided by the Asian Precipitation–Highly Resolved Observational Data Integration toward Evaluation of Water Resources (APHRODITE) project (Yatagai et al. 2009; Yasutomi et al. 2011). This is the state-of-the-art observation-based SAT data with high-resolution (0.25° × 0.25°) grids for Asia (15°S–55°N, 60°–155°E). More than 3000 daily SAT reports since the late 1970s have been obtained by the APHRODITE project. This number is up to 1.5 to 3 times greater than the data available in the Global Telecommunication System network, which was utilized by most gridded temperature products. This APHRODITE SAT product was produced using an improved interpolation and quality control system (Yatagai et al. 2012). Yasutomi et al. (2011) compared the SAT features in the APHRODITE with those derived from the Climate Research Unit (CRU) and the University of Delaware (UDel) datasets.
They found that the patterns of climatological mean and long-term trend in the three datasets are highly consistent with each other. However, the temperature in APHRODITE is slightly higher than that in the CRU and UDel data. This difference probably results from the density of input data (Yasutomi et al. 2011); it is not an issue when identifying the HW event based on a relative temperature threshold (i.e., the 75th and 95th percentiles of local daily SAT climatology).

HW are commonly regarded as a prolonged period of hot days. A modest but long-lasting HW (simply “modest HW” hereafter) is defined when daily SAT is higher than the 75th percentile for 10 consecutive days or more. To measure very hot events, we identify an extreme HW if SAT exceeds the 95th percentile for at least 3 consecutive days. The definition of HW here is similar to previous studies (Gosling et al. 2007; IPCC 2012; Lau and Nath 2014), although the values for temperature threshold and duration of hot days are varied.

b. Reanalysis and other datasets

Daily interpolated outgoing longwave radiation (OLR) available on a 2.5° × 2.5° grid from NOAA (Liebmann and Smith 1996) is used to identify convective signals of the BSISO. To analyze the changes in large-scale circulation and atmospheric and surface heat balance, several meteorological fields were collected from the ECMWF ERA-Interim reanalysis (Dee et al. 2011) at a 1.5° × 1.5° spatial resolution. Three-dimensional variables include the daily-averaged zonal and meridional wind (u and v), vertical p velocity (ω), and temperature (T) fields at 10 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 200, and 100 hPa). Two-dimensional fields used in this study are geopotential at 500 hPa (H500), surface net shortwave radiation (SSR), surface net thermal radiation (STR), sensible heat flux (SHF), and latent heat flux (LHF).

Considering the availability and reliability for all the datasets, the analyzed period in this study covers from 1981 to 2007. We will focus on the influences of BSISO on high temperature extremes during the Asian summer monsoon season [June–August (JJA)] when the two phenomena are both vigorous.

c. BSISO indices

We adopt the BSISO indices proposed by Lee et al. (2013) deriving from the first four multivariate empirical orthogonal functions (EOFs) of OLR and 850-hPa zonal wind anomalies in the Asian summer monsoon region (10°S–40°N, 40°–160°E). The first two leading EOF modes capture the canonical northward/northeastward propagating feature of the ISO with a period of ~30–60 days. This component is referred to as BSISO1. Another component referred to as BSISO2 is defined by the third and fourth EOF modes, which identify the 10–30-day northward/northwestward propagating variability. Lee et al. (2013) found that, compared to the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004), the two BSISO indices could describe a greater fraction of total ISO variability in the Asian monsoon region and better represent the northward propagating features of boreal summer ISO.

A life cycle of each BSISO component is split up into eight distinct phases. Each BSISO phase has an amplitude [(PC1² + PC2²)¹/² or (PC3² + PC4²)¹/²] greater than 1. If a BSISO component has an amplitude smaller than 1, it belongs to the insignificant BSISO (or non-BSISO) state. Table 1 lists the number of days and the averaged BSISO amplitude for each phase during 27 summers (1981–2007).

Table 1. Number of days and averaged amplitude for each phase of the BSISO during 27 summers (1981–2007 JJA); “non” indicates non-BSISO.

<table>
<thead>
<tr>
<th>BSISO1 phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>non</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of days</td>
<td>163</td>
<td>207</td>
<td>201</td>
<td>192</td>
<td>251</td>
<td>172</td>
<td>211</td>
<td>202</td>
<td>881</td>
</tr>
<tr>
<td>Mean amplitude</td>
<td>1.81</td>
<td>1.6</td>
<td>1.52</td>
<td>1.49</td>
<td>1.56</td>
<td>1.6</td>
<td>1.86</td>
<td>1.87</td>
<td>0.66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BSISO2 phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>non</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of days</td>
<td>199</td>
<td>194</td>
<td>218</td>
<td>222</td>
<td>202</td>
<td>209</td>
<td>157</td>
<td>142</td>
<td>940</td>
</tr>
<tr>
<td>Mean amplitude</td>
<td>1.72</td>
<td>1.67</td>
<td>1.63</td>
<td>1.63</td>
<td>1.59</td>
<td>1.62</td>
<td>1.62</td>
<td>1.64</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Figure 1 (Fig. 2) displays the phase composites of convection (OLR) and circulation (H500) associated with BSISO1 (BSISO2). Note that only the anomalous signals exceeding the 95% confidence level based on a Student’s t test and its effective sample sizes were shown. The effective sample sizes (n') for each BSISO phase were calculated by the first-order autoregressive process (Wilks 2011) using the following approximation:

\[ n' = n \frac{1 - \rho_1}{1 + \rho_1}, \]

where n is the original sample size and \( \rho_1 \) is the lag-1 autocorrelation coefficient.
The convective signal of BSISO1 occurs over the equatorial Indian Ocean in phases 1–2 (Figs. 1a,b) and propagates northeastward toward India and Indochina in phases 3–4 (Figs. 1c,d). An obvious wave train structure of BSISO convection and circulation extends northeastward from the tropical Indian and Pacific Oceans toward northeastern Asia and the western North Pacific (Figs. 1a–d). In phase 5, as the BSISO1 convection arrives at the South China Sea and Philippine Sea, a new suppressed anomaly appears in the equatorial Indian Ocean (Fig. 1e). Opposite structures were found between phases 5–8 (Figs. 1e–h) and phases 1–4 (Figs. 1a–d), revealing a whole life cycle of BSISO1. Different from the characteristics of BSISO1, the 10–30-day BSISO2 has a southwest–northeast-tilted horizontal structure propagating northwestward from the western Pacific and Indian Oceans toward the Asian continent (Fig. 2). During phase 1, the convective signal and associated low pressure anomaly are located in the equatorial Indian Ocean and Philippine Sea, but suppressed
convection together with a high pressure anomaly occur over the Bay of Bengal and the subtropical western Pacific (Fig. 2a). After that, the convective signal and the associated circulation pattern propagate northwestward over the Indian and East Asia longitudes (Figs. 2c,d).

d. Diagnostic equations

To elucidate the physical processes contributing to the HW occurrence in association with BSISO1 and BSISO2, the temperature budget equation and surface energy balance are analyzed. Temperature variability is modulated not only by the large-scale circulations associated with horizontal advection and vertical motion–induced adiabatic processes but also by small-scale physical processes [such as radiation and turbulent energy transfer between the surface and planetary boundary layer (PBL)]. Therefore, the temperature change at each constant pressure level could be written as follows:

\[ \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{V} + \omega \sigma + \frac{Q_1}{c_p}, \]

where \( t \) is time, \( \mathbf{V} \) represents the horizontal velocity vector, \( \nabla \) denotes the horizontal gradient operator,
\[ \sigma = (RT/c_p) - (\partial T/\partial p) \] is the static stability, \( R \) is the gas constant, \( p \) is pressure, \( Q_1 \) indicates the atmospheric apparent heat source (Yanai et al. 1973), and \( c_p \) is the specific heat at constant pressure.

As discussed by Yanai et al. (1973), \( Q_1 \) includes the radiative heating, latent heat release, and surface turbulent heat fluxes. At the PBL, \( Q_1 \) is largely modulated by the net upward flux through the surface \( (F_s) \). To understand the major contributors to the near-surface heat source, the surface energy budget equation shown in Eq. (2) is further diagnosed:

\[ F_s = \text{SSR} + \text{STR} + \text{SHF} + \text{LHF} + G, \quad (2) \]

where SSR and STR are the net shortwave and thermal (longwave) radiations at the surface, respectively. SHF and LHF denote sensible and latent heat fluxes, respectively. The ground heat flux \( G \) is generally small. Thus, it is ignored in this study. All fluxes are positive upward.

Since the warm anomaly is largely influenced by the anomalous descending motion along with low-level anticyclonic circulations, to clarify how the BSISO modulates the tendency and maintenance of low-frequency (30–60-day and 10–30-day) circulation anomaly, the streamfunction tendency equation formulated by Tsou et al. (2005) is diagnosed. This diagnostic equation was derived from the vorticity and thermodynamic equations in the isobaric coordinates for the global planetary-scale waves. For detailed derivations, refer to Tsou et al. (2005). The formulation of the three-dimensional streamfunction equation is written as

\[ \left[ \nabla^2 + \frac{f^2}{\sigma} \frac{\partial^2}{\partial P^2} \right] \frac{\partial \psi}{\partial t} = -\nabla \cdot (\nabla^2 \psi + f) - \frac{fR}{\sigma} \frac{\partial}{\partial P} \left( -\frac{\nabla \cdot \nabla T}{P} \right) - \frac{f\omega}{\sigma} \frac{\partial \psi}{\partial P} - \frac{fR}{\sigma c_p} \frac{\partial}{\partial P} \left( \frac{Q_1}{P} \right), \quad (3) \]

where \( f \) denotes the Coriolis parameter and \( \psi \) is streamfunction. The Laplacian of the streamfunction tendency is written in the left-hand side of Eq. (3). Forcing terms (in the right-hand side of the equation) include vorticity advection (first term), differential temperature advection (second term), vertical advection of static stability (third term), and differential heating (fourth term). Equation (3) is solved by the successive overrelaxation method (Tsou et al. 1987). Using this diagnostic equation, the roles of vorticity advection, temperature advection, static stability, and diabatic heating in supporting the BSISO circulation anomalies will be examined in section 4.

3. Influences of BSISO on SAT and HW in monsoon Asia

a. Summer SAT variability over monsoon regions

Climatology and variability of summer SAT over Asia is derived from the high-resolution APHRODITE dataset (Fig. 3). High summer-mean SAT over 25°C prevails over countries in South and East Asia, with the maximum temperature (over 30°C) in northwestern India and Pakistan. Lower SAT is found in the mid-latitudes and the Tibetan Plateau (Fig. 3a). Although SAT is relatively low in the midlatitudes, it exhibits great variability over Mongolia, the Kazakhs, and southern Russia (Fig. 3b). For the Asian summer monsoon area, four regions with pronounced variability of SAT are identified: central India (CI; 15°–30°N, 72.5°–82.5°E), (b) the middle and lower reaches of the Yangtze
River (YR; 25°–35°N, 102°–122°E), (c) Japan (JP; 35°–45°N, 135°–145°E), and (d) the Korean Peninsula (KP; 35°–45°N, 125°–135°E). These are also the densely populated countries or areas. We shall henceforth focus on the characteristics of summer SAT, in particular during warm events, in the four key regions.

Applying the fast Fourier transform (FFT) to the area-averaged daily SAT time series, Fig. 4 reveals the dominant periodicity of SAT in these four regions respectively. The power spectrum of regional SAT variability is obtained each year separately and then averaged for the 27 years of 1981–2007. Two statistically significant spectrum peaks (relative to the red noise) at the 10–60-day intraseasonal time scale and a high-frequency (< 10 days) synoptic scale were detected in the spectral analysis. This suggests that the major high or low temperature events may be linked to not only the high-frequency weather events but also the low-frequency BSISO activity at the 10–60-day time scale (Fig. 4).

Figures 5–7 further confirm the modulations of SAT anomaly by the BSISO. The composite anomalies of SAT associated with BSISO1 and BSISO2 phases are shown in Figs. 5 and 6, respectively, while the influence of BSISO on the extreme SAT event is illustrated by the probability density functions (PDFs) as a function of BSISO phases in Fig. 7. It should be mentioned that all anomalies in each panel in Figs. 5 and 6 were obtained against the non-BSISO state, which is independent of any phases of the BSISO life cycle. However, the non-BSISO state is almost identical to climatological mean state. In Fig. 7, PDFs are depicted as a box-and-whisker plot with SAT values collected from each phase of the BSISO modes as well as from the non-BSISO state. A box-and-whisker plot splits the set of data into quartiles and variability outside the lower and upper quartiles. The bottom and top of the box indicate the first and third quartiles, respectively. Inside the box, the line marks the median (second quartile) of the dataset. The two whiskers extending from the bottom and top of the box represent the values of 5th and 95th percentiles, respectively.

The spatial distribution of SAT anomalies over monsoon Asia is considerably modulated by the BSISO1 life cycle (Fig. 5). As the 30–60-day suppressed convection with anticyclonic anomaly propagates northward across the South Asian monsoon region (Figs. 1a–d), positive SAT anomalies appear first at the southern and central parts of India during phases 1–2 of BSISO1 (Figs. 5a,b) and then move toward the northeastern part of India during phases 3–4 (Figs. 5c–d). Along with the increase in mean SAT anomalies, the 95th (75th) percentiles of SAT in CI tends to be skewed.

![FIG. 4. Power spectra of JJA SAT over (a) central India (CI: 15°–30°N, 72.5°–82.5°E), (b) the middle and lower reaches of the Yangtze River (YR: 25°–35°N, 102°–122°E), (c) Japan (JP: 35°–45°N, 135°–145°E), and (d) the Korean Peninsula (KP: 35°–45°N, 125°–135°E), shown in the boxes in Fig. 3. Dashed curves represent the 95% and 5% significant levels of red noise spectrum (gray solid curve). The annual cycle is removed before the spectrum analysis.](image-url)
toward high values during phase 2 (3) of BSISO1 (Fig. 7a). Meanwhile, subtropical and midlatitude East Asia is affected by the 30–60-day convection and associated cyclonic anomaly (Figs. 1b–e). Negative SAT anomalies and a lower value of 75th and 95th percentiles are observed over YR, KP, and JP areas during phases 3–4 of BSISO1 (Figs. 7b–d). Opposite SAT features appear in the remaining phases of BSISO1, such as significant decreases (increases) in SAT anomaly and hot extreme tails over CI (KP and JP) during phases 7–8 of BSISO1 (Figs. 5g,h and 7c,d).

BSISO2 activity also exerts a significant influence on daily SAT anomalies in the Asian monsoon region. The SAT anomaly increases larger than 2°C over India during phases 2–4 of BSISO2 with respect to that during the non-BSISO state (Figs. 6b–d). Accordingly, a considerable positive skewness of the hot extreme tail is identified during phases 2–4 of BSISO2 (Fig. 7e). Although the median and 75th and 95th percentiles of SAT in YR show less evident change along with phases of BSISO1 (Fig. 7b), they reveal an obvious increase in phases 8–1 of the BSISO2 relative to the non-BSISO

FIG. 5. As in Fig. 1, but for the composite of SAT anomaly (contour, unit: °C). Only significant changes exceeding the 95% confidence level based on a Student’s t test and its effective degree of freedom are shaded in color.
state (Figs. 6a, h and 7f). As for the SAT variability over northeastern Asia, higher (lower) values of SAT anomaly and a hot (cold) extreme tail appear in KP and JP during phases 8–1 (3–6) of BSISO2 (Figs. 6 and 7g, h).

b. Changes in HW occurrence associated with BSISO

In association with the SAT anomalies modulated by BSISO activities discussed in the previous subsection, here we analyze changes in HW occurrence over Asia as a function of BSISO phases focusing on persistent heat conditions that can cause severe disasters. The identification of HW occurrence is based on the SAT thresholds at the 75th and 95th percentiles, as described in section 2a. Figures 8a and 8c show the spatial distributions of each threshold value at individual grid points during the summer monsoon season. The spatial patterns of SAT value at the 75th and 95th percentiles are similar to the distribution of summer-mean SAT (Fig. 3). The 75th (95th) percentile values averaged over CI, YR, JP, and KP are about 1.3°C (4.9°C), 2.2°C (3.7°C), 2.6°C (5.3°C), and 2.1°C (4.6°C) higher than their climatological JJA mean. According to the HW definitions, a modest (extreme) HW occurs when the local SAT anomaly is higher than the 75th (95th) percentile value, that is,
1.3°–2.6°C (3.7°–5.3°C) depending on region, for more than 10 (3) consecutive days in the four key regions. Figures 8b and 8d illustrate the geographical distributions of the ratios of numbers of HW days per summer (i.e., 92 days in JJA) for modest and extreme events, respectively. It is important to note that a high probability of HW occurrence is observed over the four key regions where considerable SAT variabilities on intraseasonal time scales occur (Figs. 3 and 4). Climatologically, a modest but long-lasting HW has
about a 5%–15% chance of occurring (Fig. 8b), whereas an extreme HW has about a 2%–6% chance, with high regional dependence, during entire Asian summer monsoon season (Fig. 8d). It is worth noting that HW occurrence is the highest over CI in Asia. On average, India tends to experience modest and extreme HW events for more than 14 days and about 3–4 days per summer (JJA), respectively. The modest HW days over YR, JP, and KP on average are about 7, 10, and 11 days, respectively, in a summer season.

To examine spatial characteristics of HW occurrence influenced by the BSISO activity, changes in probability of HW occurrence at each grid point for individual BSISO1 and BSISO2 phases relative to the non-BSISO states are illustrated in Figs. 9 and 10, respectively. The composite map for the changes is based on the number of HW days rather than the number of HW events. Only the days during the HW events were included. It is of importance to note that BSISO1 and BSISO2 strongly modulate HW occurrence depending on their phases and regions. Over the Asian monsoon region, robust changes are observed over not only the four key regions (CI, YR, JP, and KP) but also the Indochina Peninsula. However, the chance of HW occurrence over the Indochina Peninsula is relatively low (1%–2%; Figs. 8b,d). Even when the probability increases 200% in some specific BSISO phases, the actual frequency of HW events is around 2%–4%, which is much lower than those over the four key regions. The domain-averaged values of anomalous HW probability over the four key regions are listed in Table 2. Besides the monsoon region, the frequency of HW events in Pakistan, Mongolia, Kazakhstan, Russia, and the Maritime Continent also varies with BSISO phases. The influences of BSISO on HW occurrence in these regions are out of the scope of the current study, which focuses on the Asian monsoon area.

In JP and KP, the chance of the HW occurrence is significantly high and the spatial extent of HW events is large during the phases 7–8 of BSISO1 relative to the non-BSISO states (Fig. 9 and Table 2). The probability of modest and extreme HW increases by 80%–90% and 120%–160%, respectively, compared to the non-BSISO days in the two regions (Table 2). However, small increases (~24%) of HW probability in the CI sector are also observed in phase 3 of the BSISO1. In YR, a limited region shows a statistically significant

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**FIG. 8.** Distributions of (a) 75th and (d) 95th percentile of surface air temperature in JJA climatology (unit: °C). (b),(c) The climatological probabilities (unit: %) of modest HW (daily SAT exceeding 75th percentile for 10 days or more) occurrence and extreme HW (daily SAT exceeding 95th percentile for 3 days or more) during the period of 1981–2007, respectively. (c),(f) As in (b),(e), but for the composite for non-BSISO periods.
This result suggests that the northeastward-propagating BSISO1 with 30–60-day time scale exerts a greater impact on the HW occurrence over northeastern Asia (JP and KP) than the tropical monsoon regions (CI and YR).

In contrast to BSISO1, the northwestward-propagating BSISO2 with biweekly and 30-day time scales seems to be more related to the HW occurrence in the CI and YR areas. There is a conspicuous increase in the probability of HW occurrence over CI during the phases 2–4 of BSISO2 (Fig. 10). The highest
probabilities of both modest and extreme HW occurrences in CI appear at phase 3 of BSISO2, with about a 173% and 500% increase of likelihood, respectively, as compared to the non-BSISO period. During the phases 2 and 4, the probability of modest HW occurrence increases by more than 140% while the extreme HW shows more than a 300% increase in occurrence probability on average (Table 2). For the YR region, the chances of modest and extreme HW occurrence tend to go up in the phases 8–1 of BSISO2 (Fig. 10), during which the probability of HW occurrence increases by 20%–60% relative to the non-BSISO period (Table 2).

To verify the robustness of the results of Figs. 9 and 10, we carried out several sensitivity tests using different data sources, variables, and definitions. First, we repeated the same analysis using daily surface temperature (Tave) obtained from ERA-Interim and NCEP–DOE. Second, daily maximum surface temperature (Tmax), which has been often used to define HW, was utilized obtained from ERA-Interim with horizontal resolution of 0.75° × 0.75°. Last, the PDF of temperature for each day (D) during boreal summer was derived from temperature data during the period between D − 10 (10 days before D) and D + 10 (10 days after D) for 1981–2007 as suggested by Stefanon et al. (2012). It is found that the results of Figs. 9 and 10 are...
TABLE 2. (top) Percentage changes (%) in probability of HW occurrence averaged over the four key regions (CI: 15°–30°N, 72.5°–82.5°E; YR: 25°–35°N, 102°–122°E; JP: 35°–45°N, 135°–145°E; KP: 35°–45°N, 125°–135°E) during different BSISO1 phases relative to the non-BSISO state. The letters M and E denote the modest and extreme HW events, respectively. Only the grid points with HW changes exceeding the 95% confidence level were considered. Bold numbers denote that more than half of grid points within the area domain show a statistically significant change. An em dash (—) indicates that no HW occurrence in that phase. (bottom) As at top, but for the composite BSISO2 phases.

<table>
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<th>HW change (%)</th>
<th>BSISO1 phase</th>
<th>1</th>
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<th>3</th>
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almost identical regardless of different variables, data sources, and definitions, demonstrating that the current result of the BSISO modulation on HW is robust.

c. Key processes for the BSISO modulation on the HW

To understand key processes that result in the increased probability of HW occurrence in the key regions, we diagnose the temperature budget equation discussed in section 2d at near surface (925 hPa) during the period with a significant increase in HW occurrence. To ensure that the variability of near-surface temperature obtained from the ERA-Interim here could also capture the SAT changes derived from APHRODITE, we compared the temporal variability and the probability of HW occurrence in the two databases. The results show that the temporal correlation coefficients of daily temperature over the four key regions in JJA of 1981–2007 are around 0.8–0.9 and the distributions of HW frequency during different BSISO phases are highly consistent between the two datasets. Thus, it should be reasonable to use the reanalysis data to diagnose the processes causing the increased HW occurrence shown in the observation.

As shown in Fig. 11, the key processes to control the HW occurrence strongly depend on the regions. The HW occurrence in CI is mainly attributed to the increased diabatic heating (Fig. 11a) associated with the 10–30-day suppressed convection during phases 2–3 of BSISO2 (Figs. 2b,c). According to the surface energy budget, the enhanced diabatic heating is mainly due to the increased upward STR and SHF as the SSR is increased in a clear-sky condition (Fig. 11e). The adiabatic heating related to surface turbulent fluxes and the adiabatic heating due to subsidence associated with phases 8–1 of BSISO2 plays a leading role in the increased HW occurrence (Fig. 11b). The 10–30-day suppressed convection during phases 2–3 of BSISO2 phase contributes positively to the warm condition in CI. Over YR, the warm advection associated with anomalous circulations of 10–30-day variability during phases 8–1 of BSISO2 plays a leading role in the increased HW occurrence (Fig. 11b). The northeast–southwest-oriented high anomaly of H500 along with suppressed convective anomaly extending from the South China Sea toward the south of Japan (Figs. 2a,h) lead to high SAT to the east of YR (Fig. 12). The 10–30-day easterly anomaly between the anticyclonic anomaly in the northwestern Pacific and the cyclonic anomaly near the Philippine Sea transports the warm air toward YR (Fig. 12).

For the HW occurrences in the midlatitude monsoon areas (JP and KP), important factors are the diabatic heating related to surface turbulent fluxes and the adiabatic heating due to subsidence associated with phases 7–8 of the BSISO1 (Figs. 11c,d,g,h). The diabatic heating plays more important role on the HW of JP while the
adiabatic heating is the key player on the HW of KP. Although the convective signals of 30–60-day BSISO1 become weak when they propagate toward the mid-latitude region, the anomalous geopotential patterns clearly remain significant (Fig. 1). During phases 7–8 of the BSISO1 (Figs. 1g,h), a high anomaly of H500 is present over the JP and KP areas where subsidence and clear sky are favored. The large-scale downward motion
causes increased adiabatic heating (Figs. 11c,d). Under the clear sky, the increased SSR also prompts the increased STE, SHF, and LHF that all benefit the warming of near-surface air (Figs. 11g,h).

In sum, the northeastward-propagating BSISO1 influences significantly the high probability of HW occurrence in the JP and KP sectors during its phases 7–8 via adiabatic and diabatic warming as its convection and circulation anomalies arrive at northeastern Asia. In contrast, the northwestward-propagating BSISO2 prompts increased HW in CI during its phases 2–3 and YR during its phases 8–1 when anomalous anticyclonic circulations associated with the suppressed convections induce subsidence and warm advection over those regions. This suggests that both BSISO1 and BSISO2 directly affect SAT anomaly and HW outbreak probability in the Asian monsoon regions when their anomalous convections and circulations propagate northward toward the extratropics. This is different from the MJO impacts on SAT in the higher latitudes. The equatorially trapped MJO convective heating induces a Rossby wave train extending toward higher latitudes, resulting in circulation anomalies and SAT variations in the off-equatorial regions (Lin and Brunet 2009; Matsueda and Takaya 2015; Alvarez et al. 2016).

4. Mechanisms for the maintenance of circulation anomalies

As shown in the previous section, the near-surface prolonged warm conditions responsible for HW occurrence intrinsically link to the low-level anomalous circulations associated with the BSISO activities. A HW event occurs coincidently with the BSISO-related descending and anticyclonic anomaly at the lower troposphere. Thus, it is of importance to better understand how the BSISO-related low-frequency anticyclonic circulation is developed, intensified, and maintained to provide a favorable condition for the prolonged warm temperature anomaly and then HW event in certain parts of Asia depending on the BSISO phase. By diagnosing a streamfunction tendency equation [Eq. (3)], we have investigated key mechanisms for the maintenance of the BSISO-related circulation anomalies.

Figure 13a displays 850-hPa streamfunction and 500-hPa geopotential height anomaly regressed onto the PC2, representing the phase 2 of BSISO1 when the northwest–southeast-oriented high anomaly and HW appear over the Indian subcontinent, the Indochina Peninsula, and the Philippines as also shown in Figs. 5a and 9. In addition, there are distinct wave trains over the western North Pacific and East Asia into the extratropical North Pacific.

We investigate the effects of vorticity advection (Fig. 13b), temperature advection (Fig. 13c), static stability (Fig. 13d), and diabatic heating (Fig. 13e) on development and maintenance of the BSISO1-related anticyclonic circulation anomaly at the low-level troposphere. There are three important points in the results. First, the low-level vorticity advection plays an important role in the northward propagation and development of the
low-level circulation as suggested by previous studies (Jiang et al. 2004; Tsou et al. 2005). Figure 13b indicates that the negative streamfunction tendency due to vorticity advection occurs to the northwest of the BSISO1-related cyclonic anomalies (i.e., negative streamfunction) over the western Pacific, whereas a positive tendency is observed to the southeast of the anomalies. It suggests that the low-level vorticity advections would lead to
northwestward development of BSISO circulations. Second, the maintenance of the BSISO circulation anomalies is attributable mainly to the diabatic heating generated by the BSISO convection (Fig. 13e). The weakened (enhanced) diabatic heating associated with the suppressed (active) BSISO convections contributes to the positive (negative) tendency of the streamfunction anomaly near the center of anticyclonic (cyclonic) circulations (Fig. 13e). The positive contribution of temperature advection is relatively small (Fig. 13c). Last, the combined effect of diabatic heating, vorticity advection, and temperature advections is largely offset by the effect of vertical advection of static stability associated with anomalous vertical motions of BSISO. As shown in Fig. 13d, a negative (positive) streamfunction tendency is observed over the regions with a positive (negative) streamfunction anomaly. This indicates that adiabatic warming generated by the BSISO1-related anticyclonic anomaly would inhibit its growth once it is established and then lead to its diminishment.

Analysis further suggests that the key mechanisms for the low-level anticyclonic circulation anomaly associated with the BSISO2 are quite similar to those for the BSISO1. Figure 13f shows 850-hPa streamfunction and 500-hPa geopotential height anomaly regressed onto PC4, representing phase 6 of BSISO when the anticyclonic (cyclonic) circulation anomaly with a northeast–southwest tilt is located over the South China Sea and western North Pacific (Maritime Continent and Philippine Sea). Similarly, low-level vorticity advection plays a role in propagation and development of the circulation anomalies (Fig. 13g) whereas diabatic heating (Fig. 13j) and temperature advection (Fig. 13h) maintain them. Adiabatic warming generated by the BSISO2-related anticyclonic anomaly eventually diminish this anomaly (Fig. 13j).

This section discusses how the BSISO-related anticyclonic circulation anomalies propagate, develop, maintain, and diminish. The HW occurrence is likely modulated by the life cycle of the anticyclonic circulation anomalies. Note that the results based on regression analysis of PC1/PC3 indices are consistent with those using PC2/PC4 indices shown in Fig. 13.

5. Summary

A number of studies have been devoted to understand the role of the BSISO in causing the rainfall extremes and flooding events during the Asian summer monsoon season (Webster et al. 1998; Annamalai and Slingo 2001; Mao and Wu 2006; Yang et al. 2010; Chen et al. 2015; Hsu et al. 2016). However, little attention has been paid to BSISO influences on the heat extremes in monsoon Asia. Using an observation-based high-resolution (0.25° × 0.25°) SAT dataset over Eurasia and the real-time BSISO indices proposed by Lee et al. (2013), this study examined systematically the relationship of two BSISO modes with HW characteristics during the Asian summer monsoon season.

It is found that an enhanced SAT and high probability of HW occurrence appear consistently over the densely populated areas in central India, the Yangtze River valley in China, Japan, and the Korean Peninsula. The spectral analysis of SAT anomaly in the four key regions during JJA 1981–2007 shows significant subseasonal variability with the period of 10–60 days, suggesting the modulations of SAT by the BSISO. Differently from the impacts of the MJO on off-equatorial SAT variations via teleconnection (Lin and Brunet 2009; Matsueda and Takaya 2015; Alvarez et al. 2016), the northward-propagating BSISO may change directly the large-scale circulations and small-scale surface energy processes in the tropical and extratropical monsoon regions, which in turn results in changes in SAT anomaly and HW occurrence.

The two BSISO modes reveal different influences on the HW occurrence in the Asian monsoon regions. BSISO1 affects significantly the occurrences of high HW probability over northeastern Asia (JP and KP), whereas BSISO2 is closely connected to the increases in HW occurrence over the tropical and subtropical monsoon regions (CI and YR). This difference could be attributed to the propagating characteristics of the two BSISO modes. The 30–60-day BSISO1 shows a northeastward propagating feature from the tropics into northeastern Asia. During phases 7–8 of the BSISO1, when the suppressed convection moves into northeastern Asia, the related subsidence induces enhanced adiabatic and diabatic warming over JP and KP. Meanwhile, the probability of HW occurrence in JP and KP increases by 75%–200% relative to the non-BSISO state. The BSISO2 shows a northwestward propagating feature, moving from the tropical western Pacific and Indian Oceans toward the Asian continent. During phases 2–3 of the BSISO2, when the suppressed convection prevails over the India subcontinent, enhanced upward thermal radiation and SHF warm up the near-surface atmosphere. In these periods, the chance of HW occurrence tends to be increased remarkably (150%–500%). As the 10–30-day suppressed convection propagates from the western Pacific toward East Asia during phases 8–1 of the BSISO2, the anomalous circulations induce warm advection and adiabatic warming over YR and lead to an increased probability of HW occurrence there. The circulation anomalies associated with 30–60-day and 10–30-day BSISO play a key role in inducing a persistent warm
condition for HW occurrence. Based on the diagnosis of the streamfunction tendency equation, we identified the dominant physical processes that influence the development of BSISO-related anomalous circulation patterns. It is noted that the processes and mechanisms responsible for the development of 30–60-day and 10–30-day wave trains are similar. Consistent with previous studies (Jiang et al. 2004; Tsou et al. 2005), it is also found that the low-level vorticity advection is important to the northward and northwestern propagation of the BSISO circulations since the anticyclonic (cyclonic) tendency due to vorticity advection is observed to the northwest of the anticyclonic (cyclonic) anomaly. Different from the effect of vorticity advection, the anticyclonic (cyclonic) tendency induced by diabatic cooling (heating) anomaly appears at the center of the anomalous anticyclonic (cyclonic) anomalies of BSISO. This suggests that the effect of diabatic heating associated with BSISO deep convections plays a dominant role in maintaining the anomalous BSISO circulations. Although the amplitude is small, the effect of temperature advection also contributes positively to the maintenance of BSISO flow patterns. Once the BSISO convection and circulation anomalies have developed, however, the static stability effect related to anomalous vertical motions tends to inhibit a further growth of the BSISO. The positive contribution of combined effect of diabatic heating, vorticity, and thermal advections to the BSISO development is largely offset by the negative feedback of static stability.

This study focuses on only four key regions over the Asian monsoon area. However, it should be mentioned that the BSISO also strongly modulates HW occurrence over other regions including parts of Europe, Russia, the Indochina Peninsula, and the Maritime Continent. Further study will address how BSISO1 and BSISO2 impact HW occurrence over those regions.

The tight connection between BSISO activity and changes in HW frequency provides the potential for HW monitoring and forecasting at an extended range (Webster et al. 2010; Waliser 2011). Given the important role of BSISO in extreme weather and climate events over Asian monsoon regions, the Asia-Pacific Economic Cooperation (APEC) Climate Center (APCC) has provided real-time forecast of the BSISO indices since 2013. Kim et al. (2015) and Wheeler et al. (2017) assessed the predictability of BSISO from five dynamical forecast systems that participated in the operational BSISO forecast project in APCC. They found that several models have useful forecast skill for the BSISO indices beyond 15–20 days. Further demonstrations of the modeled modulations of HW by the BSISO and the prediction skill of HW in the Asian monsoon areas are our ongoing research.

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